Ex-Post Analysis of the Impact of National Landfill Policy for Greenhouse Gas Emissions in the Waste Sector

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Executive Summary

This research study examines the impact of Ireland's landfill policy on greenhouse gas emissions from the waste sector over the past three decades. The analysis focuses on direct methane emissions emanating from the municipal solid waste disposed to landfill sites in Ireland over the period 1990-2018.

The following key findings emerge from the analysis:

Patterns and Trends in Municipal Solid Waste Landfilled and Associated Methane Emissions

- **Over the past three decades, the quantity of the municipal solid waste landfilled in Ireland has declined by 75.9 per cent,** from 1,925.3 kilo tonnes in 1990 to 463.2 kilo tonnes in 2018. The proportion of municipal solid waste landfilled in the total municipal solid waste stood at 14 per cent in 2018, down from 92 per cent in 1990.

- **Food and paper account for the largest share in the municipal solid waste disposed to landfill over the period 1990-2018**. While the share of food waste has decreased particularly since 2010, this decline has been mirrored over the same period by an increase in the share of textiles in the solid waste disposed to landfill.

- **The reduction of the proportion of landfill disposal in the total quantity of municipal solid waste in Ireland over the past two decades by 69 percentage points is the third highest among European Union countries**. Over the same period, the proportion of recycled municipal solid waste in the total municipal solid waste in Ireland has increased by 32.3 percentage points and the energy recovery rate by 31.8 percentage points**.** The introduction of incineration of municipal solid waste has made energy recovery the main alternative treatment to landfill.

- **The total methane emissions generated from municipal solid waste disposed to landfill sites peaked in 2009** at 2,471.2 kilo tonnes CO_2 equivalent and have declined since then by 29.1 per cent standing at 1,752.9 kilo tonnes CO_2 equivalent in 2018. The net methane emissions from municipal solid waste landfilled (total methane generated net of methane recovered) have been the highest in 1995, 1,592.8 kilo tonnes CO_2 equivalent. The net methane emissions from municipal solid waste landfilled were lower by 56.5 per cent compared to their peak in 1995 and by 47.4 per cent compared to 1990.

Landfill Policy Impacts on Methane Emissions

- **To a large extent, the major landfill policy developments in Ireland have been driven by regulations and policy initiatives taken at the European Union level**, such as the Waste Framework Directives, the Landfill Directive, and the EU Circular Economy Action Plans.

- **The results of this analysis indicate that Ireland's landfill policy has been associated with substantial reductions of the methane emissions in the waste sector**. Our estimates indicate that in the absence of the policy measures implemented since 1996, the total methane emissions over the period 1990-2018 would have been higher by 15,845 kilo tonnes CO_2 equivalent and the net methane emissions would have been higher by 4,910 kilo tonnes CO_2 equivalent. Compared with a situation of no landfill policy, the total methane emissions have been lower by 27.9 per cent while the net methane emissions have been lower by 16.8 per cent.

- **The landfill levy has been an important policy instrument to achieving the reduction of the proportion of municipal solid waste disposed to landfill**. The results of this analysis show that the quantity of municipal solid waste landfilled has declined at an accelerated pace since the introduction of the landfill levy and its increase from €15 to €75 per tonne.

- **The introduction of the landfill levy has been associated with a reduction of total methane emissions by 10 per cent and a reduction by 6.8 per cent of net methane emissions.** Compared to a situation in which the landfill levy would have remained constant at €15 per tonne, the increased landfill levy has led to lower methane emissions by 7 per cent in the case of total methane emissions and by 4.2 per cent in the case of net methane emissions.

- **In the absence of targets for recycling of municipal solid waste**, assuming that recycling rates would have remained as in 2001, the total methane emissions would have been higher by 10 per cent and the net methane emissions would have been higher by 5.9 per cent.

- **In the absence of regulations for food waste disposed to landfill**, assuming that the proportion of food waste disposed to landfill in the municipal solid waste would have remained as in 2009, the total methane emissions would have been higher by 3.2 per cent and the net methane emissions would have been higher by 2.2 per cent.

Outlook of Opportunities and Challenges

- **Notwithstanding Ireland's reduction in the proportion of municipal solid waste disposed to landfill in total municipal solid waste from 92 per cent in 1995 to 14 per cent in 2018, at 38 per cent, the recycling rate of municipal waste (the proportion of the recycled waste in total municipal solid waste) is below the EU targets** (55 per cent in 2025; 60 per cent in 2030; 65 per cent in 2035) and lower than in a number of other high income EU countries.

- **Further reductions in the landfill rate to meet the EU target of 10 per cent or less in 2035** if achieved are likely to contribute to further reductions in the methane emissions in the waste sector.

1 Introduction

This research study examines the impact of Ireland's landfill policy on greenhouse gas (GHG) emissions in the waste sector over the past three decades. The analysis focuses on direct methane (CH_4) emissions from the municipal solid waste disposed to landfill in Ireland over the period 1990-2018. To this purpose, we compare actual CH_4 emissions with estimated CH_4 emissions in a range of counterfactual policy scenarios. The policy scenarios are designed assuming the absence of landfill policy or the absence of important policy instruments such as the landfill levy, targets for recycling rates, and food waste regulations.

The waste sector accounted for 1.5 per cent of Ireland's total GHG emissions in 2018 (Duffy et al. 2020).[1] Amongst the GHG emissions from the waste sector, the largest contributor is methane from organic waste in landfills. Annual CH_4 emissions can be significantly different depending on factors such as operation time, landfill capacity, and management level (Cai et al., 2014). It is thus important to design effective waste management strategies to avoid public health and environmental issues that may impose economic costs substantially higher than those to develop and operate adequate waste management systems (Kaza et al., 2018). Different strategies provide varying degrees of mitigation of GHG emissions generated from municipal solid waste, as well as transformation from waste to energy. Direct drivers of municipal solid waste composition and its rate of growth are a function of a country's environmental, economic and social conditions. The generation of municipal solid waste increases with the income level of a country and similarly the degree of sustainability is correlated with economic development (Shekdar, 2009).

The waste management strategies used nowadays include: waste disposal by landfilling and incineration; recycling; reuse; and source reduction (Iyamu et al., 2020; Kaza et al., 2018). Examples of reuse of organic waste are composting and vermicomposting. Source reduction refers to the reduction of materials and energy during the production of goods and services. Energy recovery, also known as waste to energy, is a strategy applied to waste that is not recyclable to create electricity, fuel or heat simultaneously helping to reduce methane emissions emanating from landfills. Some examples of this strategy are incineration with energy recovery, which can also be employed without recovery, landfill gas (LFG) recovery and anaerobic digestion (AD) (Astrup et al., 2015; Intergovernmental Panel on Climate Change, 2014). Two additional waste to energy strategies are gasification and pyrolysis, both a thermal processing however the former is conducted in a limited amount of air or oxygen whereas the latter in the absence of them (Ramirez & Rainey, 2019).

Waste disposal to landfill is regarded as the least preferred option in the waste management strategies with respect to GHG emissions while waste prevention is the most effective option in reducing GHG emissions followed by reuse, recycling and waste to energy strategies (Rajaeifar et al., 2017). Dong et al. (2018) find that gasification performs better than incineration from the environmental performance perspective. The authors also find that the sustainability of waste to energy strategies is contingent on the technologies used as well as the geographical area. Although there are more and less effective municipal solid waste strategies, Bogner et al. (2007) caution that strategies other than landfilling should be used in a complementary manner rather than in isolation.

[1] The largest source of Ireland's GHG emissions in 2018 was the energy sector accounting for 60 per cent of total GHG emissions while agriculture contributed 32.7 per cent and Industrial Processes and Product Use 5.8 per cent of total GHG emissions (Duffy et al. 2020).

The remainder of this report is structured as follows. Section 2 discusses patterns and trends of municipal solid waste disposed to landfill and related CH_4 emissions in Ireland over the period 1990-2018. Further, Ireland's performance with respect to the management of municipal solid waste is compared to the performance of other EU countries. Section 3 provides an overview of the key milestones of Ireland's landfill policy over the past three decades. Section 4 describes the conceptual and methodological framework for the quantification of the impact of Ireland's landfill policy on CH_4 emissions. The results of this quantitative analysis are discussed in Section 5. Finally, Section 6 concludes with a summary of the key findings and policy takeaways.

2 Patterns and Trends of Municipal Solid Waste Disposed to Landfill and Related Methane Emissions

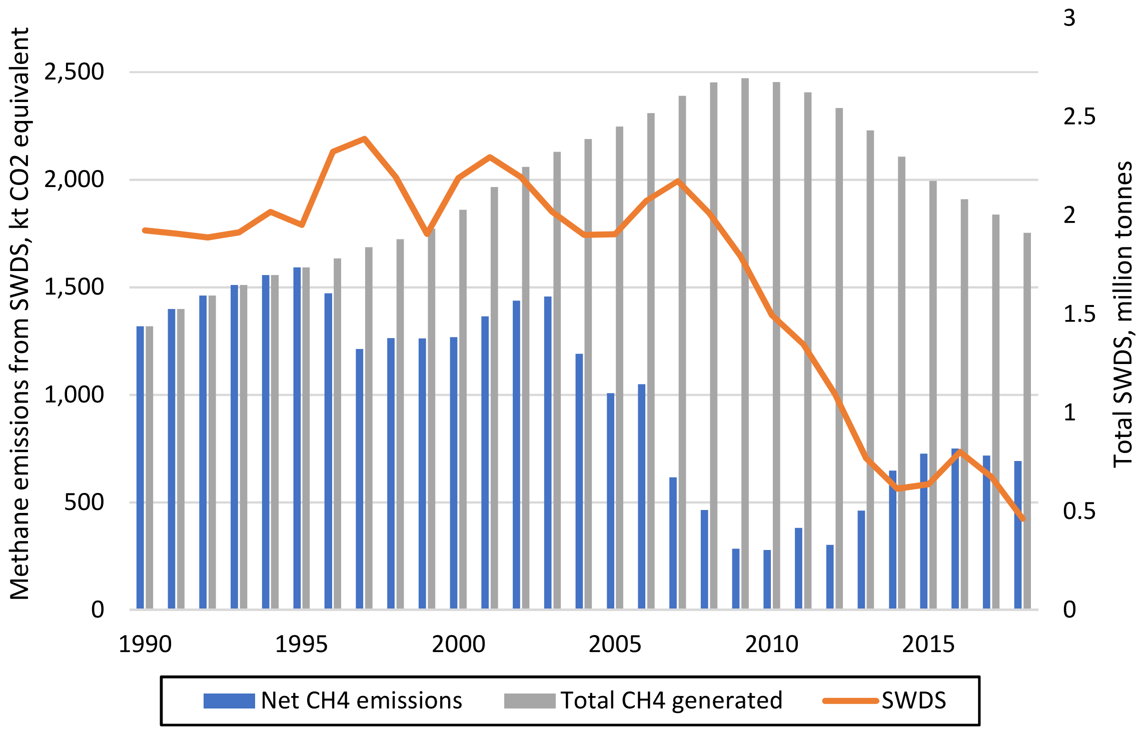
This section examines key patterns and trends in the municipal solid waste disposed to landfill and associated methane emissions in Ireland. The analysis of methane emissions focuses on direct methane emissions reported by the Environmental Protection Agency (EPA) in the National Inventory Reports 2019 and 2020 (Duffy et al., 2019, 2020). Given that Ireland's performance with respect to municipal solid waste disposed to landfill over the past three decades has been driven to a large extent by policy initiatives at the European Union level, we analyse Ireland's performance in comparison to the performance of other EU countries.

2.1 Municipal Solid Waste Disposed to Landfill and Related Methane Emissions in Ireland, 1990-2018

Municipal solid waste disposed to landfill accounted for 77.8 per cent of Ireland's total GHG emissions in the waste sector in 2018 (Duffy et al. 2020). Figure 1 shows the total and net methane (CH_4) emissions generated from municipal solid waste disposed to landfill sites (SWDS) in Ireland over the period 1990-2018. The total CH_4 generated from SWDS peaked in 2009 at 2471.2 kilo tonnes CO_2 equivalent (87.5 per cent higher than in 1990) and have declined since then to 1,752.9 kilo tonnes CO_2 equivalent in 2018 (a decrease by 29.1 per cent relative to 2009). The net CH_4 emissions from SWDS (total CH_4 generated net of CH_4 recovered) have been the highest in 1995 at 1,592.8 kilo tonnes CO_2 equivalent. At 692.7 kilo tonnes CO_2 equivalent in 2018, the net CH_4 emissions from SWDS were lower by 56.5 per cent compared to their peak in 1995 and by 47.4 per cent compared to 1990.

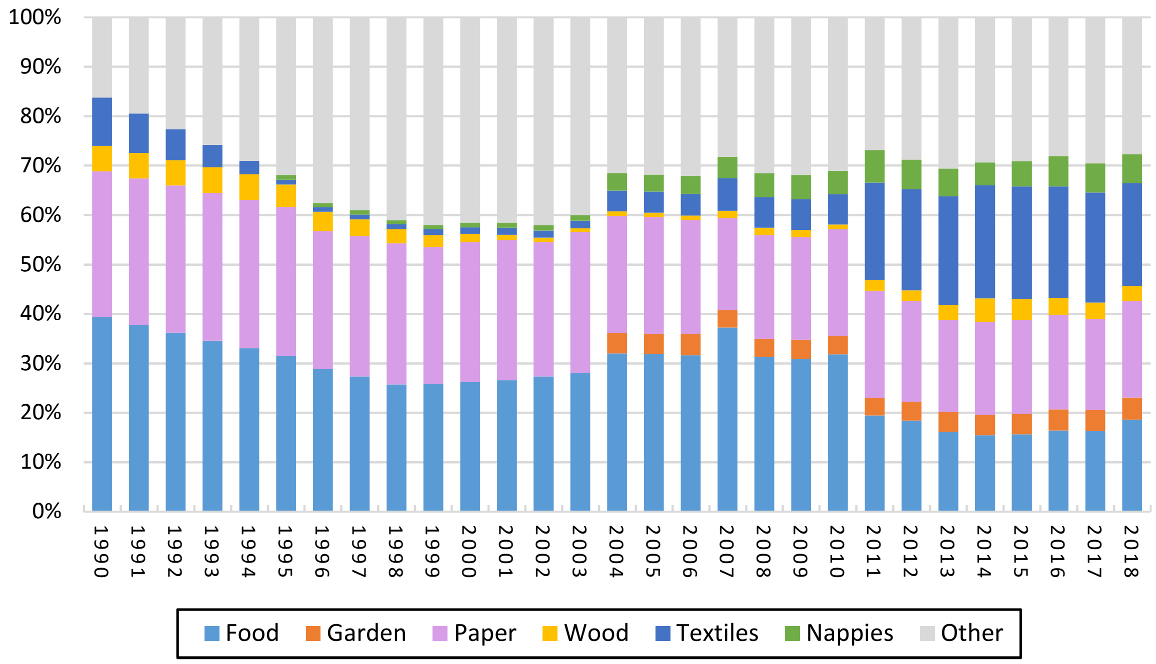
Figure 1 also shows the decline in the SWDS over the same period from 1,925.3 kilo tonnes in 1990 to 463.2 kilo tonnes in 2018 (a decrease by 75.9 per cent).

Fig. 1: Methane emissions from solid municipal waste disposed to landfill sites in Ireland, 1990-2018



Source: Authors' elaboration based on data from Ireland's National Inventory Report 2020, EPA.

Fig. 2: The composition of municipal solid waste disposed to landfill, 1990-2018



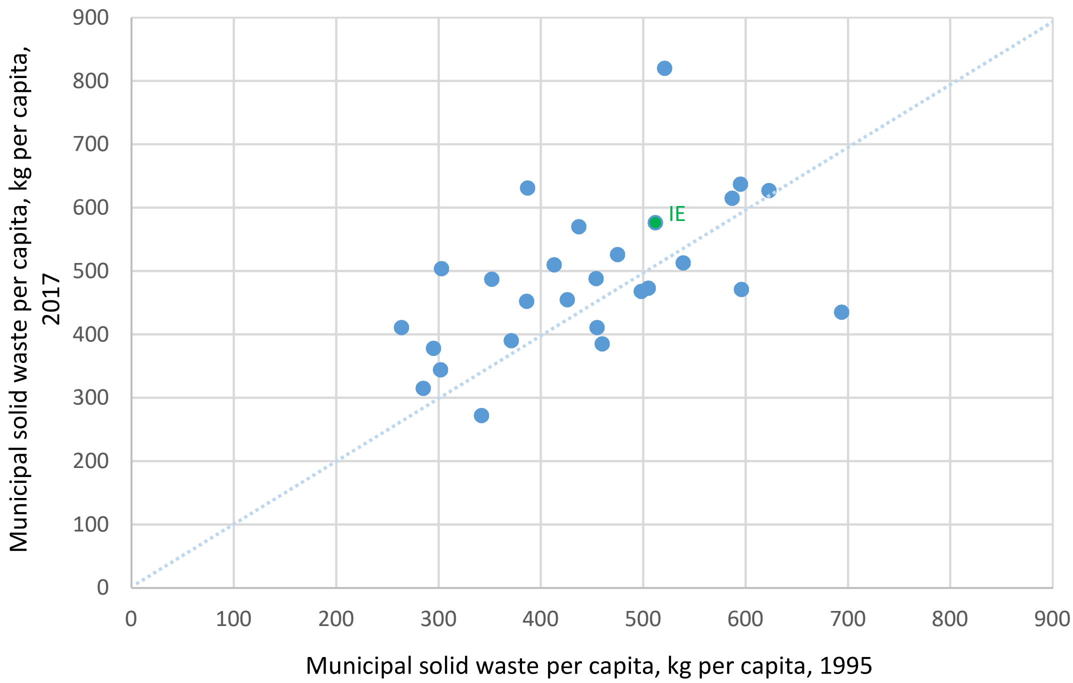
Source: Authors' elaboration based on data from Ireland's National Inventory Report 2020, EPA.

In terms of the composition of solid waste disposed to landfill over the period 1990-2018, as shown in Figure 2, food and paper account for the largest share in the municipal solid waste disposed to landfill. While the share of food waste has decreased particularly since 2010, this decline has been mirrored over the same period by an increase in the share of textiles in the solid waste disposed to landfill.

2.2 The Performance of Ireland's Municipal Solid Waste Sector in a European Context

The waste sector contributed 3 per cent of the total GHG emissions in the European Union in 2018 (Eurostat 2020). Figure 3 shows that over the past two decades, municipal solid waste per capita has increased in Ireland (from 512 kg per capita in 1995 to 576 kg per capita in 2017) as well as in many other EU countries. In eight EU countries the quantity of municipal solid waste per capita has declined over the same period (Belgium, Bulgaria, Hungary, the Netherlands, Romania, Slovenia, Spain, and the United Kingdom).

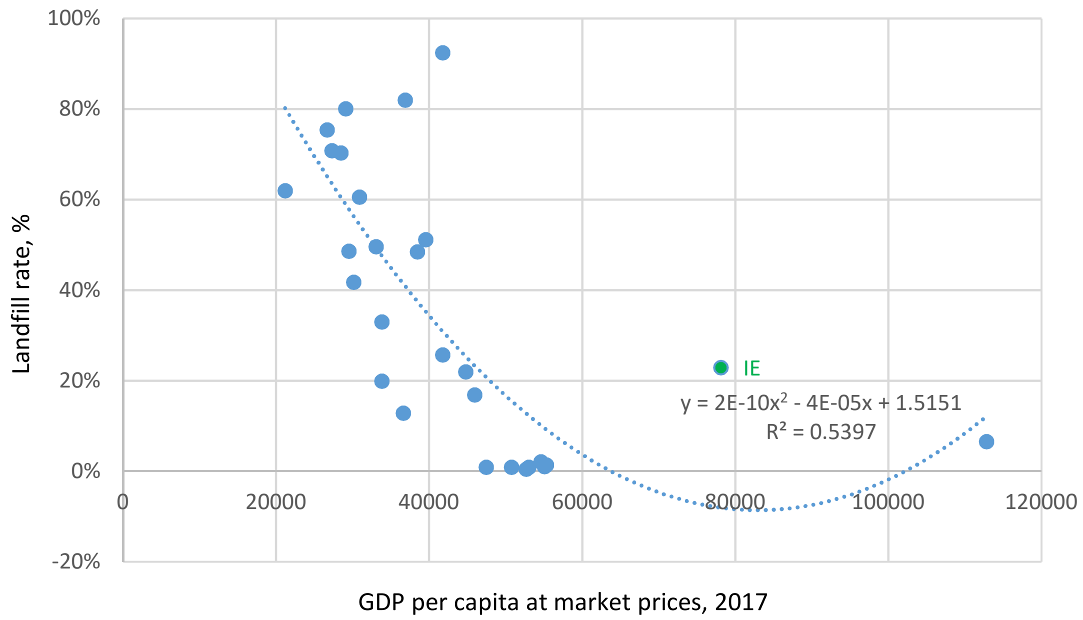
Fig. 3: Municipal solid waste per capita in EU countries, 1995-2017



Source: Authors' elaboration based on data from the Eurostat.

As shown in Figure 4, on the basis of data for EU countries in 2017, the proportion of landfill disposal of municipal waste in total municipal solid waste is negatively associated with income per capita. Ireland appears to be an outlier in the group of high income per capita EU countries with a relatively higher proportion of landfill disposal of municipal waste. This may reflect the fact that Ireland has been slow to adopt incineration as an alternative treatment of municipal solid waste to landfill. A significant incineration of municipal solid waste has taken place only in recent years.

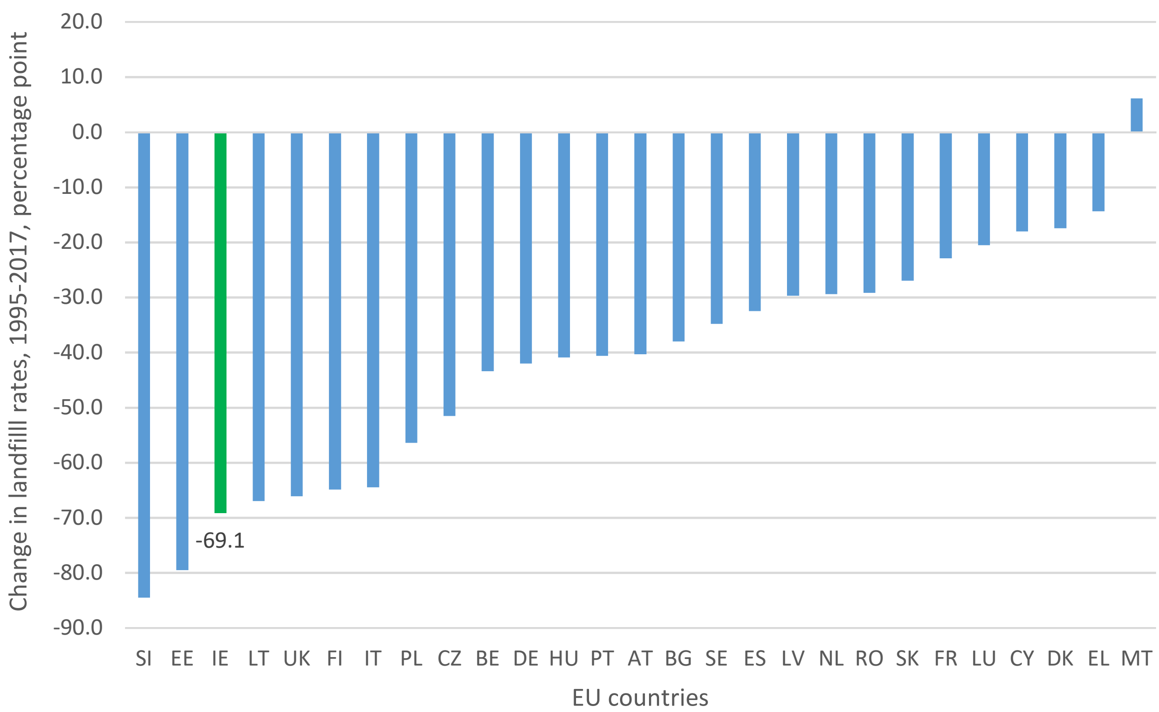
Fig. 4: GDP per capita and landfill rates in EU countries, 2017



Source: Authors' elaboration based on data from the Eurostat.

Over the period 1995-2017, the landfill rates (the proportion of municipal solid waste disposed to landfill in total municipal solid waste) have declined in all EU countries with the exception of Malta (Figure 5). Ireland's reduction of the proportion of landfill disposal of municipal waste (by 69 percentage points) is the third highest among EU countries.

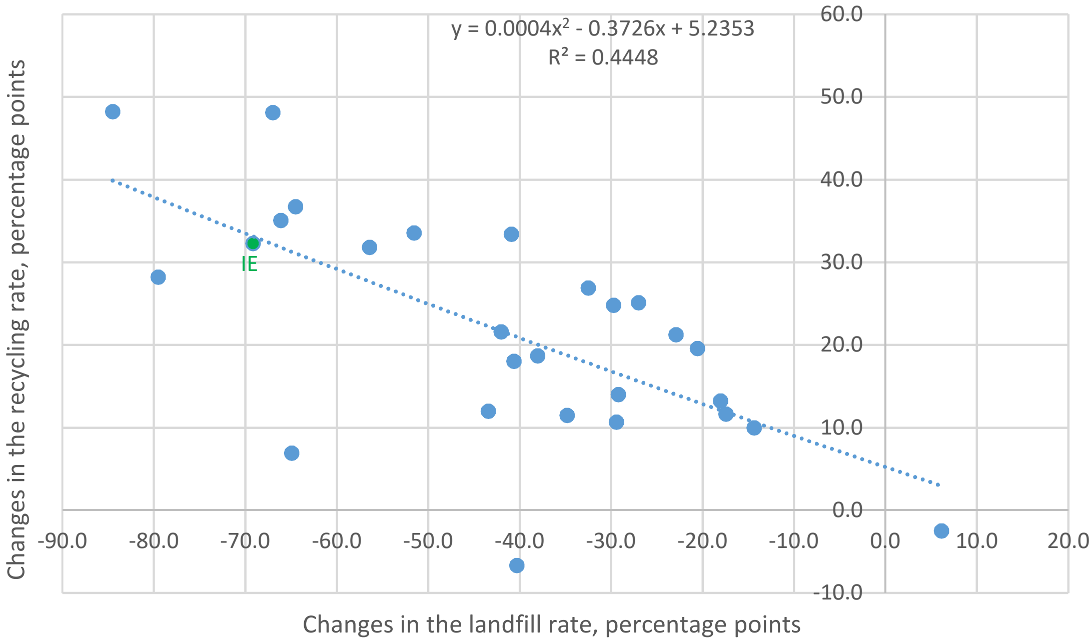
Fig. 5: Change in the landfill rate in Ireland and other EU countries, 1995-2017



Source: Authors' calculations based on data from the Eurostat.

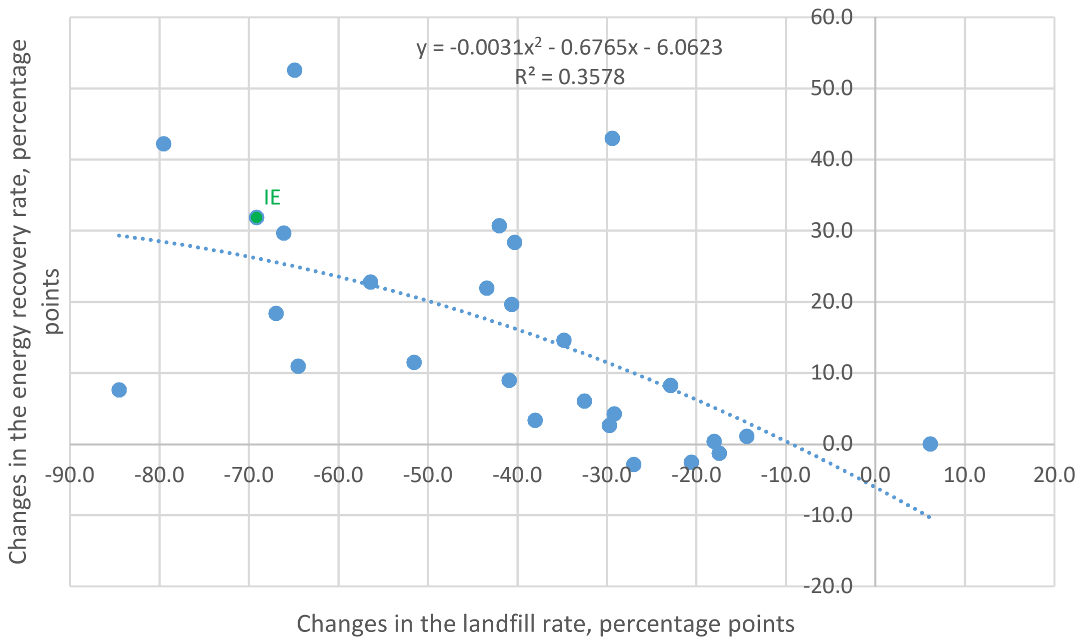
As shown in Figures 6 and 7 below, the reduction in the proportion of landfill disposal of municipal solid waste across EU countries over the past two decades has been associated with increased proportions of recycled municipal waste and higher energy recovery rates. Over the period 1998-2017, the proportion of recycled municipal solid waste in Ireland has increased by 32.3 percentage points and the energy recovery rate by 31.8 percentage points.

Fig. 6: Changes in landfill and recycling rates 1998-2017 in EU countries



Source: Authors' calculations based on data from the Eurostat.

Fig. 7: Changes in landfill and energy recovery rates, 1998-2017 in EU countries



Source: Authors' calculations based on data from the Eurostat.

3 National Landfill Policy

This section provides an overview of the key milestones in Ireland's landfill policy developments over the past decades.

As shown in Table 1, to a large extent, the major landfill policy developments in Ireland have been driven by regulations and policy initiatives taken at the European Union level, such as the Waste Framework Directives, the Landfill Directive, and the EU Circular Economy Action Plans.

The 1996 Waste Management Act has introduced the modern legal structures and regulatory framework that have greatly influenced the shift away from landfill as a waste treatment option from being the predominant one. In 1995, the proportion of municipal solid waste disposed to landfill accounted for 92 per cent of the total municipal solid waste.

A major reduction of reliance on landfill disposal and increased waste treatment options have been achieved through setting out specific targets at the EU level, in particular by the 1999 Landfill Directive implemented in Ireland in 2001. More specifically, these targets were as follows:

- **2010**: biodegradable municipal waste going to landfills must be reduced to 75 per cent of the total quantity (by weight) of biodegradable municipal waste produced in 1995 (< 916,000 tonnes);
- **2013**: biodegradable municipal waste going to landfills must be reduced to 50 per cent of the total quantity (by weight) of biodegradable municipal waste produced in 1995 (< 610,000 tonnes);
- **2016**: biodegradable municipal waste going to landfills must be reduced to 35 per cent of the total quantity (by weight) of biodegradable municipal waste produced in 1995 (427,000 tonnes).

Taken into account Ireland's initial high dependence on landfill as a waste treatment method, Ireland has been given a longer time to achieve these targets.

The 2002 Government Policy Statement "Preventing and Recycling Waste: Delivering Change" has further advanced the policy agenda for waste prevention and recycling. A key milestone in Ireland's landfill policy has been the introduction of a landfill levy at €15 per tonne. The landfill levy has been increased over time and it is currently at €75 per tonne (unchanged since 2013).

To further progress the policy agenda for waste prevention, a National Waste Prevention Programme (NWPP) has been established in 2004.

Further measures to divert biodegradable waste from landfill have been set out in the 2006 National Biodegradable Waste Management Strategy.

The implementation of the 2008 EU Waste Framework Directive has set up further targets such as preparing for reuse and recycling of 50 per cent of the quantity (by weight) of household derived paper, metal, plastic & glass.

The 2011 EPA Technical Guidance Document on Municipal Solid Waste-Pre-Treatment and Residual Management sets out the EPA standards for minimum pre-treatment of municipal solid waste accepted for landfilling or incineration.

Table 1: National Landfill Policy: Key Milestones

Year	Policy Document	Policy Actions/Instruments/Targets
1996	Waste Management Act - following from the EU Waste Framework Directive	Modern legal structures and regulatory framework Waste management planning Introduced the waste hierarchy: prevention, reuse, recycling, recovery, landfilling
1998	Government Policy Statement – "Waste Management: Changing our Ways"	Key objective: a major reduction of reliance on landfill disposal and increased treatment options Greater participation of the private sector to the management of waste 15 year recycling and recovery targets – to be achieved by 2013 • Diversion of 50 per cent of household waste from landfill • Minimum 65 per cent reduction in biodegradable wastes consigned to landfill • Recycling of 35 per cent of municipal solid waste • Recycling of 85 per cent of construction and demolition (C & D) waste (50 per cent rate to be achieved by 2003)
1999	EU Landfill Directive	**Implemented in Ireland in 2001** **2010**: biodegradable municipal waste going to landfills must be reduced to 75 per cent of the total quantity (by weight) biodegradable municipal waste produced in 1995 (< 916,000 t) **2013**: biodegradable municipal waste going to landfills must be reduced to 50 per cent of the total quantity (by weight) biodegradable municipal waste produced in 1995 (< 610,000 t); **2016**: biodegradable municipal waste going to landfills must be reduced to 35 per cent of the total quantity (by weight) biodegradable municipal waste produced in 1995 (427,000 t);

2001	Waste Management (Amendment) Act National Hazardous Waste Management Plan	Integrated regional waste management planning
2002	Government Policy Statement "Preventing and Recycling Waste: Delivering Change"	Policy agenda for waste prevention and recycling The introduction of a landfill levy
2003	Protection of the Environment Act	
2006	National biodegradable Waste management strategy	Sets out measures to divert biodegradable waste from landfilling
2008	EU Waste Framework Directive	Preparing for reuse and recycling of 50 per cent by weight of household derived paper, metal, plastic & glass Preparing for reuse, recycling and other material recovery (incl. beneficial backfilling operations using waste as a substitute) of 70 per cent by weight of construction and demolition (C&D) non-hazardous waste (excluding natural soils & stone) Establishment of a National Waste Prevention Programme (NWPP) – this has been established in Ireland in 2004
2011	Municipal Solid Waste-Pre-Treatment and Residual Management – EPA Technical Guidance Document	It sets out the EPA standards for minimum pre-treatment municipal solid waste accepted for landfilling or incineration
2020	EU Second Circular Economy Action Plan	**Waste-specific measures** Waste reduction targets for specific streams and other measures on waste prevention EU-wide harmonised model for separate collection of waste and labelling to facilitate separate collection Methodologies to track and minimise the presence of substances of concern in recycled materials and articles made thereof Harmonised information systems for the presence of substances of concern

		Scoping the development of further EU-wide end of-waste and by-products criteria Revision of the rules on waste shipments to provide greater traceability and ensure that resources are not lost overseas or dumped in third countries with less robust social or environmental protections in place.
2020	The Waste Action Plan for the Circular Economy	Sets out national steps and targets towards achieving a circular economy Waste prevention principles will be prioritised Policy coherence – a circular economy unit will be established within the Department of Environment, Climate Change and Communications The existing National Waste Prevention Programme will be reconfigured to make it Ireland's Circular Economy Programme. Led by the EPA, it will have a designated coordinating role to support the Department's circular economy unit in overseeing national, regional and local activities to improve coherence and alignment of national and local activities and ensure maximum impact. **EU Revised Targets** Recent revisions to the Waste Framework Directive introduced the following recycling rates targets for municipal solid waste • 55 per cent by 2025 • 60 per cent by 2030 • 65 per cent by 2035 In addition, the Landfill Directive has been amended to require that by 2035 no more than 10 per cent of the amount of municipal solid waste goes to landfill. Municipal waste recycling targets will be incorporated as conditions of waste collection permits (i.e. collectors will be required to achieve a 55 per cent recycling rate of municipal waste by 2025, 60 per cent by 2030 and 65 per cent by 2035). The colour coding of bins will be standardised across the State on a phased basis (general waste bin to be designated as a 'recovery' bin: colour black; mixed dry

		recycling bin: colour green; organic waste bin to be designated as 'organic waste recycling bin': colour brown). A Waste Recovery Levy of €5 per tonne will be introduced. This will apply to recovery operations at Municipal Solid Waste (MSW) Landfills, Waste to Energy Plants and Co-Incineration Plants and the Export of MSW. Further measures will be introduced to incentivise the prevention and segregation of waste, including for example, reviewing the incentivised charging regime and introducing penalties for those who fail to segregate waste

Source: Authors' elaboration based on published information by the EPA, the European Commission and the European Environmental Agency.

The 2020 Waste Action Plan for the Circular Economy sets out national steps and targets towards achieving a circular economy in Ireland. To this purpose, waste prevention principles will be prioritised.

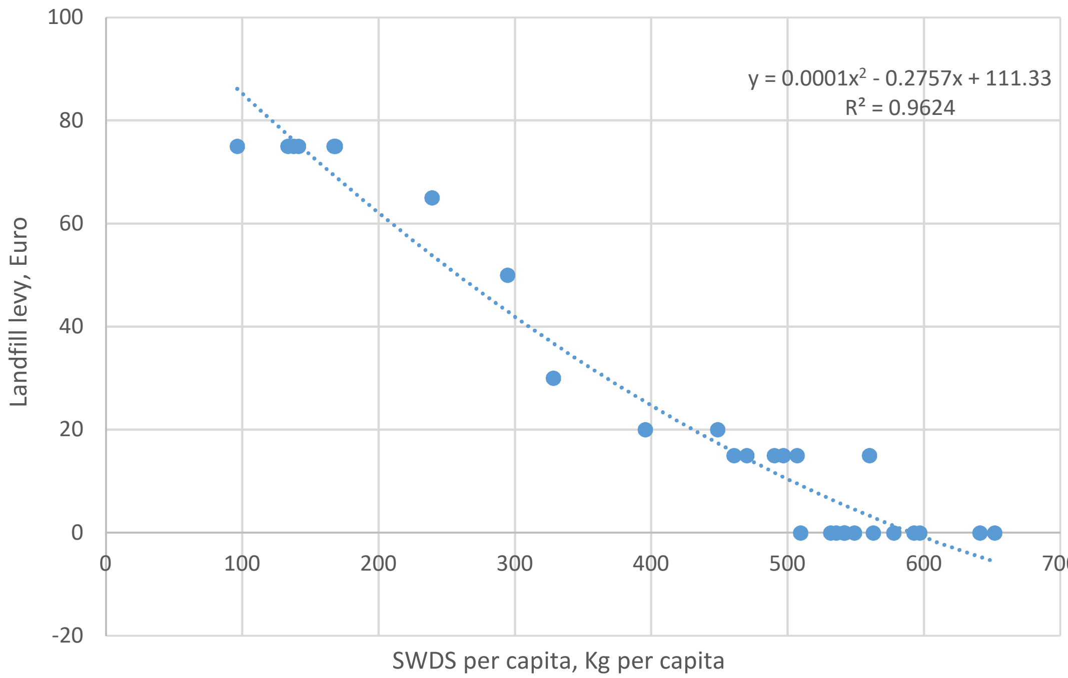
Recent revisions in the EU Waste Framework Directive has introduced the following revised targets for the recycling rate of municipal solid waste (by weight of household derived paper, metal, plastic, and glass to be prepared for reuse and recycling): 55 per cent by 2025; 60 per cent by 2030; 65 per cent by 2035.

To achieve these targets, municipal waste recycling targets will be incorporated as conditions of waste collection permits.

In addition, the EU Landfill Directive has been amended to require that by 2035 no more than 10 per cent of municipal solid waste goes to landfill.

As mentioned above, the landfill levy has been an important policy instrument to achieving the reduction of the proportion of municipal solid waste disposed to landfill. As shown in Figure 8, there is a strong negative correlation between the landfill levy (introduced in 2002) and the quantity of solid waste disposed to landfill.

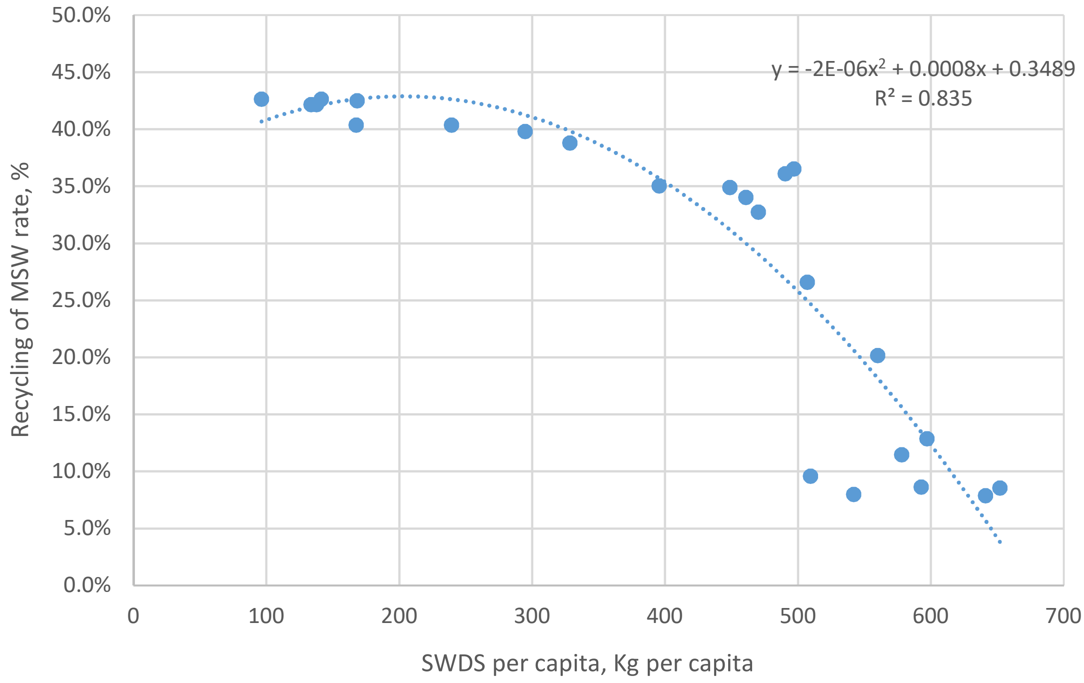
Fig. 8: Solid waste disposed to landfill sites and the landfill levy, Ireland, 2002-2018



Source: Authors' elaboration based on data from the National Inventory Report 2020, EPA.

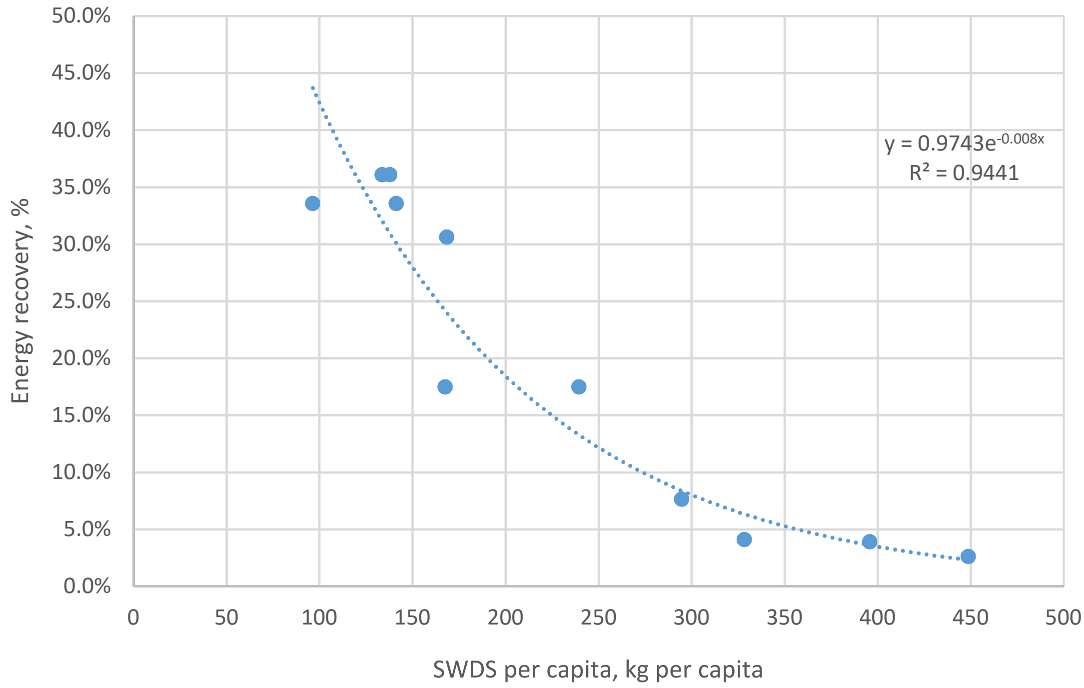
The reduction in the quantity of municipal solid waste disposed to landfill has been associated with increased rates of recycled solid municipal waste (Figure 9) and energy recovered (Figure 10).

Fig. 9: Solid waste disposed to landfill sites and the rate of recycled municipal solid waste in Ireland, 1995-2018



Source: Authors' elaboration based on data from the Eurostat and EPA.

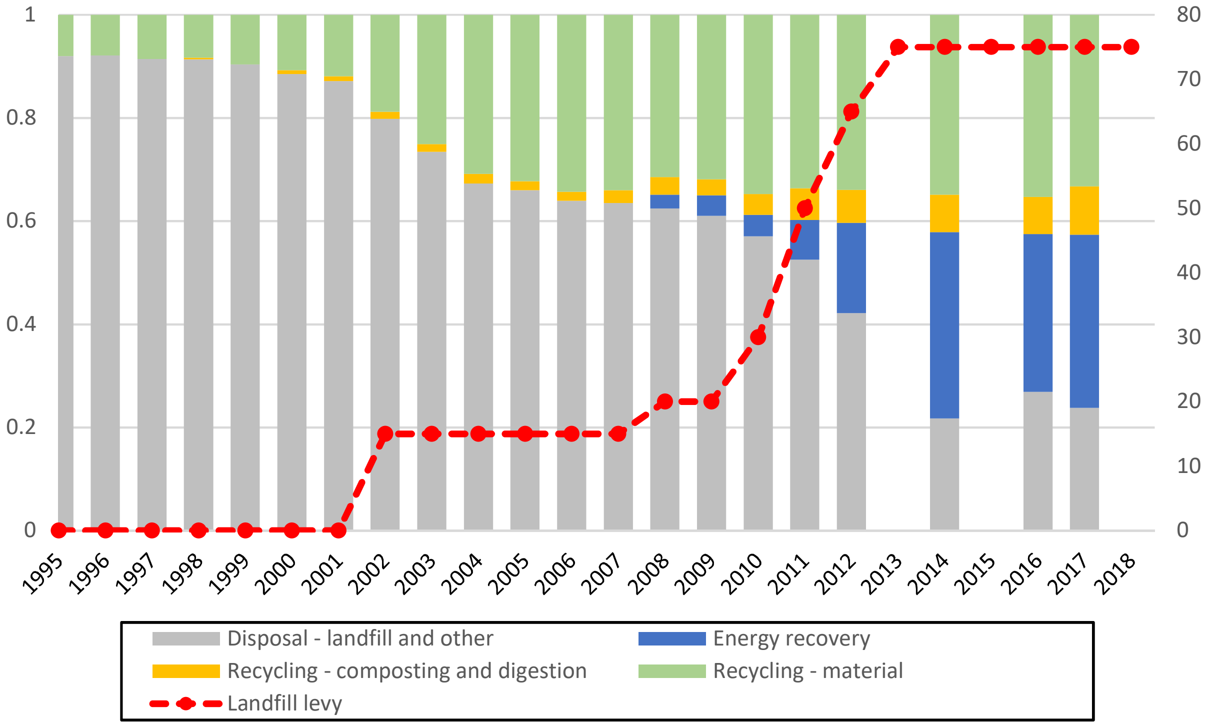
Fig. 10: Solid waste disposed to landfill sites and the rate of energy recovered from municipal solid waste in Ireland, 1995-2018



Source: Authors' elaboration based on data from the Eurostat and EPA.

Figure 11 brings together the evidence shown in Figures 8-10. The key takeaway from these Figures is that the landfill levy and its increase over time from €15 per tonne to €75 per tonne have been associated with a significant reduction of the proportion of landfill as a method of municipal solid waste treatment and an increase in the importance of recycling and energy recovery as waste treatment methods. The introduction of the incineration of municipal solid waste in 2011 has led to energy recovery being the main alternative treatment to landfill while the recycling rate of municipal waste has not changed much since then.

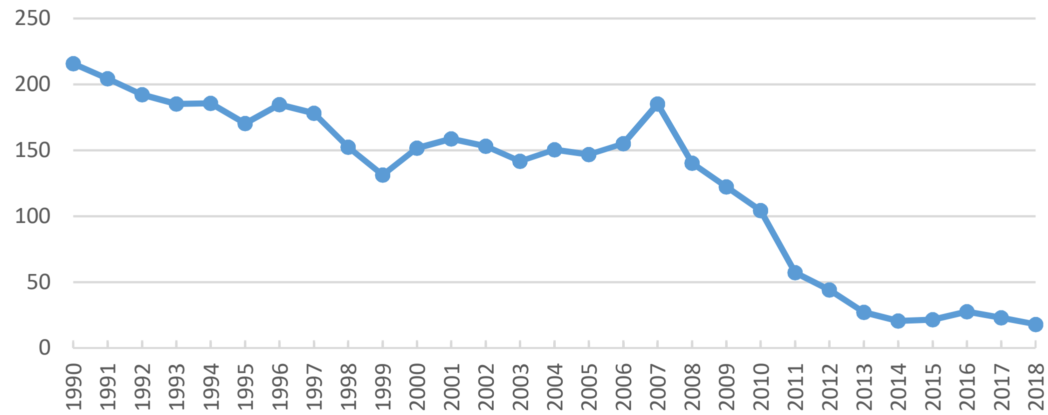
Fig. 11: Municipal solid waste treated in Ireland by method and the landfill levy, 1995-2018



Source: Authors' elaboration based on data from the Eurostat and EPA.

Figure 12 shows the decline in the food waste per capita disposed to landfill from 215.9 kg in 1990 to 17.9 kg in 2018. It appears that this decline has been accelerated since 2010, the year when the Food Waste Regulation was implemented. The fraction of food waste in municipal solid waste landfilled was around 30 per cent before 2011 and it decreased to around 19 per cent in 2018.

Fig. 12: The quantity of per capita food waste disposed to landfill in Ireland, 1990-2018



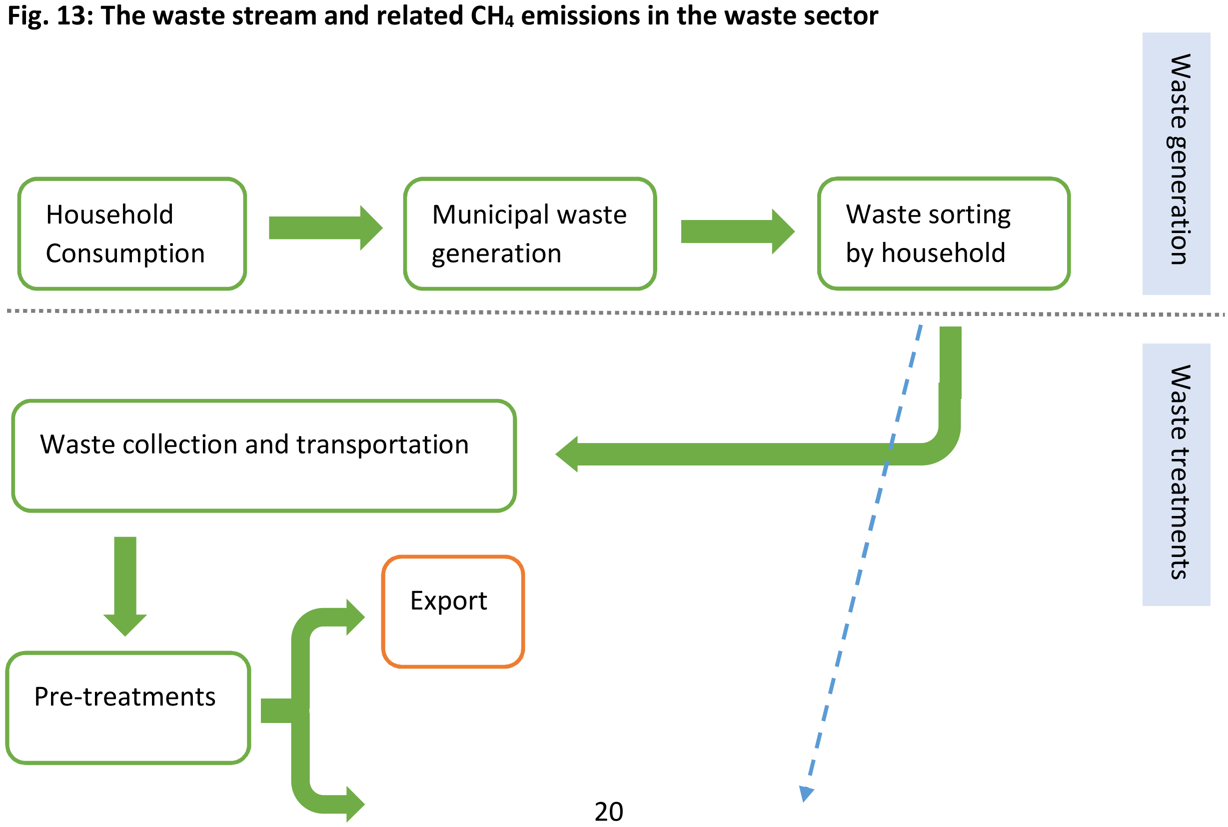
Source: Authors' elaboration based on data from the National Inventory Report 2020, EPA.

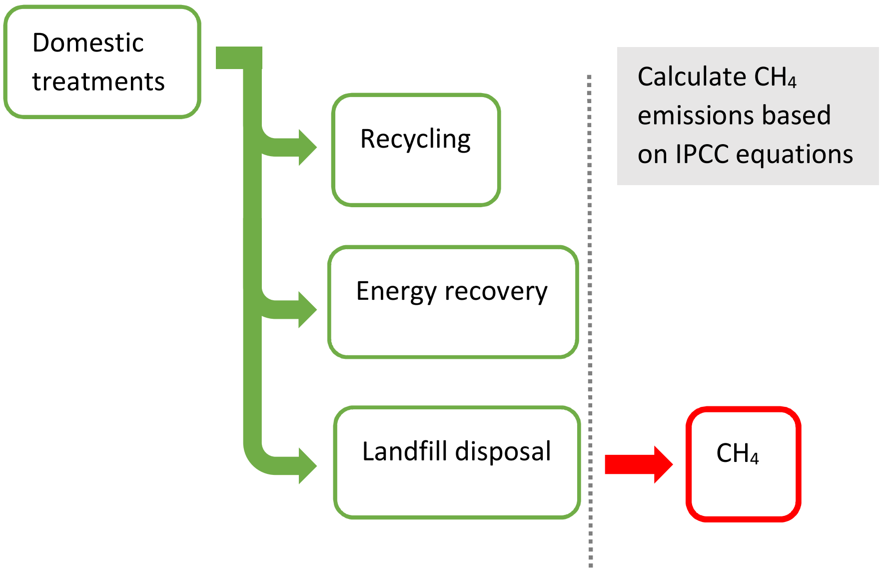
4 Quantification of the Impact of National Landfill Policy on Greenhouse Gas Emissions: Conceptual and Methodological Framework

To quantify the impact of Ireland's landfill policy on CH_4 emissions, we compare the actual CH_4 emissions with estimated counterfactual CH_4 emissions in a range of policy scenarios. The actual CH_4 emissions are the EPA estimates based on the 2006 IPCC First Order Decay (FOD) Method reported in the National Inventory Report 2020 (Duffy et al., 2020). Using available data from the EPA, we estimate counterfactual CH_4 emissions using the same methodology and predict quantities of municipal solid waste disposed to landfill in the policy scenarios considered.

Figure 13 below provides an overview of the waste stream and related CH_4 emissions in the waste sector.

Fig. 13: The waste stream and related CH_4 emissions in the waste sector





Notes: Energy recovery may emit a small amount of CH_4 due to incomplete combustion.

Source: Authors' elaboration based on available information from the EPA.

4.1 Estimating Methane Emissions Related to Municipal Solid Waste

The municipal solid waste disposed to landfill contains degradable organic carbon which is decomposed by bacteria under anaerobic conditions into methane (CH_4) and other compounds. The degradation process can take a long period, from one year to several decades depending on the conditions of the landfill sites where the solid waste is disposed. The CH_4 emissions from solid waste disposal sites are important contributors to global CH_4 emissions.

The EPA uses the 2006 Intergovernmental Panel on Climate Change (IPCC) First Order Decay (FOD) method to estimate CH_4 emissions from the solid waste disposed to landfill sites which are reported to the National Inventory of GHG Emissions. For comparability reasons, we use the same methodology to estimate total and net CH_4 emissions in a range of counterfactual policy scenarios.

IPCC First Order Decay Model

The First Order Decay method is a theoretical equations-based model which takes into account the timing of actual CH_4 emissions. This method is therefore considered to estimate more accurately the yearly CH_4 emissions in comparison to an alternative method which assumes that all potential CH_4 is released in the year when the solid waste is disposed to landfill.

Figure 14 summarises the structure of the 2006 IPCC Model to estimate CH_4 emissions from municipal solid waste disposed to landfill. The key variables used in the model are as follows:

T = the year of inventory

x = material fraction/waste category

W(T) = amount of solid waste deposited in year T

MCF = Methane Correction Factor

DOC = Degradable organic carbon (under aerobic conditions)

DOCf = Fraction of DOC decomposing under anaerobic conditions

DDOC = Decomposable Degradable Organic Carbon (under anaerobic conditions)

DDOCmd (T) = mass of DDOC deposited year T

DDOCmrem (T) = mass of DDOC deposited in inventory year T, remaining not decomposed at the end of year

DDOCmdec (T) = mass of DDOC deposited in inventory year T, decomposed during the year.

DDOCma (T) = total mass of DDOC left not decomposed at end of year T

DDOCma (T-1) = total mass of DDOC left not decomposed at end of year T-1

DDOCmdecomp (T) = total mass of DDOC decomposed in year T

CH_4 generated (T) = CH_4 generated in year T

F = Fraction of CH_4 by volume in generated landfill gas

16/12 = Molecular weight ratio CH_4/C

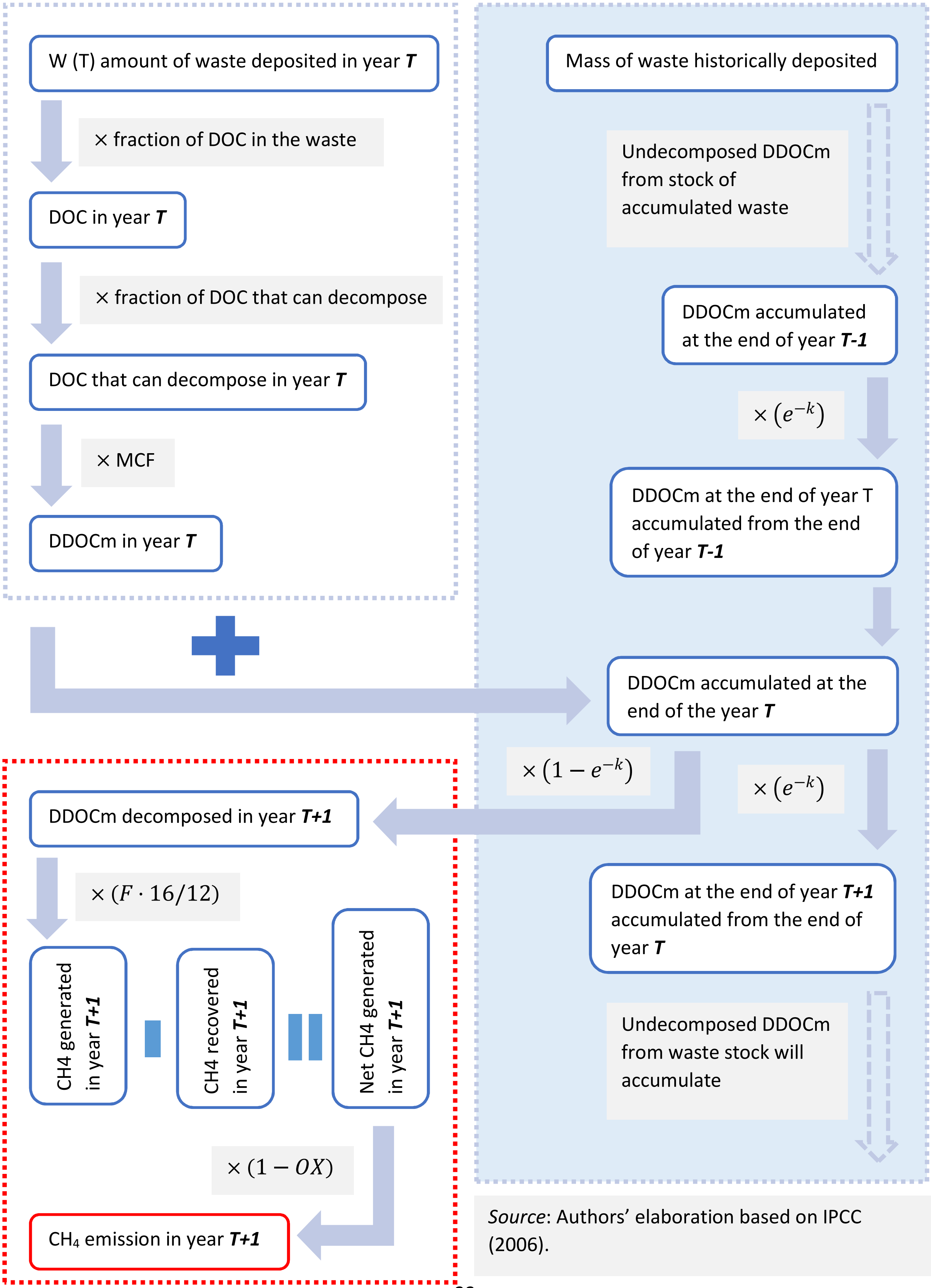
R (T) = Recovered CH_4 in year T

OX (T) = Oxidation factor in year T (fraction)

k = rate of reaction constant

M = Month of reaction start (= delay time + 7)

Fig. 14: The 2006 IPCC FOD Method to Estimate CH_4 Emissions from Municipal Solid Waste Disposed to Landfill



Source: Authors' elaboration based on IPCC (2006).

4.2 Counterfactual Analysis

To quantify the effect of Ireland's landfill policy on CH_4 emissions, we compare actual CH_4 emissions from landfill with estimated counterfactual CH_4 emissions in a range of policy scenarios. The counterfactual CH_4 emissions are estimated using the 2006 IPCC model (as in the National Inventory Report 2020) and hypothetical (predicted) quantities of solid waste disposed to landfill sites (SWDS) in the policy scenarios considered. Both total CH_4 generated and net CH_4 emissions are estimated.[2] The considered policy scenarios and associated modelling assumptions are described in Table 2 below:

Table 2: Counterfactual Policy Scenarios and Modelling Assumptions

Policy Scenarios	Modelling Assumptions
1. Business as usual – the absence of modern structures and institutional framework for the management of municipal solid waste	- The proportion of SWDS remains constant at 92 per cent of MSW over the period 1990-2018; - Unchanged waste composition as in 1995
2. No landfill levy	- SWDS changes depending on the municipal solid waste and a linear time trend
3. Constant landfill levy at €15	- Predicted SWDS as function of a constant landfill levy
4. The absence of the specific targets on recycling rates as in the Landfill Directive	- Predicted SWDS with the recycling rate as in 2001 – prior to the implementation of the Landfill Directive
5. The absence of the Food Waste Regulation	- Predicted SWDS in the absence of the Food Waste Regulation implemented in 2010

The models used to predict the quantities of solid municipal waste in the policy scenarios describedin Table 2 are described in Box 1 below.

Box 1: Modelling Solid Municipal Waste Disposed to Landfill

The predicted quantities of solid municipal waste in the policy scenarios described in Table 2 above are estimated using the following econometric models:

Scenario 1

$$log(swds/pop)_t = log(92\%) + log(msw/pop)_t \quad (1)$$

Scenarios 2-3

$$log(swds/pop)_t = \beta_0 + \beta_1 log(msw/pop)_t + \beta_2 time_t + \beta_3 log(levy)_t + \beta_4 log(levy)_t^2 + \varepsilon_t \quad (2)$$

Scenario 4

$$log(swds/pop)_t = \beta_0 + \beta_1 log(msw/pop)_t + \beta_2 time_t + \beta_3 log(levy)_t + \beta_4 log(recycling/pop)_t + \beta_5 log(energy/pop)_t + \beta_6 log(recycling/pop)_t \cdot log(levy)_t + \beta_7 log(energy/pop)_t \cdot log(levy)_t + \varepsilon_t \quad (3)$$

$(swds/pop)_t$: per capita quantity of municipal solid waste disposed to landfill sites in year t

[2] The counterfactual net CH_4 emissions are estimated assuming that the counterfactual CH_4 recovered is proportional to the counterfactual total CH_4 generated and the actual CH_4 recovered rate (the actual proportion of the CH_4 recovered in the actual total CH_4 generated).

$log(msw/pop)_t$: per capita quantity of municipal solid waste in year t

$(recycling/pop)_t$: per capita quantity of municipal solid waste recycled in year t

$(energy/pop)_t$: per capita quantity of municipal solid waste recovered for energy in year t

$time_t$: linear time trend

$(levy)_t$: the landfill levy in year t, in Euros

ε_t : error term

Scenario 5

To predict the SWDS in Scenario 5, we estimate first the per capita food waste disposed to landfill $(food\ waste/pop)$ using the following econometric model:

$$log(food\ waste/pop)_t = \beta_0 + \beta_1 log(msw/pop)_t + \beta_2 time_t + \beta_3 log(levy)_t + \beta_4 policy_t + \beta_5 time_t \cdot policy_t + \beta_6 log(levy)_t \cdot policy_t + \varepsilon_t \quad (4)$$

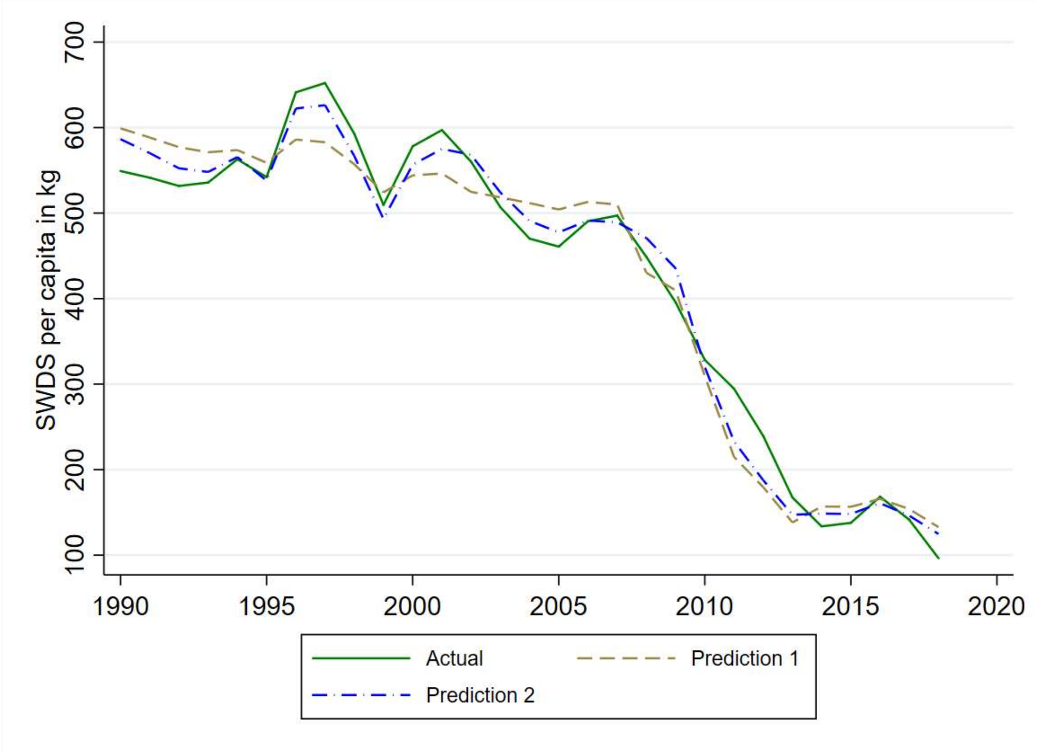
where *policy* is a categorical variable that indicates the presence of the Food Waste Regulation adopted in 2009. It equals 1 for the years after 2009. The counterfactual food waste per capita is predicted assuming the absence of the Food Waste Regulation (*policy* = 0).

The variables used in the econometric models (1) - (4) are summarised in Table A1 in the Appendix. The estimated parameters β_i are used to calculate the predicted quantity of municipal solid waste disposed to landfill sites (SWDS) in the counterfactual policy scenarios. The estimated parameters β_i obtained with the above econometric models are presented in Tables A2 and A3 in the Appendix.

Figure 15 compares the actual per capita quantity of SWDS with the predicted per capita SWDS obtained on the basis of models (2) and (3) described in Box 1 above over the analysed period. The figure shows that the predicted per capita quantity of SWDS matches closely the actual per capita quantity of SWDS.

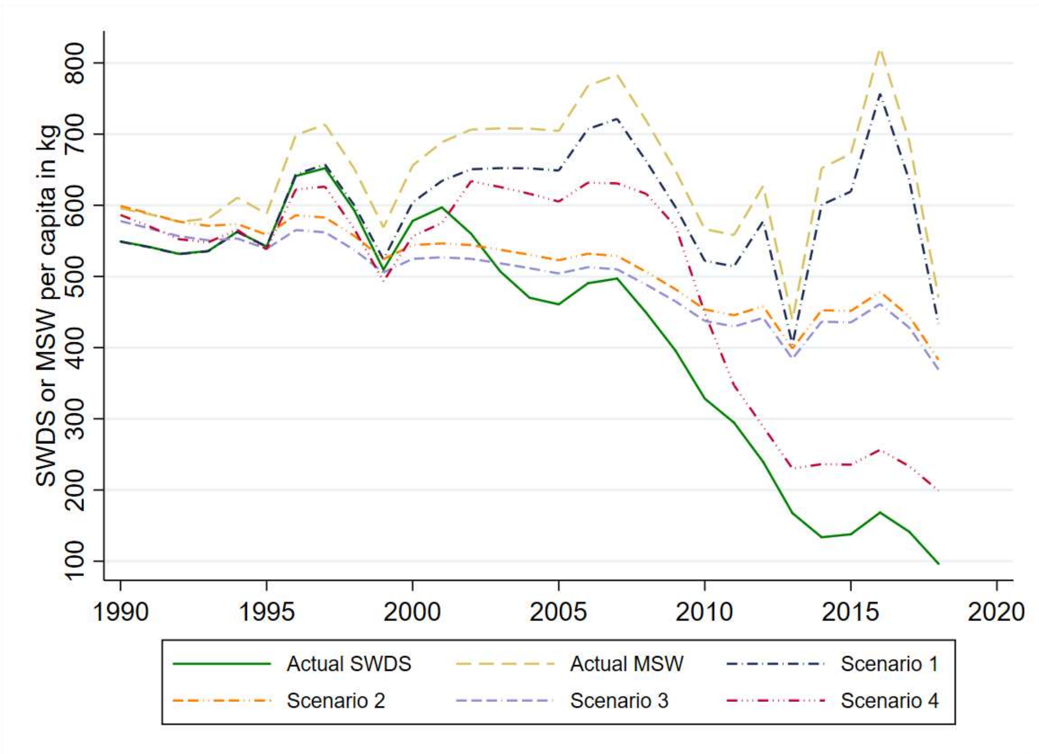
Figure 16 compares the actual per capita quantities of SWDS with the predicted per capita quantities of SWDS in the counterfactual policy scenarios 1-4. Overall, the figure shows that in the absence of landfill policy, the per capita quantity of SWDS would have been higher compared to the actual per capita quantity of SWDS.

Fig. 15: Actual and predicted per capita SWDS, 1990-2018



Source: Authors' estimates based on data from the Eurostat and EPA.

Fig. 16: Actual and predicted per capita quantities of SWDS, 1990-2018.

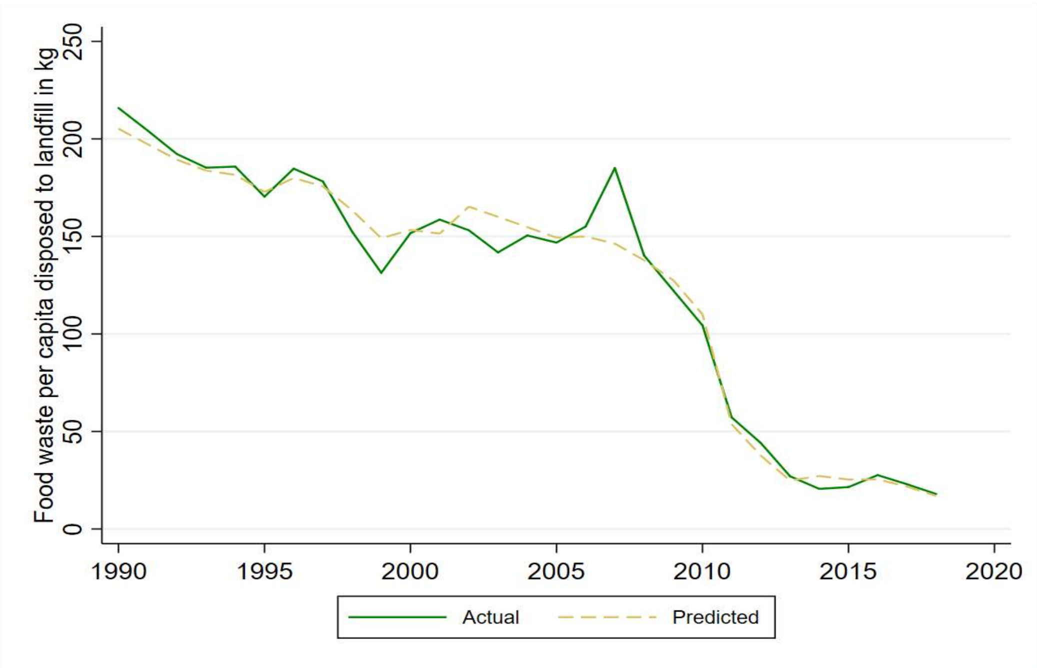


Source: Authors' estimates based on data from the Eurostat and EPA.

Figure 17 shows the actual per capita food waste disposed to landfill and the predicted per capita food waste disposed to landfill using the estimates obtained with the econometric model (4) over the analysed period 1990-2018. The figure shows that the predicted per capita quantity of food waste disposed to landfill matches closely the actual per capita quantity of food waste disposed to landfill. The predicted per capita SWDS in the case of the counterfactual Scenario 5 is also shown in Figure 18. The total quantity of SWDS is computed assuming that the quantities of other components of the waste composition do not change overtime.

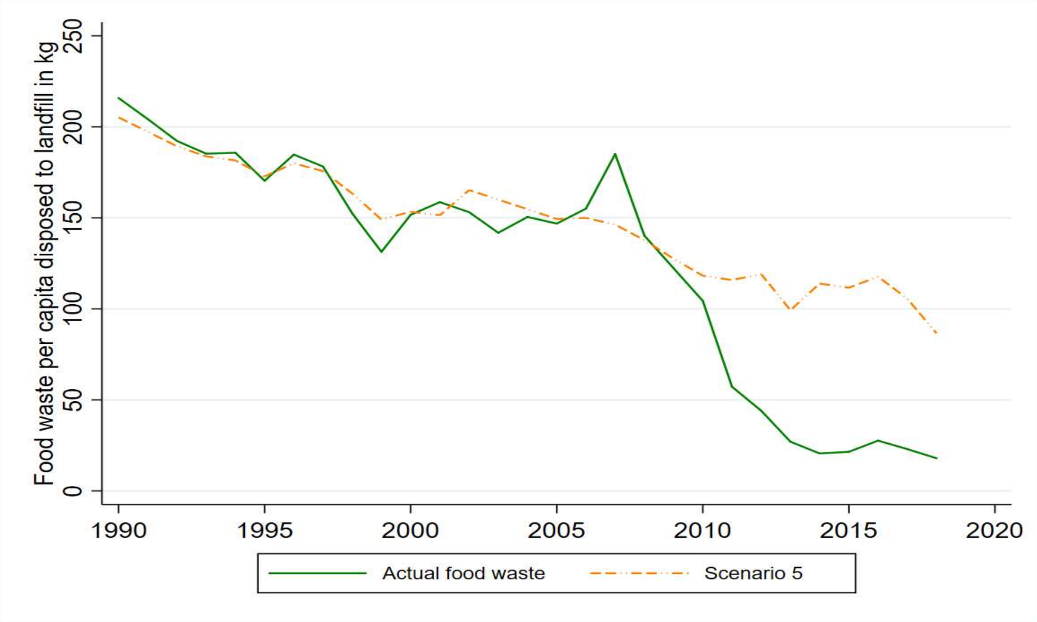
Figure 18 compares the per capita actual food waste disposed to landfill with the estimated counterfactual per capita actual food waste disposed to landfill in the absence of the Food Waste Regulations (Scenario 5). The Figure shows that in the absence of the Food Waste Regulation implemented in 2010, the quantity of per capita food waste disposed to landfill would have been substantially higher after 2010.

Fig. 17: Actual per capita food waste disposed to landfill, and the predicted per capita food waste disposed to landfill, 1990-2018.



Source: Authors' estimates based on data from the Eurostat and EPA.

Fig. 18: Actual and counterfactual per capita food waste disposed to landfill in the absence of Food Waste Regulation (Scenario 5), 1990-2018



Source: Authors' estimates based on data from the Eurostat and EPA.

5 Results

This section discusses the results of our analysis of the impact of Ireland's landfill policy on methane (CH_4) emissions in the waste sector over the period 1990-2018. The results indicate significant reductions in the CH_4 emissions associated with the key landfill policy measures in Ireland over the period. Table 3 summarises the estimated total generated and net CH_4 emissions saved in the policy scenarios discussed in Section 4.

Table 3: The impact of Ireland's landfill policy on methane (CH_4) emissions, 1990-2018

Policy Scenarios	Total CH_4 generation saved (kt)	Total CH_4 generation saved (kt CO_2 eqv.)	Total CH_4 Generation saved (%)	Net CH_4 emission saved (kt)	Net CH_4 emission saved (kt CO_2 eqv.)	Net CH_4 Emissions saved (%)
1. Business as usual	633.8	15,845	27.9	196.4	4,910	16.8
2. No landfill levy	227.6	5,690	10.0	79.5	1,987.5	6.8
3. Constant levy at €15 per tonne	158.7	3,967.5	7.0	49.2	1,230	4.2
4. No recycling rates targets	229.5	5,737.5	10.1	68.5	1,712.5	5.9
5. No food waste regulations	72.3	1,807.5	3.2	25.2	630.0	2.2

Note: The percentage of the total methane generated or net methane saved is calculated as the total methane generated or net methane saved over actual methane generated between 1990-2018.

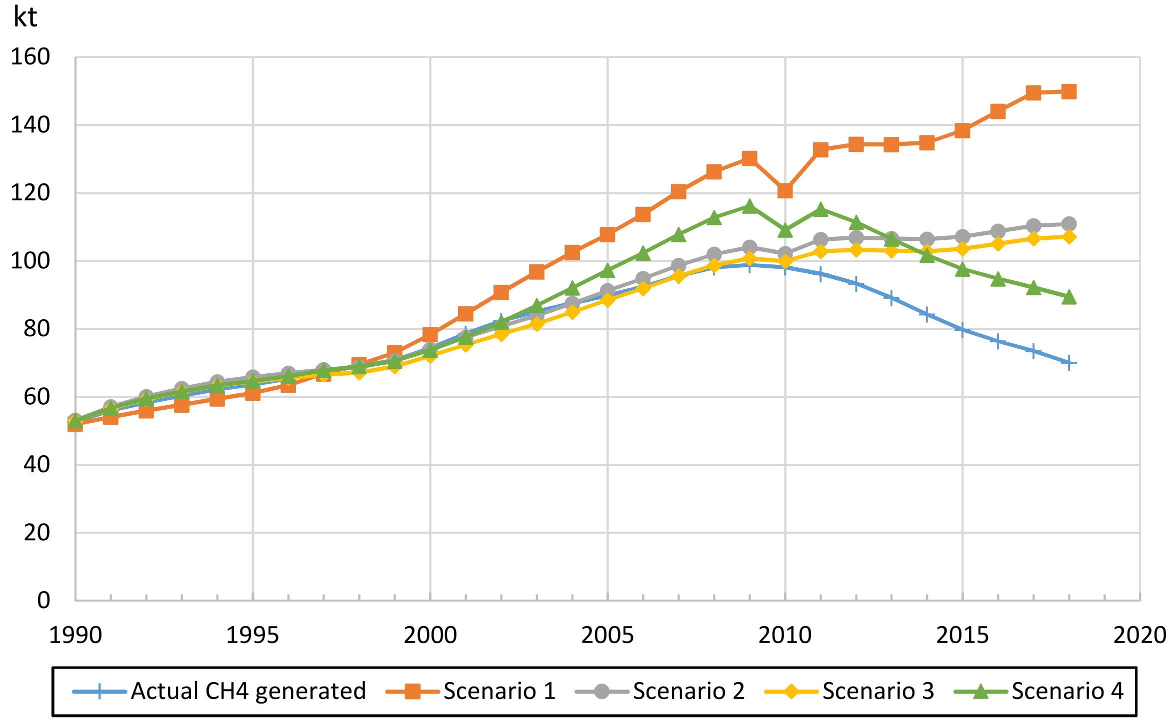
Source: Authors' estimates based on data from the Eurostat and EPA.

The key takeaways from these results are as follows:

- Compared with a situation of no landfill policy, the total CH_4 emissions have been lower by 27.9 per cent while the net CH_4 emissions have been lower by 16.8 per cent;
- The introduction of the landfill levy has been associated with a reduction of total CH_4 emissions by 10 per cent and a reduction by 6.8 per cent of net CH_4 emissions;
- Compared to a situation in which the landfill levy would have remained constant at €15 per tonne, the increased landfill levy has led to lower total CH_4 emissions by 7.0 per cent and to lower net CH_4 emissions by 4.2 per cent.
- In the absence of targets for recycling of municipal solid waste, assuming that recycling rates would have remained as in 2001, the total CH_4 emissions would have been higher by 10 per cent and net CH_4 emissions would have been higher by 5.9 per cent;
- In the absence of regulations for food waste disposed to landfill, assuming that the proportion of food waste disposed to landfill in the municipal solid waste would have remained as in 2009, the total CH_4 would have been higher by 3.2 per cent and the net CH_4 would have been higher by 2.2 per cent.

Figure 19 shows the actual and estimated counterfactual total CH_4 generated in the policy scenarios 1-4. Overall, the counterfactual total CH_4 generated over the analysed period are higher than the actual total CH_4 generated.

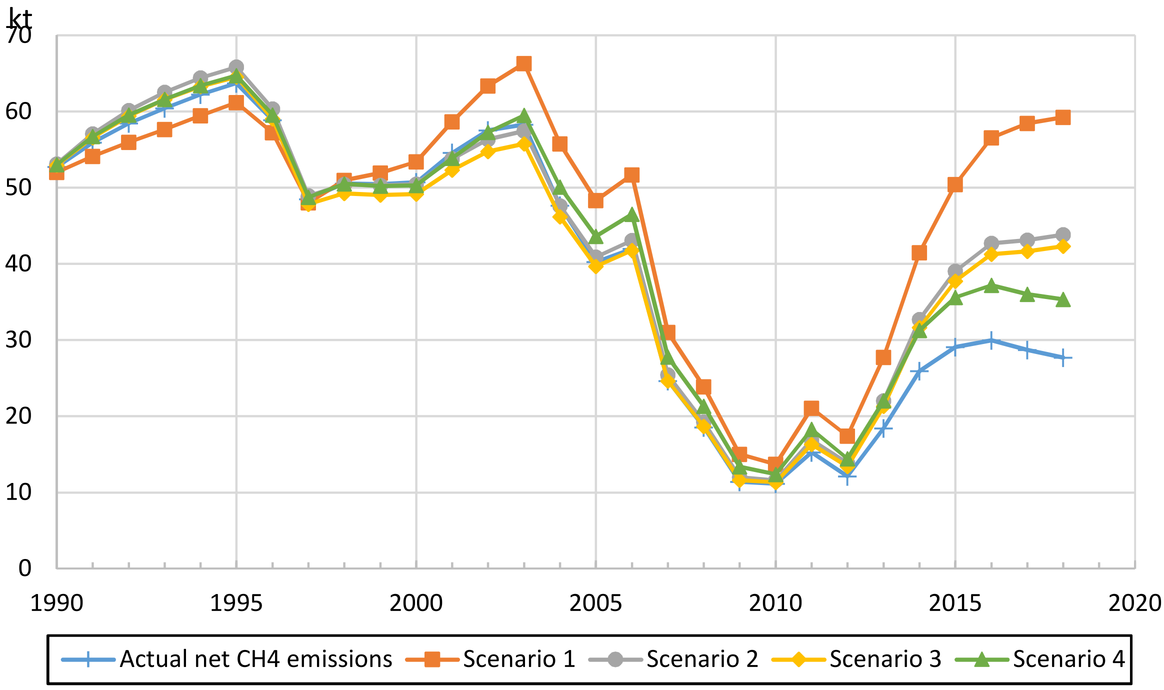
Fig. 19: Actual and estimated counterfactual total CH_4 generated, 1990-2018



Source: Authors' estimates based on data from the Eurostat and EPA.

Figure 20 shows that overall, the estimated counterfactual net CH_4 emissions are higher than the actual net CH_4 emissions in the considered policy scenarios 1-4.

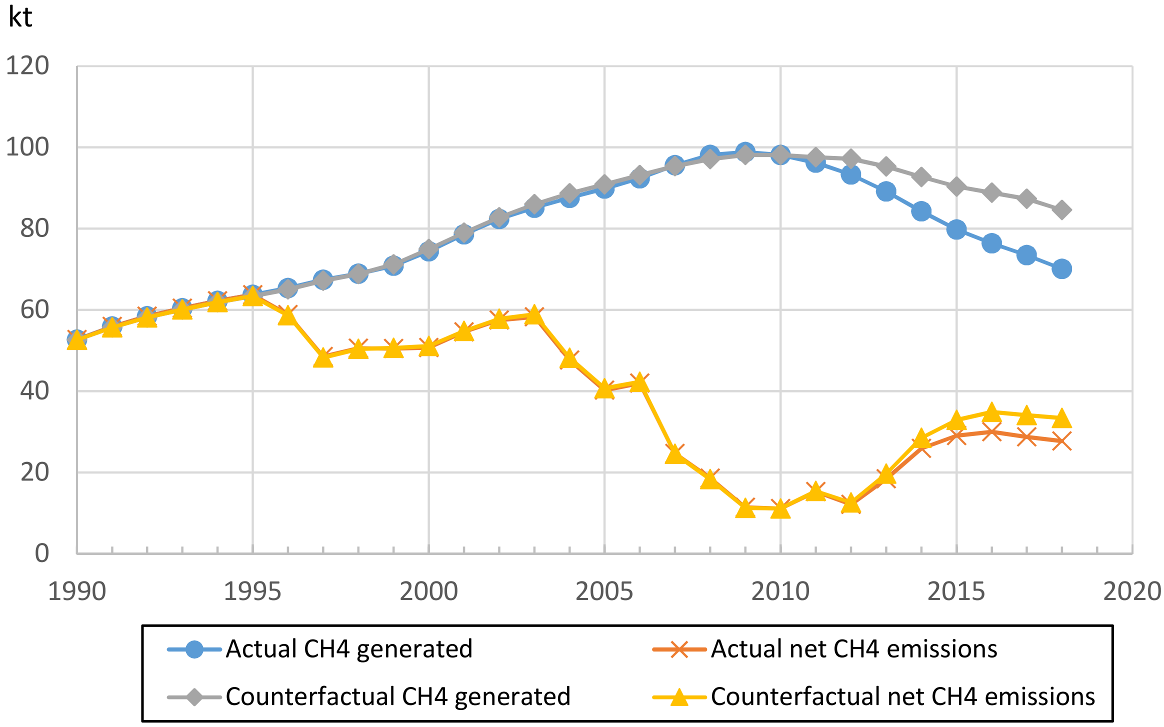
Fig. 20: Actual and estimated counterfactual net CH_4 generated. 1990-2018



Source: Authors' estimates based on data from the Eurostat and EPA.

Finally, Figure 21 compares the actual and estimated counterfactual total and net CH_4 in the absence of the Food Waste Regulation (Scenario 5).

Fig. 21: Actual and estimated counterfactual net CH_4 generated in the absence of the Food Waste Regulation (Scenario 5), 1990-2018



Source: Authors' estimates based on data from the Eurostat and EPA.

6 Conclusions

This research study examined the impact of Ireland's landfill policy on greenhouse gas emissions emanating from the waste sector over the past three decades. The analysis focused on direct methane (CH_4) emissions from the municipal solid waste disposed to landfill sites in Ireland over the period 1990-2018. To this purpose, actual CH_4 emissions were compared with estimated CH_4 emissions in a range of counterfactual policy scenarios. The policy scenarios were designed assuming the absence of landfill policy or the absence of important policy instruments such as the landfill levy, targets for recycling rates, and food waste regulations.

The key findings from the analysis are summarised below.

Over the past three decades, the quantity of the municipal solid waste landfilled in Ireland has declined by 75.9 per cent, from 1,925.3 kilo tonnes in 1990 to 463.2 kilo tonnes in 2018. The proportion of municipal solid waste landfilled in the total municipal solid waste stood at 14 per cent in 2018, down from 92 per cent in 1990.

In terms of the composition of solid waste disposed to landfill over the period 1990-2018, food and paper account for the largest share in the municipal solid waste disposed to landfill. While the share of food waste has decreased particularly since 2010, this decline has been mirrored over the same period by an increase in the share of textiles in the solid waste disposed to landfill.

The reduction of the proportion of landfill disposal in the total quantity of municipal solid waste in Ireland over the past two decades by 69 percentage points is the third highest among European Union countries. Over the same period, the proportion of recycled municipal solid waste in the total municipal solid waste in Ireland has increased by 32.3 percentage points and the energy recovery rate by 31.8 percentage points**.** The introduction of incineration of municipal solid waste has made energy recovery the main alternative treatment to landfill in Ireland.

In comparison to other high income countries in the European Union, Ireland has a relatively higher proportion of landfill disposal of municipal waste in the total quantity of municipal solid waste. This may reflect the fact that Ireland has been slow to adopt incineration as an alternative treatment of municipal solid waste to landfill. A significant incineration of municipal solid waste has taken place only in recent years.

The total methane emissions generated from municipal solid waste disposed to landfill sites in Ireland peaked in 2009 at 2,471.2 kilo tonnes CO_2 equivalent and have declined since then by 29.1 per cent standing at 1,752.9 kilo tonnes CO_2 equivalent in 2018. The net methane emissions from municipal solid waste landfilled (total methane generated net of methane recovered) have been the highest in 1995, 1,592.8 kilo tonnes CO_2 equivalent. The net methane emissions from municipal solid waste landfilled were lower by 56.5 per cent compared to their peak in 1995 and by 47.4 per cent compared to 1990.

To a large extent, the major landfill policy developments in Ireland have been driven by regulations and policy initiatives taken at the European Union level, such as the Waste Framework Directives, the Landfill Directive, and the EU Circular Economy Action Plans.

The results of this research indicate that Ireland's landfill policy has been associated with substantial reductions of the methane emissions in the waste sector. Our estimates indicate that in the absence of the policy measures implemented since 1996, the total methane emissions over the period 1990-2018 would have been higher by 15,845 kilo tonnes CO_2 equivalent and the net methane emissions would have been higher by 4,910 kilo tonnes CO_2 equivalent. Compared with a situation of no landfill policy, the total methane emissions have been lower by 27.9 per cent while the net methane emissions have been lower by 16.8 per cent.

The landfill levy has been an important policy instrument to achieving the reduction of the proportion of municipal solid waste disposed to landfill. The results of our analysis show that the quantity of municipal solid waste landfilled has declined at an accelerated pace since the introduction of the landfill levy and its increase from €15 to €75 per tonne.

The introduction of the landfill levy has been associated with a reduction of total methane emissions by 10 per cent and a reduction by 6.8 per cent of net methane emissions. Compared to a situation in which the landfill levy would have remained constant at €15 per tonne, the increased landfill levy has led to lower methane emissions by 7 per cent in the case of total methane emissions and by 4.2 per cent in the case of net methane emissions.

In the absence of targets for recycling of municipal solid waste, assuming that recycling rates would have remained as in 2001, the total methane emissions would have been higher by 10 per cent and the net methane emissions would have been higher by 5.9 per cent.

In the absence of regulations for food waste disposed to landfill, assuming that the proportion of food waste disposed to landfill in the municipal solid waste would have remained as in 2009, the total methane emissions would have been higher by 3.2 per cent and the net methane emissions would have been higher by 2.2 per cent.

Notwithstanding Ireland's reduction in the proportion of municipal solid waste disposed to landfill in total municipal solid waste from 92 per cent in 1995 to 14 per cent in 2018, at 38 per cent, the recycling rate of municipal waste (the proportion of the recycled waste in total municipal solid waste) is below the EU targets (55 per cent in 2025; 60 per cent in 2030; 65 per cent in 2035) and lower than in a number of other high income EU countries.

Further reductions in the landfill rate to meet the EU target of 10 per cent or less in 2035 if achieved are likely to contribute to further reductions in the methane emissions in the waste sector.

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Appendix

Table A1: Summary statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Log(swds/pop)	29	5.930	0.570	4.568	6.480
Log(msw/pop)	29	6.463	0.140	6.084	6.711
Log(recycling/pop)	29	4.861	0.766	3.818	5.856
Log(energy recovery/pop)	29	1.701	2.295	0	5.532
Log(food waste/pop)	29	4.591	0.837	2.887	5.375
Log(levy)	29	2.078	1.859	0	4.331

Source: Authors' calculations based on data from the Eurostat and EPA.

Table A2. Determinants of the quantity of municipal solid waste disposed to landfill

Dependent variable: $log(swds/pop)_t$

	(1)	(2)	(3)	(4)	(5)
Log(msw/pop)	1.215***	1.215***	0.353	0.334	0.915***
	(0.344)	(0.350)	(0.217)	(0.362)	(0.304)
Log(levy)		-0.0233	0.399***	0.389**	0.457
		(0.0768)	(0.0671)	(0.182)	(0.388)
Log(levy)^2			-0.149***	-0.147***	
			(0.0187)	(0.0395)	
Log(recycling/pop)				0.0182	0.0179
				(0.283)	(0.291)
Log(energy/pop)				2.29e-05	0.399***
				(0.0441)	(0.0955)
Log(recycling/pop)*log(levy)					-0.0943
					(0.0843)
Log(energy/pop)*log(levy)					-0.127***
					(0.0301)
Time trend	-0.0575***	-0.0527***	-0.0130	-0.0137	-0.0148
	(0.00567)	(0.0168)	(0.0103)	(0.0161)	(0.0147)
Constant	-1.060	-1.082	4.155***	4.204**	0.475
	(2.225)	(2.266)	(1.380)	(1.631)	(1.722)
Observations	29	29	29	29	29
R-squared	0.814	0.815	0.949	0.949	0.972

Notes: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Source: Authors' estimates based on data from the Eurostat and EPA.

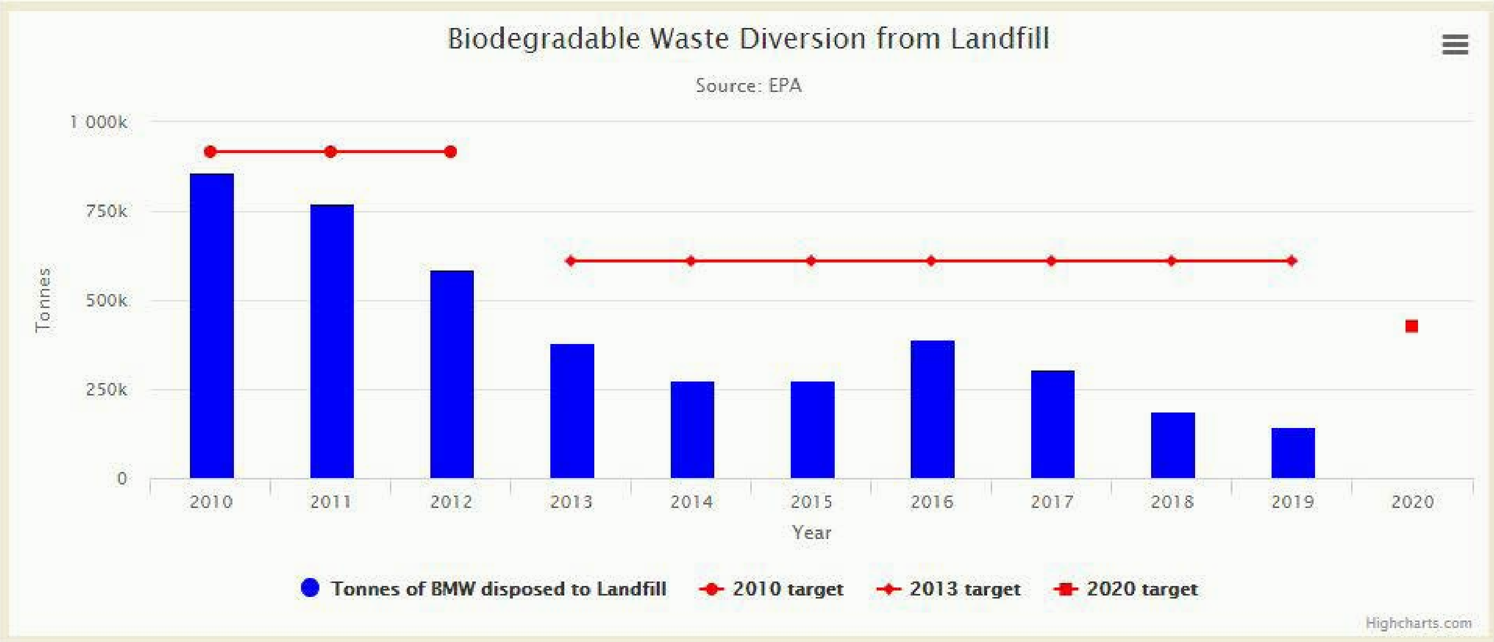
Table A3. Determinants of the quantity of food waste disposed to landfill
Dependent variable: $log(food\ waste/pop)_t$

	(1)	(2)	(3)
Log(msw/pop)	0.431	0.432	0.430**
	(0.298)	(0.305)	(0.179)
Time trend	-0.0251***	-0.0249*	-0.0333***
	(0.00802)	(0.0143)	(0.00851)
Log(levy)		-0.000738	0.0396
		(0.0576)	(0.0344)
Policy	2.864***	2.866***	5.424***
	(0.606)	(0.646)	(0.540)
Policy*Time trend	-0.164***	-0.164***	-0.0487**
	(0.0246)	(0.0261)	(0.0231)
Policy*log(levy)			-1.302***
			(0.195)
Constant	2.559	2.557	2.607**
	(1.896)	(1.944)	(1.144)
Observations	29	29	29
R-squared	0.959	0.959	0.986

Notes: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Source: Authors' estimates based on data from the Eurostat and EPA.

Ex-Post Analysis of the Impact of National Landfill Policy for Greenhouse Gas Emissions in the Waste Sector



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