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Working Paper No. 333

December 2009

Estimating Historical Landfill Quantities to Predict Methane Emissions

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Abstract: We estimate Irish historical landfill quantities from 1960 -2008 and Irish methane emissions from 1968-2006. A model is constructed in which waste generation is a function of income, price of waste disposal and, household economies of scale. A transformation ratio of waste to methane is also included in the methane emissions model. Our results contrast significantly with the Irish Environmental Protection Agency's (EPA) figures due to the differences in the underlying assumptions. The EPA's waste generation and methane emission figures are larger than our estimates from the early 1990s onwards. Projections of the distance to target show that the EPA overestimates the required policy effort.

Key words: methane emissions, landfill, modelling

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Introduction

A substantial amount of methane is emitted by waste decaying in landfills. This is a slow process, with methane being emitted for 25 years or more after waste disposal. Methane is the second-most important anthropogenic greenhouse gas. Emission reduction targets are often formulated relative to 1990. This implies that waste data going back to 1965 are needed to estimate methane emissions from landfill in 1990. In the absence of such data, a model can be used. This paper describes a method for estimating historical disposal of waste in landfills in order to predict historical and future emissions of methane, and it applies the method to data from Ireland.

Articles 4 and 12 of the United Nations Framework Convention on Climate Change (UNFCCC) state that signatory countries must publish their national inventories and removals of all greenhouse gases not controlled by the Montreal Protocol (United Nations 2009). Ireland's Environmental Protection Agency (EPA) is mandated to report emission data to the UNFCCC. These greenhouse gas inventory levels are particularly important due to Ireland's commitment to reduce greenhouse gas levels to at least 20% below 1990 levels by 2020. Biodegradable waste disposed of in landfills is an important source of methane, but these emissions are not normally directly measured: they must be imputed by plugging historical waste disposal data into a model of waste decomposition.

The measurement of waste and the gas emissions (in particular greenhouse gas emissions) that the waste emits is not an exact science. There are numerous papers which have cast doubt upon the official greenhouse gas emission figures from waste. Ramirez *et al*. (2008) consult experts and previous studies on the model parameters to construct a Monte Carlo simulation on GHG emissions. They find that there is up to a 15% uncertainty in Dutch methane emission levels at 95% confidence intervals. They believe the main contributor to uncertainty in methane emissions to be managed solid waste disposal. Similarly Winiwarter and Rypdal (2001), who use a similar methodology to Ramirez *et al*. conclude that "the amount of waste stored in landfills was identified as the parameter that contributed most strongly to trend uncertainties." They find uncertainty in Austrian methane emissions of 48.3% for 1990 and 47.5% for 1997 (again at 95% confidence intervals) which are the only two years analysed. Both papers underline the fact that there is large uncertainty in waste production and greenhouse gas emissions.

In Ireland the historical waste series is incomplete, which implies that we must first estimate waste totals before predicting methane emissions. In the National Inventory Report 2009, the EPA published statistics on Ireland's generation of BMW and non-BMW from 1990-2007. Actual data is only available in 1995, 1998 and annually from 2001 onwards. Hence we have to make a number of assumptions in order to calculate BMW generations levels for all other years from 1990-2005. Some of these assumptions include:

- Degradable Organic Carbon (DOC) is created by Municipal Solid Waste (MSW), street cleanings and sludge from municipal wastewater treatment;
- MSW per-capita generation rates from 1995, 1998, 2001 and 2004 in addition to those implied by earlier surveys are used to estimate MSW production in all years;
- The ratio of street cleanings to MSW is estimated based on the figures for 1995, 1998 and 2001-2007;
- MSW is assumed to contain DOC in the following proportions: Organics – 15%, Paper – 40% and Textiles – 40%; and
- The DOC contribution of sludge is determined from information on the Biochemical Oxygen Demand (BOD) content, the BOD removal rate and the proportion of sludge disposed to landfill.

Our calculation of EPA's projected methane emissions are based upon an EPA publication (Environmental Protection Agency 2009). This report does not explicitly project methane emission levels however it does project greenhouse gas emission levels from waste. We are assuming that methane emissions stay constant as a proportion of greenhouse gas emissions and therefore grow at the same rate.

This paper estimates Ireland's BMW generation from 1960-2008 (excluding the years where actual data is available for obvious reasons). A simple constant elasticity demand model for waste disposal is applied, using the number of households, income levels, service sector production levels and commercial price levels to predict waste quantities. Model parameters are drawn from previous research; in particular, the elasticities of waste generation with respect to household disposable income and number of persons in the household are used to estimate of residential waste, while the elasticity of demand with respect to collection charges and service sector value added are used to estimate commercial waste generation. Since these behavioural parameters are drawn from studies that used data from different time periods and jurisdictions, they may not be correct today let alone as far back as 1960. Hence it is necessary to carry out a sensitivity analysis of these parameters as a robustness test.

Using the estimates of waste generated, we then predict methane emissions in Ireland from 1968-2006. We model emissions from waste using the same model as applied by the Irish EPA. We then compare our methane emissions estimates to the EPA's figures.

The paper continues as follows. Section 2 discusses data and methods. Section 3 presents the results. Section 4 concludes.

Data and Methodology

This paper takes the actual observations of waste sent to landfill in 1995, 1998 and 2001-2006 as a staring point to calculate the data for all other years. These figures are taken from the EPA's National Waste Reports of the relevant years. We assume that residential waste generation, *RW*, is a function of both the household density elasticity of waste generation *r* (the percent change in waste per capita caused by a one percent change in the number of persons per household, *PPH*), and the household income elasticity of waste generation *s* (the percent change in waste generation per household caused by a one percent change in real average disposable income, *YD*). For year t, this would be estimated by:

$$\ln(RW_t) = \alpha + r\ln(PPH_t) + s\ln(YD_t) \quad (1)$$

The historical household income data is taken from the National Income and Expenditure Accounts which are published by the Central Statistics Office (CSO). The population data is also sourced from the CSO. Future household income data is taken from ESRI forecasts (Bergin et al., 2009).

Commercial waste generation, *CW*, is assumed to be a function of the price elasticity of demand of waste disposal *m*, the real price of waste collection *PC*, the output elasticity of service sector waste demand *n* and the value added by the services sector, *VAS*. Thus, for year *t*:

$$\ln\left(CW_t\right) = \alpha + m\ln\left(PC_t\right) + n\ln\left(VAS_t\right) \quad (2)$$

Unfortunately the CSO does not produce a wholesale price index for refuse disposal. The CSO has however produced a Consumer Price Index for refuse since 1983. We take this to be a proxy for the commercial price of refuse disposal. In the absence of other data, we assume that the real price stayed constant for the period 1960-1983. This series reports a large drop in 1997 due to the abolition of domestic water charges. As this change does not apply to waste charges and has a large effect on the results, the series is adjusted to remove the impact of the abolition of water charges. For future predictions, we assume that the real price of refuse collection is constant from 2008-2020. The level of commercial production is taken from the National Accounts, again published by the CSO. This figure is however only available from 1970-2008.. Previous to this year, the ratio of commercial waste generation to GDP within the economy is assumed constant and the actual figure is deflated for the relevant lower GDP over the 1960-1969 period. Gross Domestic Product (GDP) figures for this early period are sourced from the World Resources Institute. Post 2008 figures for VAS are taken from forecasts by the ESRI (Bergin et al., 2009).

The main waste parameter values are from a variety of previous papers. The household income elasticity of waste generation is taken from Curtis *et al.* (2009). This paper analysed panel data from 2003-2006 across the local authorities of Ireland. The data shows a household income elasticity of waste generation of 1.08. Although this figure is well above previous international studies, we feel it is more relevant as the figure is calculated on Irish data. The sensitivity analysis below does consider different parameter values. Choe and Fraser (1998) report income elasticities of waste generation from several US studies and do not find a level higher than 0.6, so testing a lower figure than the unit elasticity estimated from Irish data seems appropriate. We choose a value of 0.5. The commercial price elasticity of demand parameter is taken from Jenkins (1993) who carried out a study on nine American communities and found a result of -0.27. Another study of American data carried out by Wertz (1976) found a result of -0.15 and other experts have argued that the absolute cost of refuse disposal is so low that the commercial price elasticity of demand for waste generation is effectively zero. A sensitivity analysis of the model to price elasticity changes is undertaken below by setting the price elasticity to zero. The parameter pertaining to household economies of scale is taken from Scott and Watson (2006). They carry out a study on the imposition of waste charges in Ireland and use household numbers as a control variable. From the coefficient of this variable the household elasticity of waste generation figure can be formed. This figure is 0.486. In the sensitivity analysis, the household density elasticity of waste generation is set to 0. Finally, we assume that commercial waste has a unit elasticity with respect to the sector's value added. This represents a default position, since no direct estimates were available for Ireland.

Once the waste levels have been estimated, we predict the related methane emissions. The DOC in MSW, MSW, MSW to Landfill, Sludge and Street Cleaning figures are taken from McGettigan et al (2009). For predictive purposes, the future levels of management of DOC and the DOC in MSW are assumed to stay constant at 2008 levels (95% of DOC managed and DOC comprising approximately 20% of MSW). It is assumed that 0.6 of the DOC is dissimilated and that half of the methane remains in the landfill (i.e. does not enter the atmosphere). The methane correction factor (MCF) managed level is assumed to be 1 and the MCF unmanaged level is assumed to be 0.4. The transformation from DOC to methane is taken to be 1.33 (but see the sensitivity analysis). These parameters are taken from the National Inventory Report 2009. So while this paper uses quite a different methodology to calculate waste generation, given that level of waste generation the approach to calculate methane emissions is identical to the approach used by the EPA. Using these assumptions, it is possible to estimate the total managed and unmanaged methane emissions over the period.

Results

Table A1 shows the actual and estimated waste generation figures for Ireland from 1960-2008 using the parameters as described above. Throughout the period, total waste (BMW and non-BMW) followed an upward trend. Over the entire time period, total waste increased by 369% from its 1960 base.

The following graphs show the sensitivity of the models to changes in selected parameters. For each sensitivity test, the model was run varying a single parameter of interest. Table 1 shows the parameter values of each of the adjusted models. Model YED shows the effect of reducing the assumed elasticity of household waste demand with respect to income from the baseline level of 1.08 to 0.5. Model PED reduces the price elasticity of commercial waste demand equal to 0. This change would imply that commercial waste generation is solely a function of the level of value added by the services sector. Model Econ_Scale reduces the household economies of scale parameter to zero. Model Trans_Ratio adjusts the transformation ratio of Dissolved Organic Carbon to Methane to 1.

Figure 1 shows the total waste generation as predicted by the baseline and adjusted models and the Irish Environmental Protection Agency (EPA). The Trans_Ratio model is not included in this graph as the adjusted parameter has no influence upon the waste generated (hence the values would have been identical to the baseline model). Because the model is based on recent data and predicts earlier values, the baseline and adjusted figures converge in recent times. Although there is some divergence in the past, this is not particularly large considering the timeframe involved. The baseline and adjusted models are lower than the EPA estimates from 1990 onwards.

Figure 2 shows the baseline and adjusted models' predicted methane emissions versus the EPA's methane estimates. The base model produces estimates quite similar to three of the sensitivity test models: YED, PED and Econ_Scale. Predicted methane emissions are not very sensitive to changes in these parameters. The EPA's estimates are lower than our model up until the early 1990s and higher after this point. There are substantial differences between annual methane predictions from our model and the EPA series, reaching more than 15,000 tonnes in some years.

The scenario that tests a unit value for the Transformation Ratio ("Trans_Ratio") leads to significantly lower predicted methane emissions. Methane emissions are highly sensitive to changes in the assumed value of the Transformation Ratio parameter.

Figure 3 shows the percentage difference between the estimated level of methane emissions from 1990-2020 and the target level of methane emissions for 2020 (20% below 1990 emission levels). There is no Trans-Ratio series in this graph as the series is identical to the baseline series. In all cases, estimated emissions exceed the target. The EPA estimates are generally higher than our baseline estimates. That is, the EPA overestimates the required emission reduction effort, because the EPA overestimates the amount of waste in the past. In 2020, our estimate of the distance to target almost coincides with the EPA estimate. This is because we project a faster increase in waste than the EPA does (consistent with our faster increase in the past). In the short- and medium term, the EPA overstates the methane-from-waste problem, but it understates it in the long term.

Our baseline projection of the distance to target is very similar to the three alternative projections (Econ_Scale, PED, YED). The alternative parameter values do not have a large influence on the policy required to achieve the commitments.

Conclusion

This paper set out to estimate the levels of waste generated by Ireland from 1960-2008 in the years where actual observations were unavailable, as a means of estimating related methane emissions. Using assumed demand functions and behaviour parameters we estimated the total quantities of municipal waste produced in Ireland from 1960-2008 and methane emitted from 1968-2006.

We carried out sensitivity tests on selected parameters in the model. There was little change in the absolute waste generation levels due to changes in any parameter. The predicted methane emissions are also quite insensitive to changes in all the parameters with the exception of the Transformation Ratio. The value used for this parameter in the baseline model is in line with international standards, so its sensitivity is not a matter for concern *per se*. However, if future research were to indicate that a different value was more appropriate, it is important that this information be taken into account in emission prediction models. Overall, these sensitivity tests provide some comfort as to the robustness of the model. However, other aspects of the model such as the functional form assumed for each source of demand, is less amenable to sensitivity testing. Further research should help cast light of the sensitivity of predicted landfill methane emissions to such model design decisions.

The levels of waste generation and methane emissions estimated by our model are different from the EPA's estimates; in particular, our estimates suggest that methane emissions from landfill are significantly lower than figures reported by the EPA. This suggests that the distance to Kyoto targets may be less than currently thought, at least in the medium term. However, such variations are to be expected given the uncertainty about past waste emissions, as previously highlighted by Ramirez *et al.* (2008) and Winiwarter and Rypder (2001).

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Appendix A

Variable	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976
Services Waste, Total	94555	100024	104404	110085	116271	120106	122146	130307	142813	154142	161646	175684	189117	205610	220773	236801	257720
Residential Waste, Total	545830	574673	594393	609959	653637	655617	665657	671566	711342	739350	765202	775089	857180	925881	919390	957713	930966
BMW+nonBMW	640385	674697	698797	720044	769908	775723	787804	801873	854155	893491	926847	950773	1046297	1131491	1140163	1194514	1188686
Services Waste, Landfilled	80044	84674	88382	93191	98427	101674	103401	110309	120896	130486	136839	148722	160094	174056	186892	200460	218169
Residential Waste, Landfilled	522140	549731	568595	583486	625268	627162	636767	642419	680469	707261	731991	741449	819977	885696	879487	916147	890561
DOC in MSW									165490	172994	179413	183820	202385	218839	220207	230578	228952
Potential Methane Managed									26478	27679	28706	30147	34810	37640	38756	41504	42127
Potential Methane Unmanaged									15887	16607	17224	17353	18457	19958	19731	20291	19781
Total									42365	44287	45930	47499	53268	57598	58487	61795	61909

Variable	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
Services Waste, Total	277557	304051	327551	357938	383591	405052	496545	399527	399527	403472	410831	430993	441094	433420	466288	477281	479820
Residential Waste, Total	970160	1042931	1066274	1052394	1054911	1000584	955173	934230	934230	917817	923986	930006	931136	938597	952601	970596	967720
BMW+nonBMW	1247717	1346982	1393825	1410332	1438502	1405636	1451718	1333757	1333757	1321290	1334818	1361000	1372230	1372018	1418889	1447877	1447539
Services Waste, Landfilled	234961	257389	277283	303007	324723	342890	420342	338213	338213	341553	347783	364851	373401	366905	394729	404035	406184
Residential Waste, Landfilled	928053	997666	1019996	1006718	1009126	957157	913717	893683	893683	877983	883884	889642	890723	897861	911257	928471	925719
DOC in MSW	240163	259170	267889	270458	275440	268461	275484	254387	254387	251835	252492	257170	257249	262432	270991	274496	275038
Potential Methane Managed	45151	49761	52506	54092	56190	55840	58403	54948	54948	55404	56558	58635	59682	61934	65038	65879	66009
Potential Methane Unmanaged	20366	21563	21860	21637	21595	20618	20716	18723	18723	18132	17775	17693	17287	17216	17343	17568	17602
Total	65516	71323	74366	75728	77784	76458	79119	73671	73671	73536	74334	76328	76969	79150	82381	83447	83612

Variable	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Services Waste, Total	494639	502712	**476921**	604798	**476921**	604798	649714	**689235**	674024	962966	**967861**	**972107**	**1142526**	**1282634**	**1304662**	1436312	1523260
Residential Waste, Total	1006887	975562	**1026251**	1078805	**1026251**	1078805	1132889	**1163219**	1218554	1232132	**1329743**	**1426663**	**1416860**	**1520497**	**1562484**	1826892	1947634
BMW+nonBMW	1501526	1478274	**1503172**	1683604	**1503172**	1683604	1782603	**1852454**	1892578	2195098	**2297604**	**2398770**	**2559386**	**2803131**	**2867146**	3263204	3470894
Services Waste, Landfilled	418729	425563	**403730**	491456	**403730**	491456	527955	**560069**	547709	733465	**737194**	**607803**	**601516**	**640121**	**669056**	645022	684069
Residential Waste, Landfilled	963187	933221	**981710**	1044009	**981710**	1044009	1096348	**1125700**	1179250	1162743	**1254857**	**1294061**	**1231108**	**1234624**	**1217519**	1406417	1499370
DOC in MSW	283293	275833	**284198**	314973	**284198**	314973	331358	**350397**	369331	426233	**413031**	**388552**	**375342**	**379736**	**382190**	413994	
Potential Methane Managed	67990	66200	68208	75594	68208	75594	79526	85497	91594	107411	113997	118120	123112	135186	145232	157318	
Potential Methane Unmanaged	18131	17653	18189	20158	18189	20158	21207	21865	22455	25233	20486	14920	10810	6683	3058	3312	
Total	86121	83853	86396	95752	86396	95752	100733	107362	114049	132644	134483	133040	133922	141869	148290	160630	

Table A1 : Waste Generation in Ireland 1960-2008 (Figures in Bold are Official EPA Recordings) – Baseline Parameters

	Base	YED	PED	Econ_Scale	Trans_Ratio
Income Elasticity of Demand	1.08	0.50	1.08	1.08	1.08
Price Elasticity of Demand	-0.27	-0.27	0.00	-0.27	-0.27
Economies of Scale for the Household	0.49	0.49	0.49	0.00	0.49
Transformation from dissolved organic carbon to methane	1.33	1.33	1.33	1.33	1.00

Table 1 – Parameter Values

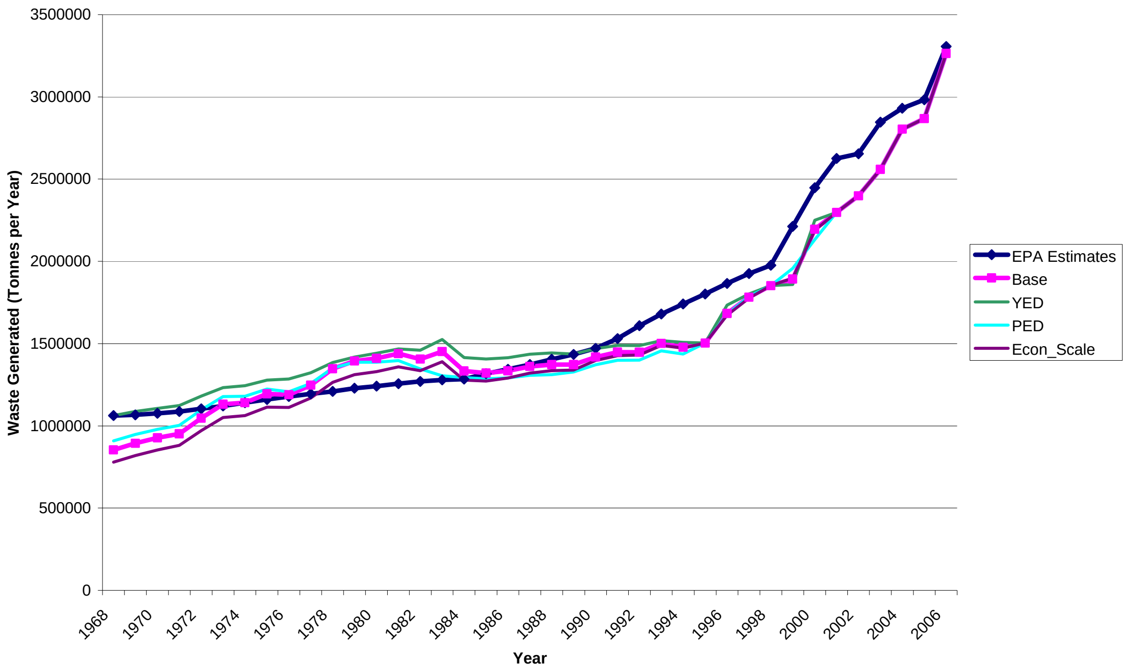

Figure 1 - Total Waste Estimates

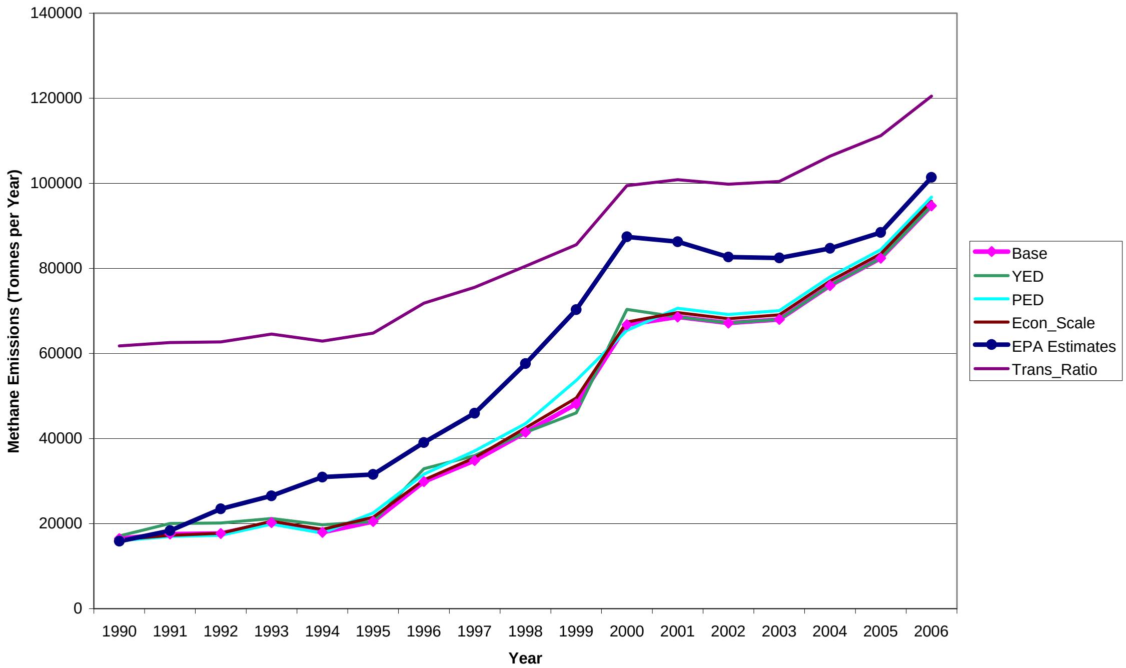

Figure 2 - Methane Emissions from landfill 1990 – 2006

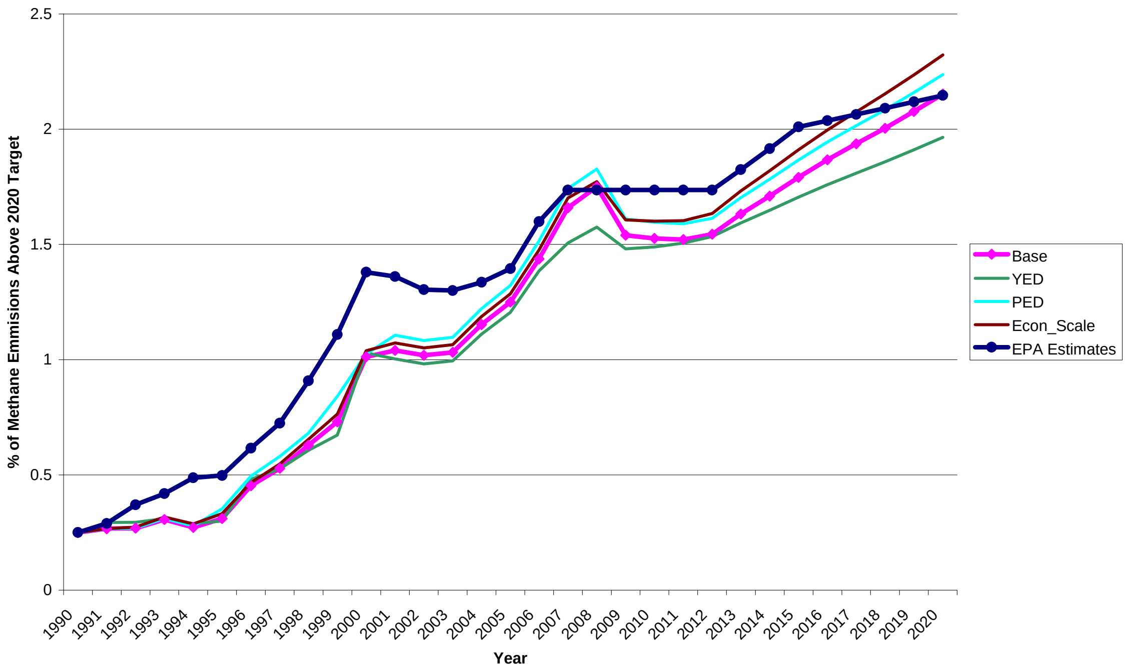

Figure 3 - Difference Between Methane Emissions and 2020 Target

Year	Number	Title/Author(s) ESRI Authors/Co-authors *Italicised*
2009		
	332	International Climate Policy and Regional Welfare Weights Daiju Narita, *Richard S. J. Tol* and *David Anthoff*
	331	A Hedonic Analysis of the Value of Parks and Green Spaces in the Dublin Area *Karen Mayor, Seán Lyons, David Duffy* and *Richard S.J. Tol*
	330	Measuring International Technology Spillovers and Progress Towards the European Research Area *Iulia Siedschlag*
	329	Climate Policy and Corporate Behaviour *Nicola Commins, Seán Lyons,* Marc Schiffbauer, and *Richard S.J. Tol*
	328	The Association Between Income Inequality and Mental Health: Social Cohesion or Social Infrastructure *Richard Layte* and *Bertrand Maître*
	327	A Computational Theory of Exchange: Willingness to pay, willingness to accept and the endowment effect *Pete Lunn* and Mary Lunn
	326	Fiscal Policy for Recovery *John Fitz Gerald*
	325	The EU 20/20/2020 Targets: An Overview of the EMF22 Assessment Christoph Böhringer, Thomas F. Rutherford, and *Richard S.J. Tol*
	324	Counting Only the Hits? The Risk of Underestimating the Costs of Stringent Climate Policy Massimo Tavoni, *Richard S.J. Tol*
	323	International Cooperation on Climate Change Adaptation from an Economic Perspective Kelly C. de Bruin, Rob B. Dellink and *Richard S.J. Tol*
	322	What Role for Property Taxes in Ireland?

	T. Callan, C. Keane and *J.R. Walsh*
321	The Public-Private Sector Pay Gap in Ireland: What Lies Beneath? *Elish Kelly, Seamus McGuinness, Philip O'Connell*
320	A Code of Practice for Grocery Goods Undertakings and An Ombudsman: How to Do a Lot of Harm by Trying to Do a Little Good *Paul K Gorecki*
319	Negative Equity in the Irish Housing Market *David Duffy*
318	Estimating the Impact of Immigration on Wages in Ireland *Alan Barrett, Adele Bergin* and *Elish Kelly*
317	Assessing the Impact of Wage Bargaining and Worker Preferences on the Gender Pay Gap in Ireland Using the National Employment Survey 2003 *Seamus McGuinness, Elish Kelly, Philip O'Connell, Tim Callan*
316	Mismatch in the Graduate Labour Market Among Immigrants and Second-Generation Ethnic Minority Groups *Delma Byrne* and *Seamus McGuinness*
315	Managing Housing Bubbles in Regional Economies under EMU: Ireland and Spain *Thomas Conefrey* and *John Fitz Gerald*
314	Job Mismatches and Labour Market Outcomes Kostas Mavromaras*, Seamus McGuinness,* Nigel O'Leary, Peter Sloane and Yin King Fok
313	Immigrants and Employer-provided Training *Alan Barrett, Séamus McGuinness,* Martin O'Brien and *Philip O'Connell*
312	Did the Celtic Tiger Decrease Socio-Economic Differentials in Perinatal Mortality in Ireland? *Richard Layte* and *Barbara Clyne*
311	Exploring International Differences in Rates of Return to Education: Evidence from EU SILC Maria A. Davia, *Seamus McGuinness* and *Philip, J.*

O'Connell

310 Car Ownership and Mode of Transport to Work in Ireland
Nicola Commins and *Anne Nolan*

309 Recent Trends in the Caesarean Section Rate in Ireland 1999-2006
Aoife Brick and *Richard Layte*

308 Price Inflation and Income Distribution
Anne Jennings, Seán Lyons and *Richard S.J. Tol*

307 Overskilling Dynamics and Education Pathways
Kostas Mavromaras, *Seamus McGuinness*, Yin King Fok

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Iulia Siedschlag, Donal Smith, Camelia Turcu, Xiaoheng Zhang

305 Do Foreign Mergers and Acquisitions Boost Firm Productivity?
Marc Schiffbauer, Iulia Siedschlag, Frances Ruane

304 Inclusion or Diversion in Higher Education in the Republic of Ireland?
Delma Byrne

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Christopher T. Whelan, Mario Lucchini, Maurizio Pisati and *Bertrand Maître*

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Edgar Morgenroth

300 Explaining Structural Change in Cardiovascular Mortality in Ireland 1995-2005: A Time Series Analysis
Richard Layte, Sinead O'Hara and Kathleen Bennett

299 EU Climate Change Policy 2013-2020: Using the Clean

276 Discounting for Climate Change
David Anthoff, Richard S.J. Tol and Gary W. Yohe

275 Projecting the Future Numbers of Migrant Workers in the Health and Social Care Sectors in Ireland
Alan Barrett and Anna Rust

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Daiju Narita*, Richard S.J. Tol, David Anthoff*

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269 A Dynamic Analysis of Household Car Ownership in Ireland
Anne Nolan

268 The Determinants of Mode of Transport to Work in the Greater Dublin Area
Nicola Commins and *Anne Nolan*

267 Resonances from *Economic Development* for Current Economic Policymaking
Frances Ruane

266 The Impact of Wage Bargaining Regime on Firm-Level Competitiveness and Wage Inequality: The Case of Ireland
Seamus McGuinness, Elish Kelly and *Philip O'Connell*

265 Poverty in Ireland in Comparative European Perspective

Richard S.J. Tol

253	Using a Census to Assess the Reliability of a National Household Survey for Migration Research: The Case of Ireland *Alan Barrett* and *Elish Kelly*
252	Risk Aversion, Time Preference, and the Social Cost of Carbon *David Anthoff, Richard S.J. Tol* and Gary W. Yohe
251	The Impact of a Carbon Tax on Economic Growth and Carbon Dioxide Emissions in Ireland *Thomas Conefrey, John D. Fitz Gerald, Laura Malaguzzi Valeri* and *Richard S.J. Tol*
250	The Distributional Implications of a Carbon Tax in Ireland *Tim Callan, Sean Lyons, Susan Scott, Richard S.J. Tol* and Stefano Verde
249	Measuring Material Deprivation in the Enlarged EU *Christopher T. Whelan, Brian Nolan* and *Bertrand Maître*
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242 The Economic Returns to Field of Study and Competencies Among Higher Education Graduates in Ireland
Elish Kelly, Philip O'Connell and *Emer Smyth*

241 European Climate Policy and Aviation Emissions
Karen Mayor and *Richard S.J. Tol*

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Karen Mayor and *Richard S.J. Tol*

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Frances McGinnity and *Emma Calvert*

238 Immigrants and Welfare Programmes: Exploring the Interactions between Immigrant Characteristics, Immigrant Welfare Dependence and Welfare Policy
Alan Barrett and Yvonne McCarthy

237 How Local is Hospital Treatment? An Exploratory Analysis of Public/Private Variation in Location of Treatment in Irish Acute Public Hospitals
Jacqueline O'Reilly and *Miriam M. Wiley*

236 The Immigrant Earnings Disadvantage Across the Earnings and Skills Distributions: The Case of Immigrants from the EU's New Member States in Ireland
Alan Barrett, *Seamus McGuinness* and *Martin O'Brien*

235 Europeanisation of Inequality and European Reference Groups
Christopher T. Whelan and *Bertrand Maître*

234 Managing Capital Flows: Experiences from Central and Eastern Europe
Jürgen von Hagen and *Iulia Siedschlag*

233 ICT Diffusion, Innovation Systems, Globalisation and Regional Economic Dynamics: Theory and Empirical Evidence
Charlie Karlsson, Gunther Maier, Michaela Trippl, *Iulia Siedschlag,* Robert Owen and *Gavin Murphy*

232 Welfare and Competition Effects of Electricity

		Interconnection between Great Britain and Ireland *Laura Malaguzzi Valeri*
	231	Is FDI into China Crowding Out the FDI into the European Union? Laura Resmini and *Iulia Siedschlag*
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2007	222	Assessing Vulnerability of Selected Sectors under Environmental Tax Reform: The issue of pricing power *J. Fitz Gerald*, M. Keeney and *S. Scott*
	221	Climate Policy Versus Development Aid

209	The Effectiveness of Competition Policy and the Price-Cost Margin: Evidence from Panel Data Patrick McCloughan, *Seán Lyons* and William Batt
208	Tax Structure and Female Labour Market Participation: Evidence from Ireland *Tim Callan*, A. Van Soest, *J.R. Walsh*