2013

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Recommended Citation

O' Mahony, T.; Zhou, P.; Sweeney, J. (2013) Integrated scenarios of energy-related CO2 emissions in Ireland: A multi-sectoral analysis to 2020. *Ecological Economics*, 2013, 93, 385-397. doi:10.1016/j.ecolecon.2013.16.016

Funder: The original research that facilitated this paper was part-funded

Integrated scenarios of energy-related CO_2 emissions in Ireland: A multi-sectoral analysis to 2020

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Abstract

This paper presents future scenarios of Irish energy-related CO_2 emissions to 2020, using a combination of multi-sectoral decomposition analysis with scenario analysis. Alternative development paths, driving forces and sectoral contributions in different scenarios have been explored. The scenarios are quantified by using decomposition analysis as a Divisia Index SCenario GENerator (DISCGEN). The driving forces of population, economic and social development, energy resources and technology and governance and policies are discussed. A set of four integrated or 'hybrid' qualitative and quantitative baseline emission scenarios are developed. It is found that sectoral contributions and emissions in each scenario vary significantly. The inclusion of governance, social and cultural driving forces are important in determining alternative development paths and sustainability is crucial. Our empirical results show that decomposition analysis is a useful technique to generate the alternative scenarios.

Keywords: Decomposition analysis; Scenario analysis; CO_2 emissions

1. Introduction

Greenhouse Gas (GHG) emissions increased significantly in Ireland from 1990 to 2007 driven by the increase in energy-related CO_2 emissions (McGettigan *et al.*, 2009). The advent of the economic recession in 2008 led to a steep drop in GHG emissions. While this may facilitate

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compliance with Ireland's Kyoto protocol target [1], achieving future targets may prove challenging. Enhanced insights into future emission levels and their driving forces, particularly energy-related CO_2 emissions[2], are consequently important inputs for mitigation policy and decision support. A historical analysis of the sectoral driving forces of CO_2 emissions in Ireland is detailed in O' Mahony *et al*. (2012). This paper builds upon O' Mahony *et al*. (2012) to develop integrated exploratory baseline scenarios from 2008 to 2020 for the same eleven final consumption sectors. The study was implemented before full data sets became available for 2008 and 2009, and as such, also offers potential insights into alternative developments during a recession. As outlined in O' Mahony *et al*. (2012), some of the driving forces historically included economic growth and the patterns of production, consumption and development that arose in tandem. While the recession has afforded 'breathing space,' the potential for rapid increase in emissions upon the resumption of economic growth remains.

Uncertainty surrounds future economic growth and the evolution of other driving forces, and consequently significant uncertainty surrounds future emissions. This poses not only methodological difficulties for energy analysts but also problems for policy-making reliant on forecasts. The dominant approach applies quantitative point forecasts [3] with accompanying forecast errors. In energy and CO_2 emissions forecasting large absolute errors occur even on short time scales (Linderoth, 2002) sometimes concealing considerable errors in the sectors, particularly for industry and transport (Winebrake and Sakva, 2005). Errors observed in an Irish

[1] Under the EU 'burden sharing mechanism' Ireland's target was to limit the increase in GHG emissions to +13% on 1990 by 2008-2012.

[2] Energy-related CO_2 emissions increased by 49.4% from 1990 to 2007 and accounted for two-thirds of all GHG emissions (McGettigan *et al*., 2009).

[3] Reporting guidelines (UNFCCC, 2000) describe three projections required in national communications; "With Measures" (WM) of currently implemented and adopted policies and measures, "With Additional Measures" (WAM) of planned policies and measures and "Without Measures" (WOM) excluding all policies and measures implemented, adopted or planned after the starting year referred to as the "baseline" or "reference" projection. Parties may report sensitivity analysis, but are recommended to limit the number of scenarios. While this process may appear less cumbersome, projection exercises that rely on single point forecasts will inevitably be subject to greater uncertainty and difficulties with accuracy, as opposed to ranges provided for by scenario approaches. Strategic policy implications will arise where forecast inaccuracy increases.

context have been noted (Kelly *et al*., 2010; Pilavachi *et al*., 2008). The reviews of Irelands' communications to the United Nations Framework Convention on Climate Change (UNFCCC) noted a significant difference between recent short term projections and requested explanation (UNFCCC, 2009; UNFCCC, 2010).

Just as inadequate intervention and regulation can come with large and avoidable social costs (Storm and Nastepad, 2007), decision-making reliant on inaccurate forecasts could also lead to avoidable social, economic and environmental costs. The Dublin workshop on national communications suggested a need to produce additional scenarios with varying assumptions such as Gross Domestic Product (GDP) growth (UNFCCC, 2004). While scenarios are frequently used for the long-term (Nakicenovic *et al*., 2000; EEA, 2000), the difficulty experienced with producing accurate forecasts highlights a potential benefit of using scenarios on shorter time scales. Scenarios in general offer an approach to manage uncertainty and make policy more robust.

The combination of scenario analysis and decomposition analysis was pioneered through input-output (IO) models such as that of Leontief and Duchin (1986). This combination of approaches was applied to the analysis of future environmental impacts by Duchin (1998) and its application has expanded in studies such as Hubacek and Sun, (2005) and Barrett and Scott (2012). Kaivo-oja *et al*. (2001) developed a conceptual framework combining a type of decomposition analysis using identities with scenario analysis enabling sustainability evaluation. Barrett and Scott (2012) outlined two main techniques in the literature for projecting model variables in scenarios: trend analysis and expert knowledge. The expert knowledge technique is regarded as more data and labour intensive but also as a more insightful and realistic projection. Differing from these earlier studies, this study combines scenario analysis with another major branch of decomposition analysis methodology called index decomposition analysis (IDA). IDA is widely used for historical emission and energy analysis, but has rarely been used in conjunction with scenario techniques or in forecasting. This has been recommended as a key area for future research (Ang and Zhang, 2000; Hatzigeorgiou *et al.,* 2008; Sorrell *et al.,* 2009). Recent studies have used different combinations of scenario approaches and IDA (Hatzigeorgiou *et al*., 2010; Agnolucci *et al.*, 2009; Steenhof, 2007; Steenhof *et al.,* 2006; Kwon, 2005; Sun, 2001). Agnolucci *et al.* (2009) used the back-casting scenario approach with the Kaya identity (Kaya, 1990) to elaborate different UK carbon reduction scenarios to 2050. These back-casting scenarios were both qualitative and quantitative, using an expert knowledge approach to model variables. The other studies were trend-based scenarios using IPAT, Laspeyres or Divisia decomposition[4,5].

This study implemented 'hybrid exploratory scenarios' that integrate qualitative and quantitative scenario techniques. The scenarios explore equally plausible alternative futures rather than the trend-based scenarios or back-casting of desirable outcomes. The implementation of a process similar to Alcamo (2001) that includes a qualitative approach and also allows for variation of historical dynamics is particularly important in national mitigation. These integrated visions of alternative development paths offer insights into key processes relevant both to reducing emissions and also the potential sources of uncertainty in projections. Sathaye *et al*. (2007) concluded that reducing emissions is not simply a question of mitigation or energy policy, but is inherently linked to the underlying wider development path. Developing these more broad holistic perspectives on processes of change is consequently policy relevant in all states. In discussing methodological implications, Fisher *et al*. (2007) highlighted the advancement in the literature of the integration of qualitative and quantitative approaches as a way forward. This

[4] Trend-based scenarios produce quantitative results as a reference or Business As Usual (BAU) projection and can include optimistic and pessimistic alternatives.
[5] Hatzigeorgiou *et al*. (2010) is based on the results of the EU PRIMES energy and emissions forecasts of DGTREN, (2005).

paper is an example of this approach, innovative both by attempting this with shorter-term scenarios and in combination with IDA.[6]

The remainder of this paper is organised as follows. Section 2 documents further the scenario analysis and decomposition analysis methods and their integration as employed in this study. Section 3 presents the literature review of the evolution and interaction of scenario driving forces in Ireland. The results of the integrated scenarios are presented in Section 4. Section 5 synthesises and discusses results and presents uncertainties and limitations. Section 6 concludes this study.

2. Methodology

2.1. Scenario Analysis

There are numerous approaches to producing alternative scenarios. These can be broadly categorised as quantitative, such as variant projections, and qualitative, using narrative storylines. Both of these broad approaches have limitations which can be overcome by hybrid combination (Fisher *et al.*, 2007). The scenarios of this study are linking tools that integrate storylines and quantitative modelling. These exploratory scenarios deliberately explore what might happen if the development of scenario driving forces take a particular direction (Börjeson *et al.*, 2006). While recent research has sought to enhance the engagement of optimisation modelling with uncertainty (Usher and Strachan, 2012), quantitative approaches have often relied on the continuation of historical dynamics through Business As Usual (BAU) or reference scenarios. Theexploratory scenario approach of this study allows for the emergence of potential

[6] The two previous studies that applied the Divisia index with scenarios (Sun, 2001; Hatzigeorgiou *et al.*, 2010) used the trend based approach and PRIMES forecast results respectively.

new dynamics and trend changes to occur[7]. These can be expressed quantitatively through different combinations of input data that correspond to the logics of each scenario. The scenario analysis in this study has three main objectives; i) to explore plausible alternatives and the resulting emissions range, ii) to explore underlying changes in the development path and sectors, iii) to combine qualitative and quantitative scenario approaches, in response to the limitations of purely quantitative techniques variously proposed (Fisher *et al*., 2007; Swart *et al*., 2004; Neilsen and Karlsson, 2007; Morita *et al*., 2001; Nakicenovic *et al*., 2000). This involves the elevation of crucial and often overlooked non-quantifiable driving forces; social, cultural and governance. As a non-probabilistic approach similar to that of Nakicenovic *et al*., (2000), it can give insight into uncertainty in projections and aid mitigation analysis and policy-making. The scenarios follow guidance such as Alcamo (2001), EEA (2000) and van Notten *et al*., (2003) and are constructed as 'baseline' to exclude additional climate or energy policy post 2006.

Similar to Nakicenovic *et al*. (2000) the scenario process begins with the literature review of scenario driving forces[8].This crucially important stage of the scenario analysis adopts a transdisciplinary approach to explore the evolution and interaction of scenario driving forces under the headings of; population, economic and social development, energy resources and technology and governance and policies. Scenario generation is then initiated using the scenario axes framework (van't Klooster and van Asselt, 2006), and scenario logics to fully differentiate four alternative qualitative scenarios storylines. Similar to the Storyline and Simulation (SAS) approach (Alcamo, 2001), the axes and logics then provide input into the selection and checking of numerical estimates of driving force change in the IDA model. The scenarios are checked and integrated by applying two important principles of scenario construction; plausibility of change

[7] The dynamics explored may have considerable impact on future emissions based on their evolution and interaction occurring as events and processes that are discernible in the system today.
[8] As recommended by Alcamo (2001), this stage also takes cognisance of historical trends and forecasts. Exploration of plausible future change in the scenarios themselves should not be bound solely by these.

(Nakicenovic *et al*., 2000) and internal consistency within the scenarios (Postma and Liebl, 2005). The scenarios can then be amended where necessary as in the SAS approach. While internal consistency is an important consideration within the scenarios it also has its limitations in a complex world (Mander *et al*., 2008) and a formal consistency analysis was consequently not applied in this example.

2.2. Decomposition Analysis and Scenario Quantification

The IDA model used for scenario quantification is a multi-sectoral decomposition framework. It explains changes in energy-related CO_2 of eleven final energy consuming sectors; four economic, six transport and the residential sector. Six driving forces or 'effects' are analysed in the IDA in each of the economic and transport sectors and five in the residential sector. The effects measured are detailed in Table 1. It employs the Log Mean Divisia Index I (LMDI I) of Ang and Liu (2001) implemented for historical analysis of these sectors in O' Mahony *et al*. (2012). The decomposition scheme is detailed in Appendix A.

Table 1 Effects measured in the DA

Symbol	Effect	Description
$\mathbf{C}_{emc}$	Carbon emissions coefficient effect	Emissions coefficient of fuels including electricity.
$\mathbf{C}_{ffse}$	Fossil fuel substitution effect	Change in fossil fuel shares through substitution.
$\mathbf{C}_{repe}$	Renewable energy penetration effect	Penetration of renewable energy in the demand side.
$\mathbf{C}_{inte}$	Economic sector intensity effect	Energy intensity in each of the economic sectors.
$\mathbf{C}_{es}$	Economic share effect	Change in the structural share of economic activity

		between the economic sectors.(industry, commercial services, public services and agriculture)
C_{et}	Economic total effect	Change in aggregated total economic activity.
C_{intt}	Transport intensity effect	Energy intensity in each of the transport sectors.
C_{ts}	Transport share effect	Change in the structural or modal share of transport activity (road private car, road public passenger, road freight, rail, domestic aviation and unspecified and fuel tourism).
C_{tt}	Transport total effect	Change in aggregated total transport activity.
C_{intr}	Residential intensity effect	Change in residential energy intensity.
C_{hn}	Household number effect	Change in the number of households.
C_{tot}	Total CO_2	Change in total CO_2 emissions of the aggregated sectors.

While O' Mahony *et al*. (2012) is a historical analysis from 1990 to 2007, this paper quantifies scenarios annually from 2008 to 2020 through the same framework using it as a *Divisia Index SCenario GENerator* (DISCGEN). As the scenarios are visions of plausible alternative futures, the emission trajectories arise based on the development path of each scenario. Quantitatively these are expressed in the evolution of 'effects' or compositional factors in each sector, termed by Agnolucci *et al*. (2009) as 'varying the decomposition ratios'. Change is assigned to variables consistent with the logics of each scenario[9]. For a given level of activity in each sector, energy consumption is determined by the energy intensity of that activity and fuel shares determine consequent CO_2. The emissions coefficient of electricity varies on the basis of primary fuels

[9] The DISCGEN is used for scenario analysis by assigning activity levels in each sector and scenario. Energy intensity is then adjusted by modifying final energy consumption (fuel shares and renewables) to meet the given activity level in each sector. Such a process was termed varying the decomposition ratios by Agnolucci *et al*. (2009). While all data inputs and decomposition ratios can be modified in modelling with IDA, energy intensity is a particularly useful indicator. It establishes a direct relationship between activity and energy consumption in the decomposition model. It is also readily comparable across scenarios and with past performance.

consumed to meet demand[10]. Scenario driving forces are placed in a "logics" framework by scenario narratives, aiding the process of assigning numerical estimates of input variables. Cognisance is taken of historical patterns and projections and forecasts of energy and activity to consider what may be plausible change. This process should still permit new dynamics to evolve in the scenarios and should not be a reproduction of these trends. Existing projections of CO_2 are used for comparative purposes, rather than to check for plausibility, to avoid the limitation of restricting the scenarios to current dynamics or existing trends.

3. Literature review of scenario driving forces

3.1. Population

Ireland's population grew significantly up to 2007[11] related to the two key factors; net migration and high fertility rates (CSO, 2009). Migration had the dominant impact but is the most uncertain determinant of population change. As labour migration has dominated in Europe for decades (Zaiceva and Zimmermann, 2008) it is linked to economic growth and at a deeper level to perceived income disparities, quality of life and migration policy. Increasing Irish fertility rates are anomalously high (Feld, 2005) and seen as unlikely to be maintained. Irish population projections do not explicitly consider economic developments (CSO, 2008) and given the recession tempered growth is likely. The scale effect of population change has been shown to have a relatively minor impact on emissions in Ireland (O' Mahony, 2010) as affluence and the accompanying lifestyle and identity factors were more important.

Urbanisation has important links to increasing energy use (Poumanyvong and Kaneko, 2010), but in Ireland, low-density spatial development patterns through urban sprawl and urban-rural

[10] Allowing for an annual generation efficiency improvement of 1.46% as calculated for Ireland from 1990-2007 (Dennehy *et al.*, 2009).
[11] From 1990 to 2007 the population of the Ireland grew by an estimated 23.77% to 4,339,000 (CSO, 2009).

migration are significant to emissions. This includes one-off housing in the countryside and is directly linked to policy, investment decisions and lax regulation of development (EEA, 2006; DOEHLG, 2002). Urban sprawl is strongly associated with higher motorisation of transport and greater use of private car (Kahn Ribeiro *et al*., 2007) increasing the potential for carbon lock-in. This study links population change to energy through demographic units of households and private car as recommended (Gaffin, 1998; Nakicenovic *et al*., 2000).

3.2. Economic and social development

Ireland experienced unprecedented economic growth through the 1990's to become one of the richest European Union (EU) Member States. Deep structural change occurred towards Information and Communication Technology (ICT), computer manufacturing and pharmaceuticals. An abrupt halt occurred in 2008 despite optimistic predictions of continuing growth (Fitzgerald *et al*., 2008; Bergin *et al.* 2003; Rae and van den Noord, 2006). In tandem with the global recession, Ireland experienced a collapse in the construction industry, sudden correction in over-valued house prices, rising unemployment and a consequent banking and public finance crisis. The economy entered deep recession leading to European Union/ International Monetary Fund (EU/ IMF) intervention in 2010. While the importance of monetary and fiscal policy errors are recognised, the severity of the collapse in the housing market, the financial system and consequently the deep recession have been strongly linked to weak governance and regulation of finance (Regling and Watson, 2010; Honohan, 2010) and by association, of development. A failure to appropriately regulate spatial development has equity, quality of life, environmental and economic implications (EEA, 2006). This can also be posited for the failure to appropriately regulate the finance of development. It can have long-term financial and emissions implications of lock-in to capital and energy intensive development[12]. The recent outcome in Ireland corresponds with Morita *et al.* (2001), where falling GHG's are associated with higher government intervention, and rising GHG's with the opposite.

Irish economic development policy facilitated structural change to lower energy intensity branches of the economy[13] but technical energy intensity improvement appears low (Cahill and Ó Gallachóir, 2009). In governance, 'innovation', 'the smart economy' and 'green growth' are consistently highlighted as priorities for economic development and recovery (DETE, 2009; Forfás, 2009). In addition to production, consumption patterns have a significant impact on emissions. Purchasing power facilitates enhanced choice but actual consumption decisions occur with underlying social and cultural factors expressed through identity, behaviour and lifestyle (Toth *et al.*, 2001)[14]. There is currently limited support for a turning point in the relationship between per capita energy use and/or carbon emissions in Organisation for Economic Cooperation and Development (OECD) nations (Richmond and Kaufmann, 2006). While economic growth is a key driver of emissions (Sathaye *et al.*, 2007) it could yet evolve in distinctly different directions in future development paths. This is based not only on growth rates, but also on the type of growth. Economic growth projections are fraught with uncertainty as is evident in continual revisions (Fitzgerald *et al.*, 2008; Bergin *et al.*, 2009; IMF, 2009; OECD, 2009; DGECFIN 2009). Newer forecasts have varied predominantly on the depth of contraction and timing of recovery. Bergin *et al.* (2009) predicted GDP contraction of -8.2% in 2009, -1.0% in 2010, and average annual growth of 5.6% from 2010-2015 and 3.3% from 2015-

[12] Recent analysis has suggested "green growth" offers a stronger and more resilient path than BAU "brown growth" in the medium to long term (UNEP, 2011).
[13] Through export led growth of high-value added manufacturing and services of lower energy intensity (Kaivo-oja and Luukkanen 2004; Diakoulaki and Mandaraka, 2007).
[14] The importance of lifestyle is reflected in the large differences between energy per capita across nations only partly explained by weather and wealth (OECD/ IEA, 1997).

2020. Even the "prolonged recession scenario" is proving excessively optimistic with significant challenges remaining in the desired return to growth.

3.3. Energy Resources and Technology

In Ireland, both Total Primary Energy Requirement (TPER) and Total Final Consumption (TFC) increased significantly from 1990-2007. Growth occurred in all sectors, particularly transport, where both activity demand and energy intensity increased (O' Mahony *et al*., 2012), but change in intensity, was heterogeneous across the sectors. In the economic sectors, structural evolution towards energy extensive high-value added branches was important. Weak output growth was forecast across the industry, public and agriculture sectors (Fitzgerald *et al*., 2008), this will deliver reduced structural change, but Capros *et al*., (2008) projected industry energy intensity improvement at -2.4% per annum to 2020 and -2.2% in the services and agriculture. The aggregated transport sector is the largest consumer of energy in Ireland. Economic, policy, behavioural and spatial development drivers have increased demand for freight and passenger services. A modal shift occurred towards more energy intensive transport modes and increased intensity within mode, a pattern common worldwide (Kahn Ribeiro *et al.*, 2007). Howley *et al.* (2008) forecast a 2.4% annual growth in transport energy from 2010-2020 but Kahn Ribeiro *et al*. (2007) stressed that demand can be shaped by key uncertainties including fuel costs, type of economic development, energy efficiency and transport infrastructure [15]. The issue of infrastructure and technology lock-in is important, not just in physical and capital terms, but socially and culturally in terms of habit formation. In the residential sector, final energy use increased by 29% from 1990-2007. Factors acting to increase energy and carbon emissions include; house numbers, floor area and increasing internal temperature (O' Mahony *et al*., 2012).

[15] Kahn Ribeiro et al. (2007) proposed that demand can be shaped by key uncertainties including oil peak and replacement fuels leading to increased fuel costs, shape and rate of economic development, transport technology, energy efficiency and policies to avoid for example heavier more powerful cars, and, transport infrastructure and alternatives to private cars.

The increasing use of appliances raised electricity consumption, as did space-heating with electricity. Energy intensity improved considerably by the successive improvement of the thermal performance of new housing.

The impending peak in oil and gas production is contested (Sims *et al.*, 2007; OECD/ IEA, 2008; Campbell, 1997; Laherrère, 2001). Sims *et al.* concluded that there are sufficient reserves of most types of energy resources to last at least several decades, a conclusion adopted in this study. While the probability of future fuel price increases is high (Rout *et al.*, 2008), it has been observed that demand is becoming insensitive to price and income is the primary driver of fuel demand (OECD/ IEA, 2006). While Ireland is heavily dependent on energy imports, particularly oil and gas, it possesses a substantial potential wind resource and the Corrib gas field (OECD/ IEA, 2007)[16]. In energy supply, Ireland has experienced a substantial transition to gas, while peat, oil and coal have all declined. It is estimated that ocean energy, including wind and wave, could contribute up to 66% of all-island electricity demand (OECD/ IEA, 2007). Unless there is major policy change, future capacity will likely be met by gas and non-renewable options as flexible dispatch plant (DCENR/ DETI, 2008). For technological change, diffusion of existing technology and knowledge is of most significance (Halsnæs *et al.*, 2007) and Carbon Capture and Storage (CCS) and nuclear energy are both excluded[17]. While these uncertainties can be more readily accounted for, the recession has undermined energy forecasts. Fitzgerald *et al.* (2008) emphasised a continued growth at a reduced rate and Howley *et al.* (2008) and Capros *et al.* (2008) forecast less growth.

[16] The other indigenous fuel source, peat, is a carbon intensive traditional fossil fuel (derived from naturally occurring partially decayed vegetation in wetlands). It is mostly used for electricity generation and domestic heating but has declined in supply share as the energy system has modernised on both the supply and demand side.

[17] Although the technology exists, the use of CCS is in its infancy and is not expected to be significant until 2030 (CEC, 2008). A statutory prohibition is in place in on nuclear energy (Government of Ireland, 1999). It is consequently implausible to consider that a nuclear power plant could commissioned by 2020 even if it were deemed desirable.

3.4. Governance and Policies

Governance is a more inclusive concept than government, involving multiple scales and multiple actors including the roles of the market and civil society in tandem with the state (Sathaye *et al.*, 2007). Aside from mitigation or energy policy, governance moves to prominence as a driver of emissions as it influences wider domains in the development path, including key aspects such as transport and the forms of economic development. At the state level, the development path is influenced through policy choices arising from the political culture, regulatory policy style and public expectations of the nation. According to Fisher *et al.* (2007) it is social and cultural processes that ultimately shape institutions and how they function. It can then be postulated, that the evolution of governance and its societal impetus can evolve in different directions that can embody stronger or weaker manifestations of sustainability. This implications for the emissions trajectory [18] , stronger conceptions of sustainability would tend to evolve towards immaterialisation, dematerialisation and decarbonisation of development[19]. In the decomposition this manifests as less energy intensive patterns of development in general and greater improvements in energy intensity and fuel switching respectively. Notwithstanding concerns of carbon lock-in, economic growth can be leveraged towards a lower emissions trajectory, through directing on-going and capital investment, and through developing institutions and societal preferences more conducive to mitigation and environmental protection (Sathaye *et al.*, 2007). Apart from general policy concerns, in determining energy and mitigation policy relevant to these baseline scenarios, the three central policies included in EPA (2008) are relevant. These

[18] Given the commonalities with sustainable development, 'sustainability' would tend to entail greater balance between the social, environmental and economic in a development pathway (Sathaye *et al.*, 2007).
[19] Tapio *et al.* (2007) provided these three useful concepts to understand change in emissions.

include; 15% renewables in gross electricity by 2010, growth in biofuels to 2% of road transport fuels by 2008 and a continuation of the Emissions Trading Scheme (ETS) beyond 2012[20].

3.5. Scenario driving force synthesis

Economic growth is one of the major driving forces of emissions in Ireland (O' Mahony *et al.*, 2012). Its' influence on energy requirement is not linear and can evolve in different directions depending on the type of development as production and consumption can evolve into more energy extensive, or alternatively, more energy intensive forms. Population growth is uncertain due to its link to economic growth, and the effect of the unforeseen recession in reducing existing population projections may be significant. Historically, related economic and population growth led to a housing boom of dispersed pattern settlement. The spatial and financial patterns of this housing boom both increased emissions and led to systemic economic risks[21]. These are strongly linked to light or absent regulation in both planning and finance. These outcomes are therefore linked to both governance and policy and in turn are interconnected with society and culture. In characterising governance, the concept of '*sustainability*' may be applied to contextualise the pattern of a '*development path'* (Fisher *et al.*, 2007) as a relationship of economy and society to energy and emissions. Stronger or weaker sustainability can be represented in a development path, and further in the scenario quantification using the DISCGEN, through key effects such as activity and energy intensity. While activity and technological drivers are important, governance, society and culture cannot be quantified and may only be known qualitatively, but may be critical in determining future emissions.

4. Results

[20] The carbon tax which was postponed and eventually implemented in Ireland in late 2009 is outside of the scope of the baseline.
[21] Systemic economic risks arose through high-risk financial and lending practices and their inadequate regulation.

The following presents the integrated qualitative and quantitative scenarios of sectoral energy CO_2 emissions. These include both the storyline of development and quantification through the DISCGEN. In order to develop a set of four plausible alternative scenarios for the evolution of energy CO_2 emissions, the scenario axes technique (van't Klooster and van Asselt, 2006) was used to select two driving forces of high uncertainty and high impact. When conceptualised in this form, from the discussion in section 3, the driving forces of '*economy*' and '*sustainability*' are both prominent. This scenarios are not an attempt to definitively state the sustainability or desirability of development paths, but it does overcome the theoretical difficulties outlined by Girod *et al*. (2009) where the scenarios of the Special Report on Emission Scenarios (SRES) (Nakicenovic *et al*., 2000) are described as "more economic or more environmental". In Fig. 1, the articulation of "*strong sustainability*" is denoted as discussed in section 3.4., as the development of governance and underlying social and cultural processes, which tends to lead towards immaterialisation, dematerialisation and decarbonisation [22]. In contrast, "*weak sustainability*" tends not to lead to these patterns as strongly. O´Mahony (2010) details the logics of scenario development providing signals for the choice of numerical inputs and Tables of

[22] Recognising the emerging basic principles of sustainability described in Sathaye *et al*. (2007).

changes in decomposition indices.

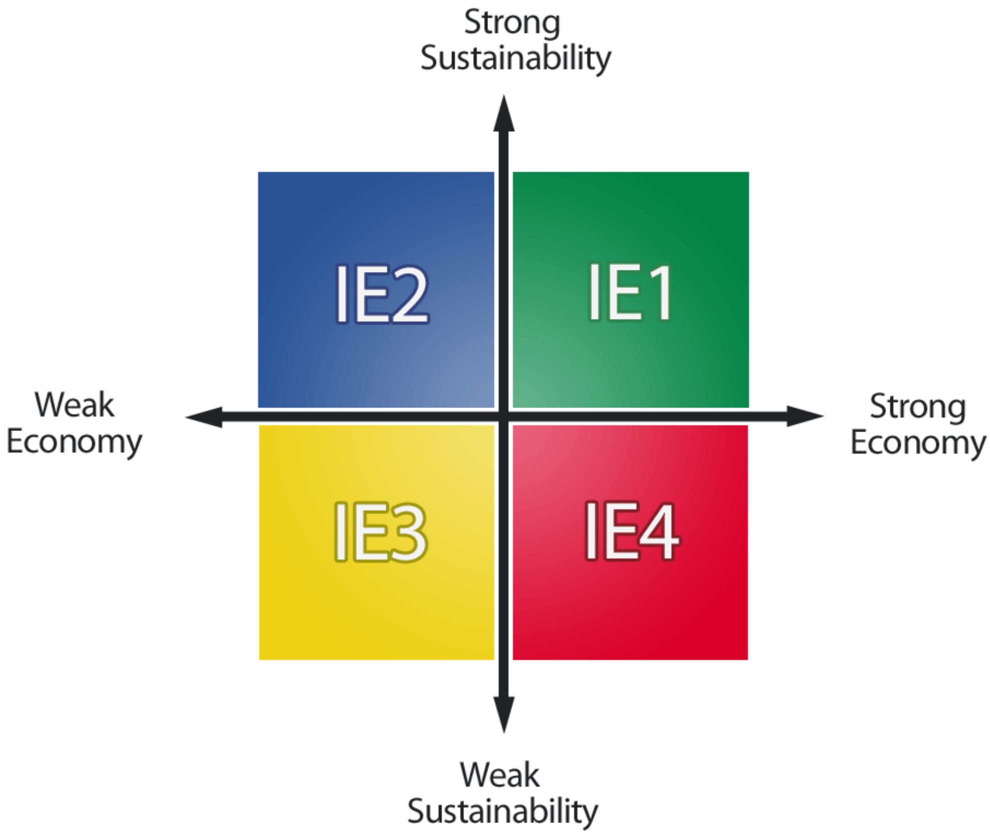

Fig. 1. Scenario axes

The scenarios have been developed in keeping with the logics of the scenario axes. Fig. 2-5 illustrate the sectoral emissions trajectories and decomposition results for each of the four scenarios. Activity levels are presented in Appendix Table B1, final energy consumption in Appendix Table B2 and data on fuel shares in electricity generation in Appendix Table B3.

4.1. Scenario IE1

Scenario IE1 combines high economic growth with stronger sustainability developing in governance and lifestyles. Post-recession, growth increases robustly driven by a buoyant services sector. Prosperity is accompanied by a transition towards sustainability as quality of life, social equity and environmental quality are prized by society. The stronger application of sustainability favours increases in energy efficiency, decarbonisation and energy extensive economic development. Sustainability, coupled with available capital for technological replacement tends to improve energy intensity in all sectors. Modernisation and investment towards lower CO_2 fuels and renewables reduces consumption of coal and peat and increases gas. Local government is enhanced in decision-making, and democratic participation is fostered through creative democracy, public dialogue and formal and informal education. Society seeks to address the dichotomy between citizen and consumer and cultural identity is less defined by consumption. Immaterial goods and quality of life are high on the public agenda which is reflected in government and institutions. The role of the market is perceived as delivering societal, environmental and economic goals and policies are directed to shift market priorities.

Electricity consumption increases and the expansion of gas and wind replace coal and oil-fired generation. Economic growth tends to occur in the office-based services sector and research delivering lower energy intensity. Growth also occurs in the less energy intensive branches of industry such as ICT. The transport sector begins a process of fundamental change. In spatial planning, urban sprawl is discouraged, passenger and freight traffic growth is curbed and there is a modal shift to public transport. House completions reduce considerably in lower intensity forms through improved thermal performance and smaller floor areas. Carbon emissions in 2020 are lower than in 2007 as the recessionary drop in emissions has a sustained effect on the emissions trajectory. The modification of governance and society towards sustainability alters the relationship of economic and societal well-being with energy and emissions.

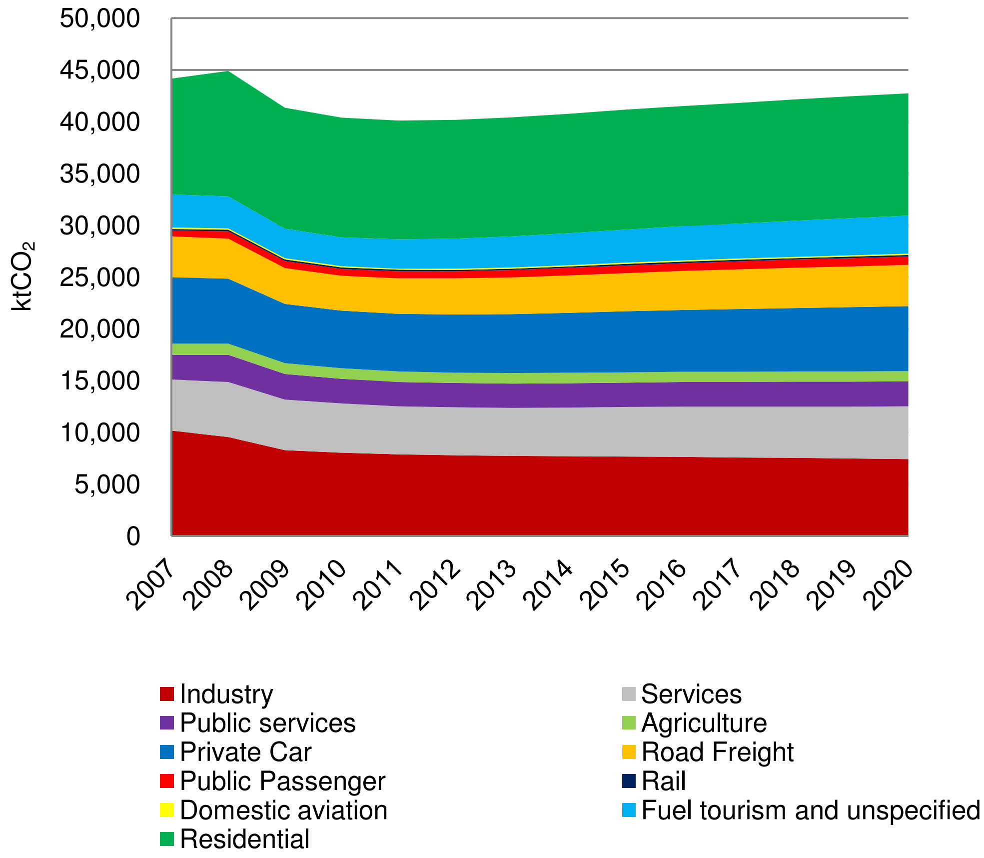

Fig. 2. Sectoral contribution to total CO_2 scenario IE1 2007-2020

4.2. Scenario IE2

Scenario IE2 evolves with lower economic growth and stronger sustainability in governance, consumption patterns and lifestyle choices. Less prosperity reduces scope for technical efficiency with less investment capital. Growth that occurs is pursued in the services sector. Sustainability favours energy extensive economic development and transport and decarbonisation. Balancing the demands of society with a weakened economy are a challenge but a bottom-up emphasis on change leads to strengthened grassroots activism, collective action and role for civil society. Good governance and synergies among policies are a priority of central government. Environmental and political-education are used to counter social exclusion and change consumption patterns with a priority on well-being, community and lifestyle. Infrastructure and urban development are directed towards reducing transport demand and countering urban sprawl while enhanced regulation improves environmental quality.

In industry and commercial services, weak output growth is directed towards less intensive branches, but industry intensity does not reduce at the same rate as IE1. Public service output grows more slowly and agricultural economic activity does not recover from the recession by 2020. Transport intensity improves where there is investment in fleet replacement. Passenger traffic shifts towards public transport while biofuels reach 3.33% of fuel consumption in 2010. The cultural identity is less consumerist-individualist and encourages diversion from consumer expenditure on transport and less house completions. Energy consumption and carbon emissions increase at a slow rate in scenario IE2. Low activity growth and the manifestation of sustainability in the development path act in concert to suppress growth in emissions.

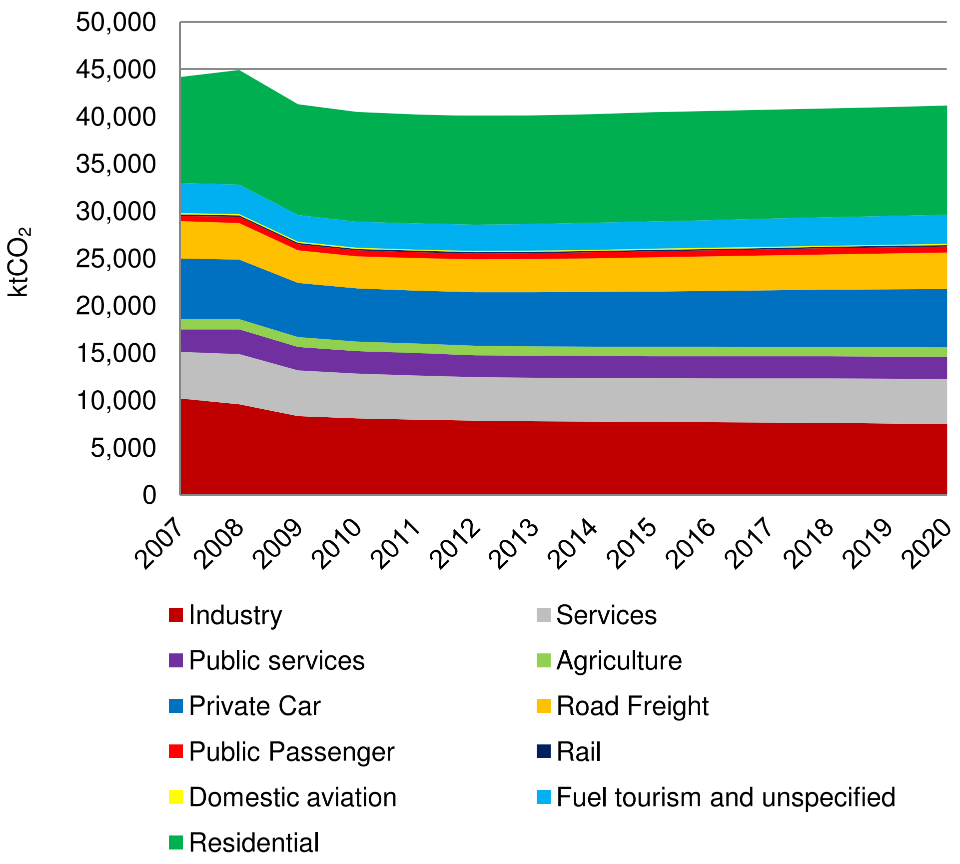

Fig. 3. Sectoral contribution to total CO_2 IE2 2007-2020

4.3. Scenario IE3

Scenario IE3 is the weakest economic growth scenario where a robust recovery fails to take hold. The evolution of governance and society is inclined to weaker sustainability and consumption patterns, and lifestyle choices are predisposed to higher energy consumption. Reduced prosperity lowers public and private investment and scarce resources increase competition and conflict. Government adopts a market driven top-down style and democratic participation and bottom-up actions are hampered. Social equity outcomes are downgraded in public discourse and social exclusion increases as public investment is reduced and public services deteriorate. Governance loosens restrictions on private enterprise and government intervention is shunned. The development of the built environment is weakly regulated and the resulting development sprawls in urban and rural areas. This engenders a closer link between quality of life and increased mobility requirements.

Growth is concentrated in industry regardless of energy intensity and other sectors decline as a share of total economic activity. Industry experiences lower intensity improvements with less emphasis on eco-efficiency or restructuring while in services weak recovery and fuel substitution lessen the emissions profile. Public services energy intensity increases and in agriculture does not improve. In power generation incentives from the ETS are limited, fuel requirements are met by coal and oil and also peat for security of supply. Urban sprawl and transport intensive development results from weak regulation, hampering economic competitiveness. Passenger traffic growth occurs in private cars and consumers favour larger engines while passenger occupancy falls. Industry increases freight traffic and intensity does not improve as logistics and capacity utilisation are inefficient. Despite the restricted wealth creation in this scenario, mobility choice favours taxis over bus and coach and rail traffic expands only modestly as road modes are favoured. In the residential sector, the economic downturn softens house completions. Lower thermal performance results and appliance use increases. Total energy and carbon emissions increase at a slow rate. Although underlying conditions are ripe for a higher emissions trajectory, weak activity induces a dampened growth in emissions.

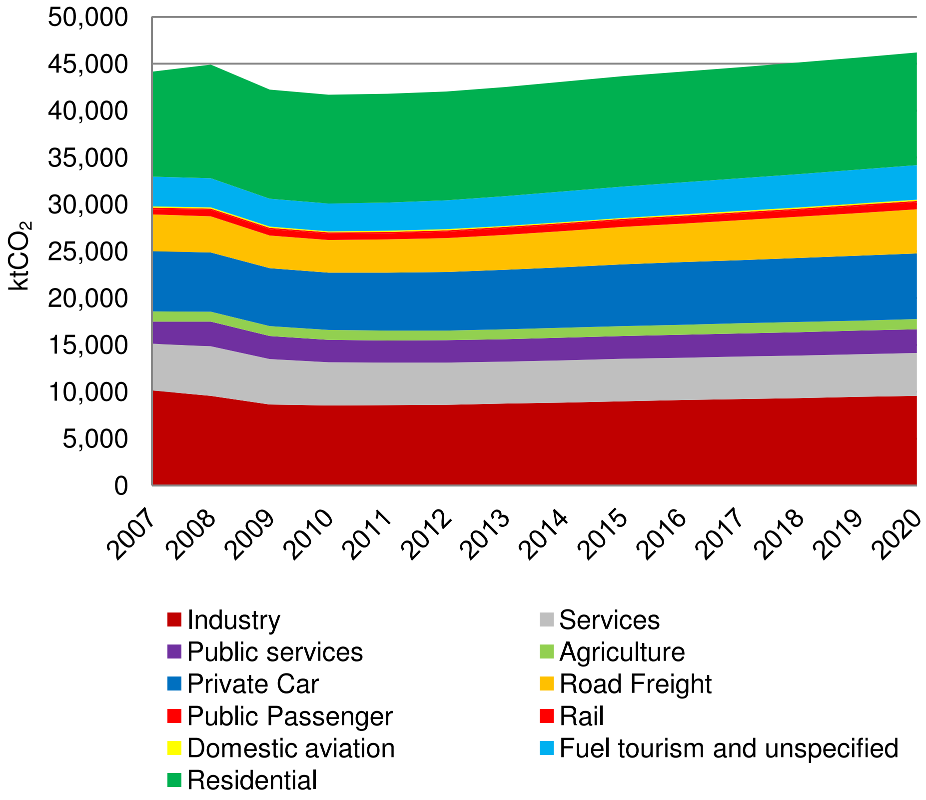

Fig. 4. Sectoral contribution to total CO_2 IE3 2007-2020

4.4. Scenario IE4

Scenario IE4 is the most robust economic scenario driven primarily by manufacturing. Sustainability is weak across governance and society and high economic growth is paramount. Intensity improvements are nonetheless facilitated by output increases and capital for investment in technological replacement. The reduced priority on sustainability stimulates less decarbonisation of fuel shares or penetration of renewables. Decision-making is top-down, but light regulation and a weakened role for government is favoured. Social exclusion and income inequality receive little attention and impaired social equity results. The absence of a shift to sustainability fails to dilute the energy-economy relationship. The lifestyle is consumerist-individualist and personal identity is expressed through the perception of wealth. Urban sprawl expands with dispersed development and government investment prioritises road infrastructure. Environmental regulation is weak and environmental quality deteriorates with increasing pressures and higher resource use.

Industrial output growth is sought across all branches and a weaker ETS fails to encourage fuel substitution. The service sector does not grow sufficiently to increase emissions after the recession. In electricity generation, demand is met by the maintenance of peat and oil although coal contracts as a primary fuel. IE4 is a scenario of expansion in transport demand. Freight experiences low capacity utilisation and favours larger engine sizes and private car is a status symbol of wealth while taxi use expands. In this scenario the expression of consumer identity is evident in the development of the residential sector. Consumers seek larger houses, higher thermal comfort levels and increased use of appliances while awareness and concern for energy efficiency is low. The buoyant economy and rising population sees a return to investment in housing but there is also an investment in comfort and moving to cleaner fuels. Scenario IE4 retains a strong link between societal well-being, economic performance and energy consumption in the development path. This leads to the evolution of a higher emissions trajectory.

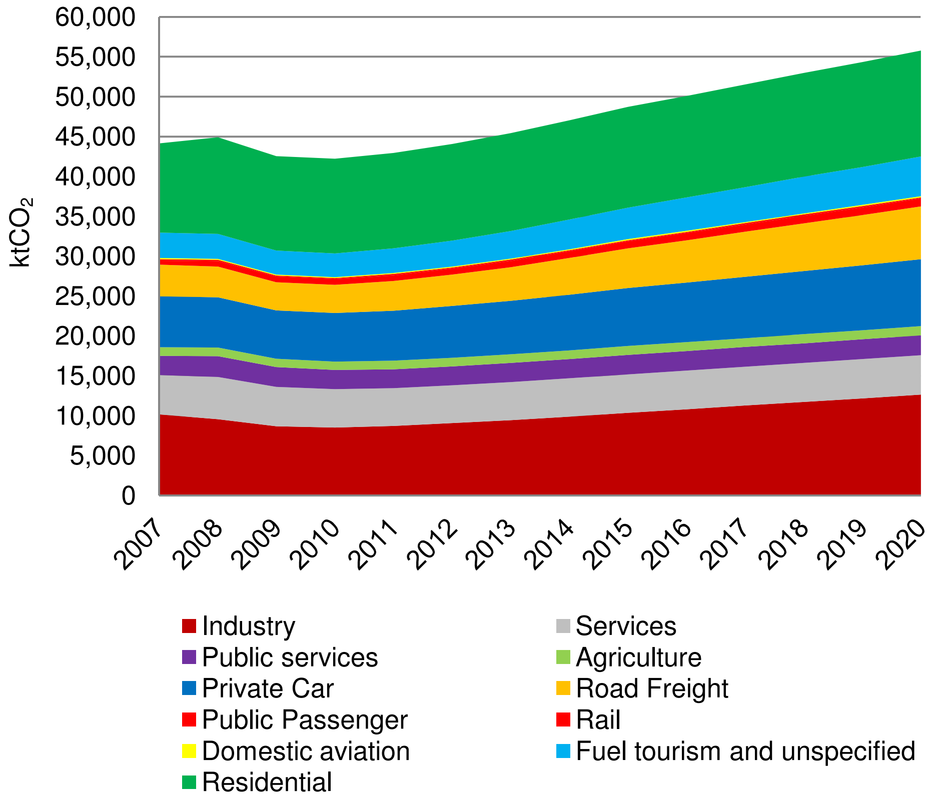

Fig. 5. Sectoral contribution to total CO_2 IE4 2007-2020

5. Synthesis and discussion

5.1. Sectoral scenario synthesis

The sectoral scenarios explore divergence in the evolution of emissions up to 2020 as a range of plausible outcomes. They do not rely solely on historical patterns or existing projections but apply different dynamics to the past. Distinct quantitative and qualitative differences involve not only technical and economic parameters but explicitly represent the evolution of social, political and cultural aspects in response to the criticism of Nielsen and Karlsson (2007). Economic growth is important, but the nature of development is crucial in determining the relationship with emissions. Once the post-recession recovery occurs, emissions begin to rise in all scenarios (Fig. 6) but the emissions trajectories in the four scenarios involve a reduction on 2007 levels in scenarios IE1 and IE2 of -3.2% and -6.8%, and an increase of +4.6% and +26.3% in scenarios IE3 and IE4. In the stronger sustainability scenarios IE1 and IE2, growth in output is dominated by services and in IE3 and IE4 by industry. Following the scenario logics for transport, under scenarios IE1 and IE2 spatial development does not sprawl and mobility choices are directed towards public and more energy extensive modes. In scenarios IE3 and IE4 lifestyle preferences for citizens and operational decisions for freight are characterised by private and more energy intensive modes and spatial development tends to increase travel distances. The evolution of transport, through governance and societal choices, is towards technological, infrastructural and cultural lock-in to higher energy demand in IE3 and IE4. In the residential sector, scenarios IE3 and IE4 involve higher house completion rates and more detached and semi-detached dwelling types with larger floor areas. Scenarios IE1 and IE2 tend towards lower energy intensity and higher fuel substitution and renewable energy penetration.

In unifying an articulation of the patterns of development in the scenarios, immaterialisation, dematerialisation and decarbonisation are higher in the stronger sustainability scenarios IE1 and IE2. The influence of sustainability through governance and society tends towards curbed growth in emissions regardless of economic growth rate corresponding to the conclusion of Sathaye *et al.* (2007) as lower emissions are not necessarily associated with lower economic growth. Governance and society in particular can influence the evolution of technological change and development type, but also key factors of carbon lock-in such as spatial pattern, infrastructure and culture. In the stronger sustainability scenarios, cultural identity and lifestyles are less defined by consumption and decision-making is more bottom-up and participative. These scenarios tend to be less market-driven driven in approach placing a higher value on social equity, well-being and environmental protection.

The weaker sustainability scenarios involve the strongest and weakest economic growth rates for IE4 and IE3 respectively. In IE4, the market-driven approach increases short-term economic growth, and the instability of IE3 depresses growth. In the strong economy scenarios IE1 and IE4, capital investment in technological change is higher, improving energy intensity and decarbonisation.

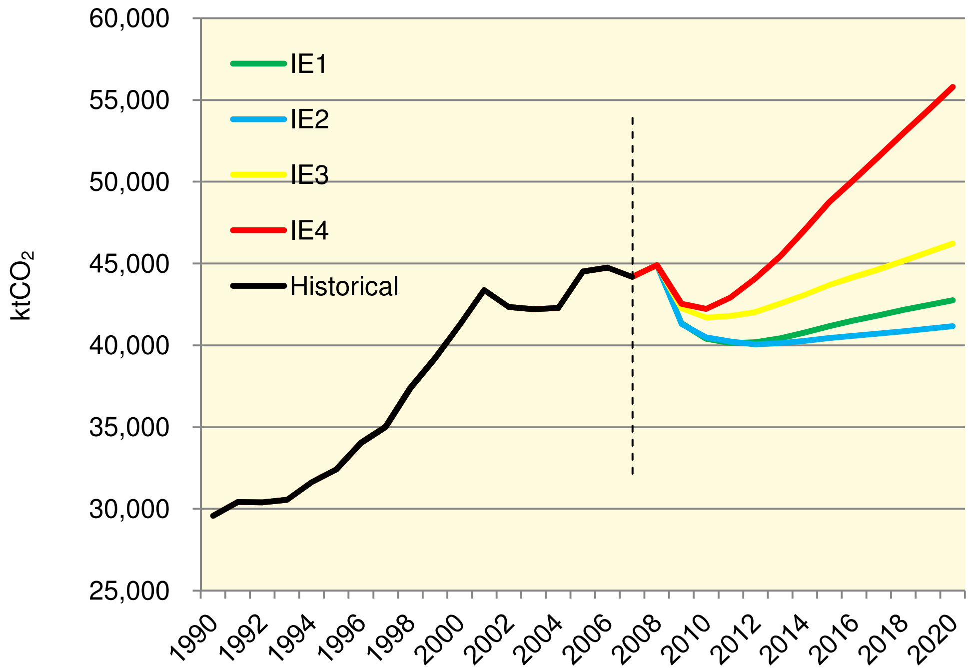

Fig. 6. Trajectories of sectoral scenario energy CO_2 2007-2020

In terms of the relationship across the scenarios, the influence of weaker sustainability is particularly salient with scenario IE3. Despite lower economic growth than IE1 and IE2, emissions are higher and emissions trajectories cross over (see Fig. 6). Alternative evolutions of the system depend on a myriad of factors underlying the economy that modify the development pathway. Evolution is not just based on initial conditions but also on the social and cultural philosophy that underpins decisions at all scales from personal lifestyle to national governance.

5.2. Comparison with existing CO_2 projections for Ireland

In these baseline or "non-intervention" scenarios emissions continue to increase in the absence of further policy intervention. Emissions growth rates are more tempered than historically but vary substantially. There are a limited number of projections and no scenarios of Irish energy CO_2 available for comparison. Those projections available at the time of this study (Fitzgerald *et al.*, 2008; Tol, 2009; EPA, 2009; Capros *et al.*, 2008)[23] also illustrate a continuing upward curve. These various projections present with a number of fundamental differences to the scenarios including; modelling method and structure, base year and economic growth rates[24]. But it is instructive to compare the various projections for the pattern and size of growth in emissions enabling broad conclusions to be drawn. Existing projections for Ireland have been hampered by a difficulty in accounting for physical transport activity as opposed to its inclusion as an economic function. Given the size and growth rate of transport emissions in Ireland, this challenge is of particular analytical and policy significance and has been addressed for the first time in this study.

[23] Additional forecasts of Irish energy and CO_2 have been made including annual revisions of official forecasts. Only those available at the time of this study are compared to promote ease of understanding and emphasise potential problems evident with point forecasts. The recession in Ireland further highlights accuracy difficulties with CO_2 point forecasts errors of up to 9.1% for the first forecast year (Devitt *et al.*, 2010). There are strategic implications of relying on point forecasts for policy-making which become more salient as errors increase. The UNFCCC have requested an explanation of substantial short-term revisions in official Irish national emissions projections (UNFCCC, 2009; UNFCCC, 2010).

[24] Economic growth rates are amended annually in successive national energy and emission projections.

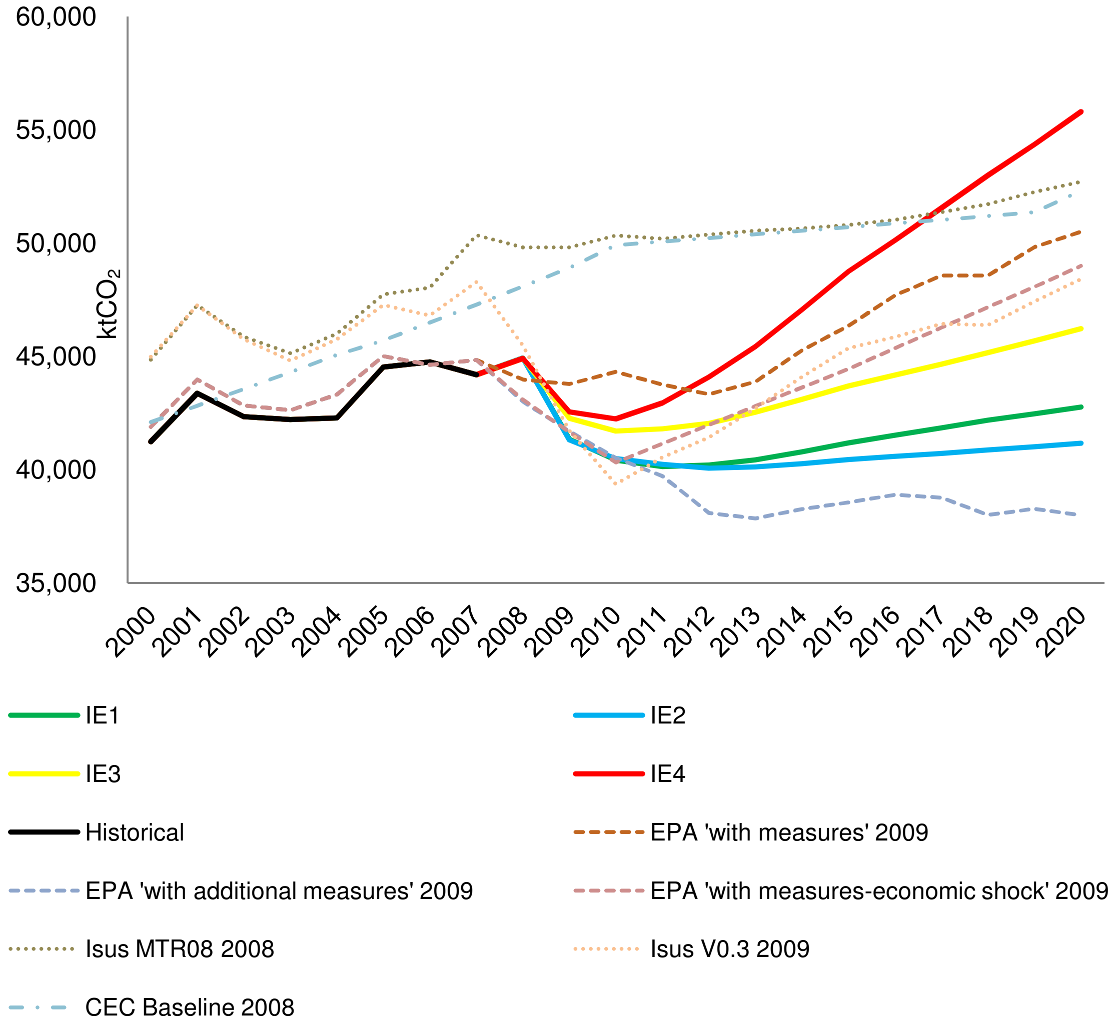

Fig. 7. Comparison of scenarios to existing national emissions projections

In Fig. 7 the scenario quantifications bound the upper and lower limits of existing projections with the exception of the "*with additional measures*" forecast (EPA, 2009). The key difference observed with existing forecasts is the clustering of results in a range between IE3 and IE4 at the higher end suggesting two important findings. Firstly, the use of the similar economic growth rates in Irish emissions projections is weakening results by failing to adequately account for uncertainty in economic growth projections and reproducing similar thinking. Inaccuracy and the illusion of certainty in forecasts are problematic (OECD/ IEA, 2003), particularly for policy and decision-making. Secondly, and more fundamentally, there appear to be similar dynamics between these projections and the weaker sustainability scenarios. As predictions can be self-fulfilling, this can render it more difficult to change undesirable trends (Börjeson *et al*., 2006).

The single comparable projection to the lower range of the emissions envelope (IE1 and IE2), is the official Irish projection "*with additional measures*" (EPA, 2009) including additional policies and measures to March 2009. The fundamentally altered dynamics in IE1 and IE2 represents an underlying shift to a lower emissions trajectory in the absence of additional policy. Two of the projections were produced before the recession materialised "*IsusMTR08"* (Fitzgerald *et al*., 2008) and "*CEC baseline"* (Capros *et al*., 2008) and its impact is particularly notable. "*ISus V0.3*" (Tol, 2009) shows a marked downward revision to the previous iteration. The projections documented above are, with a single exception for enhanced policy, skewed towards higher growth. In contrast, the scenarios of this study explore a wider envelope and potential lower outcomes. These result not just from alternative economic projections, but fundamental changes in the relationship of society and economy to energy and emissions. The variation in outcomes can help in the consideration of forecast uncertainty and also the driving forces relevant to future mitigation.

5.3. Uncertainties and limitations

Nakicenovic *et al*. (2000) described future uncertainties as those arising from inadequate scientific understanding, data gaps and the inherent uncertainties of future events. Scenario analysis is a tool used to respond to uncertainties in complex systems. Hybrid scenarios integrate factors that cannot be quantified and different combinations of input data provide a type of sensitivity analysis. The scenarios of this study; are not predictions or forecasts, do not attempt to accurately quantify individual years, are not intended to be inherently desirable or undesirable and exclude wildcard or low-probability events. Rates of change may appear linear in some multi-annual periods, as it is the overall magnitude of change that is sought.

Similar to Agnolucci *et al*. (2009) the DISCGEN model does not explicitly consider the effect of price on energy consumption, rebound effects, the relationship of price or inflation to output growth, or in this case detail structural change within industry. As the function of IDA is to disaggregate driving forces of change in an aggregate, inter-relationships are not represented in the IDA but are considered in the discussion of scenario driving forces and in the scenarios themselves. Despite these limitations, a range of output growth rates are explored in the scenarios that allow for alternative evolutions of the economy and its relationship with energy and emissions.

6. Concluding remarks

It would appear from the diversity of development paths explored in the scenarios that there is not one single likely development path but a range of plausible outcomes. The presentation of alternative scenarios encourages the audience to consider alternative outcomes during policy development and monitoring. Emissions trajectories diverge not just based on alternative economic growth rates, but on the nature and structure of growth and other driving forces. These development paths lead to different sectoral contributions that can be established in either higher or lower intensity forms of economic, transport and residential evolution. This has considerable long-term policy significance for mitigation by the potential to limit growth in emissions by following higher sustainability pathways. It reinforces the assertion in Sathaye *et al*. (2007) that "climate policy alone will not solve the climate problem" and will be more costly and unlikely to succeed in the absence of sustainable development. The scientific significance of the results is in the divergent emission totals arising from different sectoral patterns on the timescale to 2020. This also suggests the utility of creating alternative scenarios, even on short to medium term time scales, in response to the forecast errors discussed by Linderoth (2002).

On the longer timescale there is a debate in the scenario community on the use of the probabilistic and storyline approaches to scenarios (Webster and Reilly, 2005). From a methodological point of view, there is a strong argument for the use of storyline narrative. It can be used in transdisciplinary approaches to uncertainty for change in key factors that cannot be explored quantitatively**.** The integration of qualitative and quantitative elements within the scenarios allows the depiction of the 'softer' social, political and cultural drivers. Similar to Agnolucci *et al*. (2009), the DISCGEN is a useful tool for constructing different future sectoral configurations, in this case based on different assumptions about the evolution of driving forces in the sectors. Primarily, it allows assumptions on future change in sectoral activity, intensity and fuel shares to be varied in different scenarios. In terms of engaging with uncertainty, it facilitates comparison with projections of energy, emissions and activity, but more importantly it permits the exploration of alternative dynamics and development paths to those of current point forecasts. By implementation with the SAS type approach, it also allows integration with qualitative driving forces that cannot be quantified. It is abundantly clear that current forecasting approaches have proven highly valuable from many perspectives, including consideration of factors such as price and macroeconomic effects. Nonetheless, scenario analysis, integration with qualitative inquiry and the application of IDA are other approaches to be considered in the toolkit of analysing and creating the future.

The results illustrate that it is not just economic growth but a complex array of driving forces that lead to change in emissions. The influence of governance and society is substantial in dictating not just societal choices of fuel mix and renewables but in determining the ultimate relationship of economy and society to energy and emissions. As per Kwon (2005), the scenarios emphasise the importance of continuous monitoring of each of the compositional factors that determine emission trends. This is highlighted by the variation in the emissions trajectories resulting from the scenarios. Similar to Kwon, by tracking change in CO_2, in compositional factors and in underlying causes, it would be possible to establish the main factors leading to the difference between the actual emissions trends and the scenarios. This would enable the reiteration of the scenario model and aid the identification of suitable policies to achieve CO_2 targets. The scenarios could also aid in the revision and refinement of forecasts required for reporting to the EU and UNFCCC, and in the consideration of alternative developments and uncertainty. While carbon lock-in is of particular concern in Ireland, and the transport sector remains a challenge to mitigation policy, it shows signs of being curbed in stronger sustainability scenarios. All scenarios show a growth in emissions after the recession in the absence of the additional mitigation policy which will be required to meet targets. Sustainability offers a potentially low or no cost basis for emission reduction where it improves delinking but is also ultimately crucial to emissions reduction efforts.

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Appendix A

The following appendix presents the LMDI I decomposition framework used in this study for scenario quantification and in O' Mahony *et al*. (2012) for historical analysis. The basic mathematical formulae for IDA and LMDI I can be found in Ang (2004) developed from work by Ang and Liu (2001). The approach used in this study 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 A1.

Table A1 Meaning of each variable in Eqs. (1), (2) and (3)

Item	Meaning	Item	Meaning
$\mathbf{C}_{tij}$	CO_2 emissions fossil fuel *i* sector *j* year *t*	$\mathbf{Y}_t$	Total economic output year *t*
$\mathbf{FF}_{tij}$	Consumption fossil fuel *i* sector *j* year *t*	$\mathbf{TD}_{tj}$	Passenger/ Freight Distance sector *j* year *t*
$\mathbf{FF}_{tj}$	Total consumption fossil fuels sector *j* year *t*	$\mathbf{TTD}_t$	Total Transport Distance year *t*
$\mathbf{E}_{tj}$	Total energy consumption sector *j* year *t*	$\mathbf{THN}_t$	Total Household Number year *t*
$\mathbf{Y}_{tj}$	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;

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

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

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

The steps required to develop Eqs. (4), (5) and (6) as LMDI I are detailed in Ang and Liu (2001). These give the determinant effects in each of the sectors described in Table A2 along with the nomenclature used for results. These effects can be categorised into three groups: the intensity effects C_{emc}, C_{inte}, C_{intt} and C_{intr}, the structure effects C_{ffse}, C_{repe}, C_{es} and, C_{ts}, and the scale effects C_{et}, C_{tt} and C_{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 Gross Value Added (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 TFC 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 A2 Definition of determinant effects from Eqs. (4), (5) and (6)

Item Eq. (4), (5) and (6)	Effect	Definition	Effect type
CE_{ij}	Cemc	Carbon emissions coefficient effect	Intensity
FS_{ij}	Cffse	Fossil fuel substitution effect	Structure
RE_{j}	Crepe	Renewable energy penetration effect	Structure
EIE_{j}	Cinte	Economic sector intensity effect	Intensity
ES_{j}	Ces	Economic share effect	Structure
ET	Cet	Economic total effect	Scale
EIT_{j}	Cintt	Transport intensity effect	Intensity
TS_{j}	Cts	Transport share effect	Structure
TT	Ctt	Transport total effect	Scale
EIR_{j}	Cintr	Residential intensity effect	Intensity

HN	Chn	Household number effect	Scale

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 $j = 1,2 \ldots 4$, Eq. (7) can then be re-written as:

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

Further to this, for each of the transport sectors for $j = 5,6 \ldots 10$, Eq. (8) can then be re-written as:

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

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

$$C_{tot} = C_{emc} C_{ffse} C_{repe} C_{\text{int}\, r} C_{hn} \tag{12}$$

In order to further aggregate the indices of change in C_{tot} for each of the individual sectors for $j = 1,2,3 \ldots 11$ 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:

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

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,…, 11;

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

Appendix B

Table B1 Sectoral activity levels in 2007 and in the scenarios in 2020

Sector	2007	IE1	IE2	IE3	IE4
Economic Total (GVA)	167,057	218,416	188,675	174,856	228,036
Industry	56,754	61,883	56,520	65,559	93,984
Commercial Services	100,911	141,303	122,828	99,959	124,324
Public Services	5,529	5,998	5,666	5,575	5,746
Agriculture	3,863	3,862	3,661	3,764	3,981

Transport (p-km and t-km)	72,395	82,360	75,685	78,198	95,363
Private Car	41,414	44,187	42,051	43,063	49,220
Road Freight	18,707	19,776	18,663	21,779	30,547
Road Public	9,791	14,732	12,212	11,049	12,978
Rail total	2,312	2,819	2,628	2,180	2,470
Rail Passenger	2,183	2,648	2,498	2,115	2,399
Rail Freight	129	170	130	65	72
Domestic Aviation	170	133	131	127	148
Fuel tourism and unspecified	-	-	-	-	-
Residential (House no.'s)	1,518,778	1,998,778	1,863,778	1,828,778	2,113,778

Table B2 Sectoral energy TFC including electricity in 2007 and in the scenarios in 2020

Sector/ ktoe	**2007**	**IE1**	**IE2**	**IE3**	**IE4**
Industry	2,691	2,212	2,133	2,545	3,428
Commercial Services	1,076	1,187	1,061	982	1,083

Public Services	595	636	607	627	632
Agriculture	301	293	283	306	329
Private Car	2,183	2,260	2,172	2,445	2,912
Road Freight	1,284	1,300	1,249	1,530	2,157
Road Public	180	268	219	247	329
Rail total	48	43	40	39	43
Domestic Aviation	54	43	42	44	51
Fuel tourism and unspecified	1,043	1,209	1,014	1,217	1,634
Residential	2,919	3,377	3,192	3,213	3,636
Total	12,372	12,828	12,013	13,193	16,233

Table B3 TPER of fuel shares in electricity generation (ktoe) 2007 and in the scenarios in 2020

Fuel	**2007**	**IE1**	**IE2**	**IE3**	**IE4**
Coal	1,124	500	730	944	821
Oil	376	66	65	75	83

Peat	438	565	565	700	622
Gas	2,737	4,042	3,622	3,092	4,342
Renewables	237	440	440	440	440
Total	4,912	5,613	5,422	5,251	6,308