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Co-benefits of the Irish Carbon Tax and the European Emissions Trading System on Outdoor Air Pollution in Ireland

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Abstract: Climate policies designed to cut carbon dioxide (CO_2) emissions can also reduce harmful air pollutants, delivering health and environmental co-benefits. Using a computable general equilibrium model for Ireland, this paper examines how carbon taxation and the EU Emissions Trading System (ETS) affect non-CO_2 pollutants – NO_x, SO_x, NH_3, $PM_{2.5}$, PM_{10}, and NMVOC. SO_x declines more than CO_2 under both policies. Carbon taxation results in greater reductions in transport, services, residential, and agricultural pollutants, whereas sectors covered by the ETS experience larger reductions when ETS prices rise. The response of NH_3 emissions is minimal, highlighting the need for specific air pollution measures.

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I INTRODUCTION

Increasing greenhouse gas (GHG) emissions from human activities since industrialisation has led to climate change. Climate change is the greatest environmental problem of our time, causing sea level rise, temperature increases, and greater climate variability. These climatic changes in turn have many impacts on societies and economies, affecting, e.g. human health, the occurrence of droughts, floods, and other natural disasters, and agricultural production and coastal infrastructure (Baccini *et al.*, 2008; IPCC, 2012; Lincke *et al.*, 2018). Outdoor air pollution is an interrelated environmental problem that negatively impacts human health. These health impacts also have economy-wide implications and can reduce global GDP (Lanzi *et al.*, 2018; OECD, 2016). Both climate change and outdoor air pollution are driven by the burning of fossil fuels, among other causes. As such, climate policies aiming to reduce GHG emissions will also impact emissions of air pollutants and vice versa.

This paper examines the role that climate policies focused on reducing GHG emissions can play in reducing Irish air pollution. The focus is on the two main climate policies currently in place in Ireland: Irish carbon taxation, enforced at the national level, and the European Union (EU) Emissions Trading System (ETS), enforced at the EU level. The EU ETS price has fluctuated over the course of 2025; on January 3rd, it was €74.26, and on September 29th, it was €76.79 (Trading Economics, 2025). The Irish carbon tax is €63.5 per tonne in 2025, and Ireland has committed to an increasing trajectory, with the level reaching €100 per tonne by 2030. The EU ETS permit allocation is currently under phase IV; however, the EU 'Fit for 55' policy package, which is being introduced, will tighten the EU ETS and likely result in significantly higher permit prices. The aim of this paper is to investigate how these policies affect outdoor air pollution and to gain insights into how their effects differ by policy. Though this paper focusses on Ireland as a case study, similar results could be expected in other countries which are part of the EU ETS and apply national carbon taxation.

To this end, an intertemporal CGE model, known as the Ireland Environment, Energy and Economy (I3E) model, is applied. This model consists of 37 production sectors, ten carbon commodities and 32 other commodities, ten household groups based on an urban-rural distinction and income levels, and three types of labour. I3E also explicitly includes various fossil fuel inputs and their associated GHG emissions and process-related emissions (i.e. cement production). In the paper, the I3E model is further developed to include emissions of air pollutants both from fossil fuel combustion and other sources.

The air pollutants included in this study are nitrogen oxides (NO_x), sulphur oxides (SO_x), non-methane volatile organic carbon (NMVOC), particulate matter ($PM_{2.5}$ and PM_{10}) and ammonia (NH_3). Pollutant levels are calculated based on fossil fuel usage by sector, using specific fossil fuel input emission factors. Furthermore, emission factors are also based on the level of sectoral output, depending on the pollutant and sector, e.g. for manure and fertiliser production.

Authors in China and the United States of America (US) have compared the impacts of different decarbonisation policies on outdoor air pollution (Cheng *et al.*, 2015; Thompson *et al.*, 2014; 2016; Zhang and Zhang, 2020). However, the unique combination of the EU ETS and a national carbon tax, both falling under different jurisdictions, has not yet been compared in the literature. This paper contributes to the literature by directly comparing these climate policies and by including more outdoor air pollutants than in the previous literature. Additionally, a detailed sector analysis of these effects is conducted to assess which sectors are driving these results.

The results show that climate policies significantly reduce the emission of air pollutants in Ireland. Increasing both the EU ETS price and the carbon tax further reduces emissions across all pollutants in most sectors relative to increasing only the carbon tax. However, there are clear differences across pollutants and sectors depending on whether only the carbon tax or both carbon policies' prices are increased.

This paper shows the importance of considering air pollution co-benefits when setting climate policies. Increasing the carbon tax, either alone or in combination with an increase in the EU ETS price, reduces air pollutant emissions. This would reduce air pollution-related morbidity and mortality, benefiting society (Matus, 2005). From a policy perspective, the results highlight the need to coordinate environmental policies and assess them not only on their climate performance but also on their performance across other environmental outcomes, such as air pollution. Moreover, it is also important to understand what air pollutant reductions can be expected in Ireland due to EU-level policies, which are beyond the control of Irish policymakers.

Section II provides an overview of the literature. Section III briefly describes the method in a non-technical manner. Section IV explains the conducted scenarios and discusses the results. Section V concludes.

II LITERATURE REVIEW

There are different types of decarbonisation policies with varying impacts across sectors and regions. Governments can set a price per unit of carbon dioxide by implementing a carbon tax, which is applied to each ton of GHG emitted. Emission Trading Systems (ETS) work by restricting the quantity of carbon dioxide that can be emitted, creating allowances to cap emissions. These allowances can be traded, with supply and demand in the market determining the price of an allowance to emit a tonne of CO_2 (Weng *et al.*, 2022a). In theory, carbon taxation and the ETS should result in similar patterns of emission reduction, which are driven by the cheapest methods. Some countries may choose to set a limit on the amount of carbon without creating an ETS. Other decarbonisation policies can involve encouraging the use of renewable energy rather than fossil fuels or adopting abatement technologies (Bollen and Brink, 2014; Bollen, 2015; Kou *et al.*, 2022; Valriberas *et al.*, 2023). Countries may adopt none, one or more of these policies at the same time.

Carbon dioxide and air pollutant emissions vary by sector. Air pollutant emissions are either from the fuel used, processes, or outputs (OECD, 2016). Power generation can be coal-intensive, thereby emitting large quantities of CO_2 and SO_2, as well as NO_x, PM_{10} and $PM_{2.5}$ (Koolen and Rothenberg, 2019; Mier *et al.*, 2022). Industrial sectors can emit SO_2, NO_x and $PM_{2.5}$ (Li *et al.*, 2018; Mier *et al.*, 2022; Yang and Teng, 2018). The transport sector emits NO_x, Black Carbon (BC), and $PM_{2.5}$ (ExternE, 1999; Koolen and Rothenberg, 2019; Yang and Teng, 2018). The residential sector emits $PM_{2.5}$, PM_{10} and O_3 (tropospheric ozone) (Koolen and Rothenberg, 2019; Zhang *et al.*, 2017). The agriculture and food manufacturing sectors emit NH_3, SO_2, NO_x, $PM_{2.5}$, BC and Organic Carbon (OC) (Bauer *et al.*, 2016). Air pollutants can travel with the wind; thus, populations in different regions or countries may be exposed to the air pollutants from these sectors (OECD, 2016; Zhang *et al.*, 2017). O_3 has a longer lifespan and can travel further in the air than $PM_{2.5}$ (Zhang *et al.*, 2017). Air pollutant emissions depend on the fuels used, energy consumption, energy efficiency and abatement technologies (Dong *et al.*, 2015; Li *et al.*, 2018; Shi *et al.*, 2022). These can vary between countries and even within a country; thus, regional policies can help control for this variation (Jaramillo and Muller, 2016; Li *et al.*, 2023; Valriberas *et al.*, 2023).

Decarbonisation policies may reduce air pollutants through a variety of impact mechanisms. A single impact mechanism may be used or a combination of them. By increasing the direct (carbon tax) or implicit (ETS) price of carbon dioxide, industries may choose to switch from carbon-intensive fossil fuels to renewable energy (Bollen and Brink, 2014; Bollen, 2015; Driscoll *et al.*, 2015; Kou *et al.*, 2022; Valriberas *et al.*, 2023). Since the use of fossil fuels emits air pollutants, such as SO_2 and NO_x, air pollutants can be reduced by switching to cleaner fuels. Carbon pricing can also increase energy efficiency, which reduces the amount of fuel needed to produce the same output. As such, evidence shows that improving energy efficiency can reduce the amount of air pollutants emitted, even when fossil fuels are used (Driscoll *et al.*, 2015; Hu *et al.*, 2022; Shi *et al.*, 2022; Vandyck *et al.*, 2018). Additionally, by reallocating production from the firms that pollute more to those that pollute less, Yan *et al.* (2020) found that air pollution was reduced. Shi *et al.* (2022) found that adopting abatement technologies can also reduce air pollution. These impact mechanisms could be part of a single policy or separate decarbonisation policies (Bollen and Brink, 2014; Bollen, 2015; Kou *et al.*, 2022; Koolen and Rothenberg, 2019).

The types of abatement technologies used and the intensity of the adoption of these technologies can differ between sectors (Bollen and Brink, 2014; Bollen, 2015; Valriberas *et al.*, 2023). Sectors that have already adopted the cheapest abatement technologies might need to adopt more expensive abatement technologies to reduce emissions. This could increase the marginal abatement cost for such sectors (Valriberas *et al.*, 2023). Vrontisi *et al.* (2016) found that whilst some sectors saw a reduction in output because of decarbonisation policies, when more abatement technologies were needed the sectors that produce such technologies saw an increase in output. Some abatement technologies may be able to reduce air pollution, as well as GHGs (Matus, 2005).

Although decarbonisation policies can reduce air pollutants, a carbon tax and ETS are insufficient to meet National Emission reduction Commitments Directive (NECD) targets; specific air pollution policies are still necessary. The literature has found that whilst a carbon tax can reduce air pollution, the combination of a carbon tax and air pollution policies (e.g. air pollutant taxes) is more effective at reducing air pollution (Kiuila *et al.*, 2014, 2019; Li *et al.*, 2022). This combination of a carbon tax and an air pollutant tax also has a lower social cost than just a carbon tax (Mier *et al.*, 2022). Nevertheless, the focus of this paper is on the impact of decarbonisation policies on air pollution; thus, policies specifically targeting air pollutants are excluded from this analysis.

While a carbon tax and an ETS can be effective in reducing air pollution, the extent of this reduction varies by sector and the type of abatement technology employed. For instance, when coal is used in the electricity production sector, it releases CO_2, SO_2 and other pollutants. Thus, by reducing coal use in response to a carbon tax or an ETS, there is a significant reduction in both CO_2 and SO_2, as well as other associated pollutants (Hu *et al.*, 2022). In the transport sector, a carbon tax might result in agents switching from petrol to diesel cars as diesel cars release less CO_2 per kilometre driven. While this decreases CO_2, this decision results in an increase in NO_x, SO_x, PM_{10} and $PM_{2.5}$ (Environmental Protection Agency, 2024; García-Gusano *et al.*, 2015). However, if agents choose to switch from a petrol or diesel car to an electric car, both CO_2 and the associated air pollutants are reduced. As such, the abatement technology used is important for estimating air pollution reductions.

2.1 Emission Trading Systems

Emission Trading Systems (ETS) operate in different regions, including the EU, China, and the US (Cao *et al.*, 2021; Cheng *et al.*, 2015; Dong *et al.*, 2022; García-Gusano *et al.*, 2015; Hu *et al.*, 2022; Thompson *et al.*, 2014; 2016; Yan *et al.*, 2020; Zhang and Zhang, 2020). Whilst the stringency, punishments and targets may differ depending on the country or region in which they operate, the general structure remains the same (Yan *et al.*, 2020).

An ETS works by setting a total number of carbon allowances and allocating these allowances across sectors covered by the ETS. These allowances can be traded; the carbon price is determined when supply equals demand. Firms with a Marginal Abatement Cost (MAC) below the carbon price find it more cost-effective to reduce their emissions and sell their carbon allowances (Coase, 1960; Weng *et al.*, 2022a). Other firms with a MAC greater than the carbon price will choose to purchase allowances rather than reduce emissions. Bayer and Aklin (2020) found that the EU ETS was effective in reducing carbon dioxide emissions during the period under review.

There are different methods that can be used to calculate the allocation of allowances. The benchmarking method computes allowances based on existing carbon intensity data and is the most stringent method (Weng *et al.*, 2022a; Zhang and Zhang, 2020). Alternatively, the allowances can be based either on historic emissions or historic output (Zhang and Zhang, 2020). Although emission trading systems are typically used for decarbonisation, China has also implemented an SO_2 ETS (Hu *et al.*, 2022; Huang *et al.*, 2021). The EU ETS uses the benchmarking method to allocate free allowances (European Commission, n.d.).

Evidence suggests that carbon emission trading systems have been effective at reducing carbon dioxide and air pollutant emissions. Research has found that the Chinese carbon ETS reduced NO_x, SO_2, $PM_{2.5}$, PM_{10} and CO_2 emissions (Cao *et al.*, 2021; Cheng *et al.*, 2015; Dong *et al.*, 2022; Hu *et al.*, 2022; Li *et al.*, 2021; 2023; Liu *et al.*, 2021; Weng *et al.*, 2022a; 2022b; Yan *et al.*, 2020). But Shi *et al.* (2022) found that this reduction in SO_2 was less than proportional to the reduction in CO_2. One study found that the EU ETS caused a reduction in coal use and thus SO_2 emissions in Spain (García-Gusano *et al.*, 2015). Another found that the EU ETS was associated with a reduction in SO_2, $PM_{2.5}$ and NO_x emissions (Basaglia *et al.*, 2024). In the US, evidence suggests that the carbon ETS was effective at reducing $PM_{2.5}$ and O_3 emissions (Driscoll *et al.*, 2015; Thompson *et al.*, 2014; 2016).

The impact of an ETS on air pollution will depend not only on the total amount of allowances issued, but also on how they are allocated and traded across sectors. Hence, it is not surprising that there is mixed evidence on the effectiveness of the ETS in reducing air pollutants, relative to other decarbonisation policies. Two studies found that the Chinese ETS was more effective at reducing NO_x, SO_2 and $PM_{2.5}$ relative to carbon limits or renewable energy policy (Cheng *et al.*, 2015; Zhang and Zhang, 2020). However, in the North East of the US, their Clean Energy Standard (CES) – which aims to reduce fossil fuel usage in electricity production – was more effective at reducing NO_x and SO_2 emissions compared to their ETS (Thompson *et al.*, 2014; 2016). Most of the ETS reductions were driven by switching away from fossil fuels in the industrial, power and residential sectors (Thompson *et al.*, 2014; 2016).

2.2 Carbon Taxes

Governments can set the price of carbon dioxide through a carbon tax. This functions by making it more expensive to emit carbon dioxide. Those who want to avoid this cost switch to less carbon-intensive fuels, reduce energy consumption, reduce output or implement abatement technologies (Kiuila *et al.*, 2014; Li *et al.*, 2018). As such, carbon dioxide emissions are reduced.

Carbon taxes can also reduce air pollutant emissions. Evidence from Europe and China shows that carbon taxes can be effective at reducing NO_x, SO_2, $PM_{2.5}$, PM_{10}, VOCs and CO_2 (Kiuila *et al.*, 2014, 2019; Li *et al.*, 2022; Markandya *et al.*, 2018; Mier *et al.*, 2022). This may work through a switch away from fossil fuels (Kiuila *et al.*, 2014; Li *et al.*, 2018). If wind energy is used instead of fossil fuels, evidence suggests that there is a reduction in NO_x, SO_2 and CO_2 (Denny and O'Malley, 2006). However, if decarbonisation efforts involve a switch to biomass, there may be an increase in NO_x and $PM_{2.5}$ emissions (Bollen and Brink, 2014; Bollen, 2015; Kiuila *et al.*, 2014; Mier *et al.*, 2022; Vandyck *et al.*, 2020). Whilst the adoption of abatement technologies may reduce air pollution, if carbon capture and storage (CCS) is used and powered by fossil fuels, this may increase air pollution (Mier *et al.*, 2022; Yang *et al.*, 2013).

Carbon taxes have been compared to air pollutant taxes in the literature. Whilst there is evidence that both can reduce air pollution and carbon dioxide emissions, both Mier *et al.* (2022) and Wei *et al.* (2020) found that the social cost of a carbon tax is lower than that of an air pollutant tax. But some literature has shown that using both a carbon tax and an air pollutant tax may be more effective at reducing air pollution and may be less costly than only using an air pollutant tax (Kiuila *et al.*, 2019; Li *et al.*, 2022; Mier *et al.*, 2022; Wei *et al.*, 2020). However, Kiuila *et al.* (2014) found that both taxes decreased energy consumption. Nevertheless, decarbonisation policies have a limited effect on lowering NH_3 as a substantial portion of these emissions comes from agriculture (Li *et al.*, 2018).

III METHODS

3.1 The I3E Model

The I3E model is a dynamic, multi-sectoral, multi-household, small open-economy CGE model for Ireland. CGE models are advantageous for analysing the impact of decarbonisation policies on air pollution because they model detailed linkages between different production sectors, households and the government. This allows us to analyse the impact of changes in the carbon tax or EU ETS price on all goods, across all production sectors, labour markets, capital markets and households. For example, a carbon tax that increases the price of diesel will also affect the production costs of sectors that use diesel inputs. This, in turn, will affect the good's price, and as the model captures agents' behavioural responses to these price changes, the good's demand will also be affected. Finally, the demand for labour and capital will shift, resulting in a change in household income. Particularly with energy policies, where all production sectors and households use energy, understanding the secondary effects is essential.

Figure 1 gives an overview of the interlinkages in the I3E model. This model is calibrated using the Irish Energy Social Accounting Matrix (ESAM); the technical description is available in de Bruin and Yakut (2021a and 2021b).

The model economy comprises ten representative household groups (RHGs) based on area of residence (urban or rural) and disposable income (five quintiles in each area of residence). Each RHG maximises its intertemporal utility subject to its budget constraint. The usual Euler equation that relates consumption of two consecutive periods derives the optimal sequence of the composite consumption. The composite consumption is disaggregated across commodities based on an expenditure minimisation problem with a detailed nested consumption structure.

Figure 1: Interlinkages Within the I3E Model

Source: Authors' own.

The production side comprises 37 sectors producing 42 commodities. Four sectors' investment decisions are a positive function of their net-of-tax sectoral profits, whereas the remaining sectors determine their physical investment by solving intertemporal dividend maximisation problems. The energy demand of production sectors plays a crucial role in environmental policy. Differences in the composition of energy demand across sectors are considered in their nested production structures with different elasticity of substitution values.

As an EU Member State, the total emissions of all Irish firms operating in power and heating generation, air transportation, and manufacturing and services sectors (with a combustion capacity above 20 MW of thermal-rated input) are subject to the EU ETS (European Commission, 2024). Firms subject to the EU ETS do not pay the Irish carbon tax to avoid double taxation. The I3E model distinguishes between ETS and non-ETS emissions, and firms directly internalise changes in the EU ETS, such as the price and legislation, e.g. a decrease in free allowances. Based on these exogenous changes, the optimal combination of capital, labour, energy, and other intermediate inputs that minimises production costs also changes.

All scenario paths considered in this paper incorporate changes regarding energy commodities, including the pattern of international energy prices, the EU ETS price, and the level of the carbon tax between 2014 (the base year) and 2040.

3.2 Incorporating Outdoor Air Pollution

Outdoor air pollution data were incorporated into this model to answer the research question. The authors retrieved emission factors per fuel and sector from the Irish Environmental Protection Agency (EPA) (Environmental Protection Agency, 2024). The fuel usage in the I3E model is calibrated based on energy use data from the Sustainable Energy Authority of Ireland's (SEAI) Energy Balance (Sustainable Energy Authority of Ireland, 2024). These emission factors were applied to carbon commodity use in each sector to calculate resulting air pollutant emissions, which were then compared with the official air pollution statistics in the base year to ensure consistency. Air pollution from other processes (e.g. manure usage, enteric methane, waste, road paving, cremation, degreasing and solvent use) is linked to the relevant output. As an example, ammonia emissions from manure are assumed to increase in line with increases in beef production, and waste-related pollutant emissions are assumed to increase in line with waste production. Emissions data from Eurostat (2023) were applied to estimate these air pollutant levels. Data from 2019 are used for this analysis; it is assumed that the emission coefficients do not vary over time.

After mapping the data to the I3E sectors, the model calculated the emission coefficients using input demand per sector, applying emissions data for each fuel by sector and sectoral output using emissions data from Eurostat (2023). These were then multiplied by the input demand and sectoral output, respectively, for each scenario. No air pollution policies are included in these scenarios.

IV RESULTS AND DISCUSSION

This paper includes three policy scenarios for Ireland, namely Business as Usual (BaU), Carbon tax (CT) and Carbon tax and ETS (CT_ETS) (see Table 1). BaU assumes no additional policies are introduced. This scenario implements numerous changes affecting the Irish economy between 2014 (the base year) and 2023 to reflect the current Irish economy. These changes include the pattern of international energy prices, the increase in EU ETS price (up to 2023), the decline in EU ETS allowances (as projected for Phase IV (2020-2030) of the EU ETS) and changes in the composition of electricity production across sectors. The EU ETS price increased from €6 in 2014 to €82 in 2022 and remains at this price in the future. The BaU scenario also includes the increased carbon tax from €20 to €48.50 over the period 2014 to 2023, as well as COVID-19-related changes in demand, supply, and public balances. In addition to these realisations, along the path of the CT scenario, the carbon tax increases post-2023 by €7.50 annually up to 2029 and by €6.50 in 2030, reaching €100 in 2030 (as committed to by the government, Department of the Taoiseach, 2020), and stays constant until the end of the model horizon.

Table 1: Definition of Scenarios

Scenario	*Explanation*
BaU	Business as Usual (constant carbon tax and EU ETS price post 2023)
CT	Increasing carbon tax and constant EU ETS price
CT_ETS	Increasing carbon tax and increasing EU ETS price

Source: Authors' own.

In July 2021, the European Commission released the 'Fit for 55' package, which sets out policies to achieve at least 55 per cent reductions in emissions below 1990 levels by 2030. The 'Fit for 55' package includes a proposal for amending the ETS Directive, including a more ambitious EU ETS emissions reduction target of 62 per cent and the phase out of free allocation in some sectors. These developments in the ETS are expected to increase ETS prices further, though the exact magnitude of this change is highly uncertain (European Union, 2022). Based on this, we model a hypothetical steady increase in the EU ETS price from €82 in 2022 to €150 in 2030. The EU ETS price then remains at €150.

The increases in the carbon tax and EU ETS price reduce emissions, but they dampen output and thus economic growth. There is a reduction in GDP in both the CT (by 1.7 per cent) and CT_ETS scenarios (by 2.1 per cent) relative to the BaU scenarios.

4.1 Aggregate Results

The primary aim of the carbon tax and the EU ETS is to decrease CO_2 emissions; however, an increased carbon price can reduce emissions of air pollutants too. Higher carbon prices make carbon-intensive fuels more expensive, prompting firms, households and public services to switch away from them. Since the use of coal, diesel, kerosene, jet kerosene, LPG, fuel oil, peat, and other petroleum products emits air pollutants in addition to carbon, reducing their use also reduces their co-pollutants, i.e. air pollutants.

Table 2 shows that the carbon tax (CT scenario) reduces CO_2 by 6.3 per cent relative to BaU in 2040. The Irish carbon tax is also effective at reducing SO_x, NO_x, PM_{10}, $PM_{2.5}$, NMVOC and NH_3, as seen when comparing CT to BaU in 2040 in Table 2, with the reduction ranging from 1.3 per cent (NH_3) to 8.5 per cent ($PM_{2.5}$). With the exception of $PM_{2.5}$ and SO_x, the CT scenario results in a lower percentage of air pollutant emission reduction than CO_2 emission reduction. In other words, the carbon tax does a better job at reducing carbon than reducing carbon dioxide.

An increase in the EU ETS price (CT_ETS scenario) reduces CO_2 by 11.6 per cent relative to BaU in 2040. In the CT_ETS scenario, there is also a further reduction in air pollutants relative to the CT scenario; hence, the EU ETS price increase also reduces air pollutants. The extent of this further reduction differs depending on the pollutants, but it is generally lower compared to the CT scenario; in other words, the carbon tax reduces more air pollution than the ETS price increase. This further decrease is triggered by increased switching away from carbon-intensive fuels as the EU ETS price has increased. A detailed sector analysis is needed to determine whether the size differs by sector, as some sectors are covered only by the carbon tax, only by the EU ETS, or by both.

Table 2: Percentage Change in Air Pollutants and Carbon Dioxide Emissions Relative to BaU in 2040

Pollutant	*Scenario*	*Percentage change*
CO_2	CT	–6.29
	CT_ETS	–11.57
SO_x	CT	–7.14
	CT_ETS	–13.26
NO_x	CT	–4.83
	CT_ETS	–6.87
PM_{10}	CT	–5.19
	CT_ETS	–6.89
$PM_{2.5}$	CT	–8.49
	CT_ETS	–10.21
NMVOC	CT	–2.44
	CT_ETS	–3.02
NH_3	CT	–1.29
	CT_ETS	–1.46

Source: Authors' calculations.

For both CO_2 and SO_x, there is a considerable reduction in emissions under the CT scenario, but a smaller further decrease (84 per cent and 86 per cent respectively) under the CT_ETS scenario. The reduction under the CT scenario is driven by households, as they reduce fossil fuel use as a result of the dampened economy.

The electricity production sector is covered by the EU ETS, which is the driver behind the reduction in CO_2 and SO_x emissions under the CT_ETS scenario.

There is a smaller further reduction in emissions under the CT_ETS scenario for NO_x (42 per cent), PM_{10} (33 per cent) and $PM_{2.5}$ (20 per cent) relative to the CT scenario compared to CO_2 and SO_x. Most of the transport sector is covered by the carbon tax; as this sector is a key contributor to NO_x emissions, it constitutes the main driving factor behind the decrease in emissions in CT compared to BaU, as shown in Table 2. The further reduction under the CT_ETS scenario is driven by changes in the manufacturing sector, electricity sector and air transport subsector. Most of the reductions for PM_{10} and $PM_{2.5}$ in the CT scenario are from households reducing fossil fuel consumption. But this effect is greater for $PM_{2.5}$ because household emissions are the largest source of these emissions, whilst this is not true for PM_{10}. The further reduction under the CT_ETS scenario is driven by changes in manufacturing emissions for PM_{10} and $PM_{2.5}$. Seventy-nine per cent of the manufacturing sector is covered by the EU ETS (see Appendix B). But the reduction in this sector is twice as large for PM_{10} compared to $PM_{2.5}$ because it emits double the volume of PM_{10} emissions.

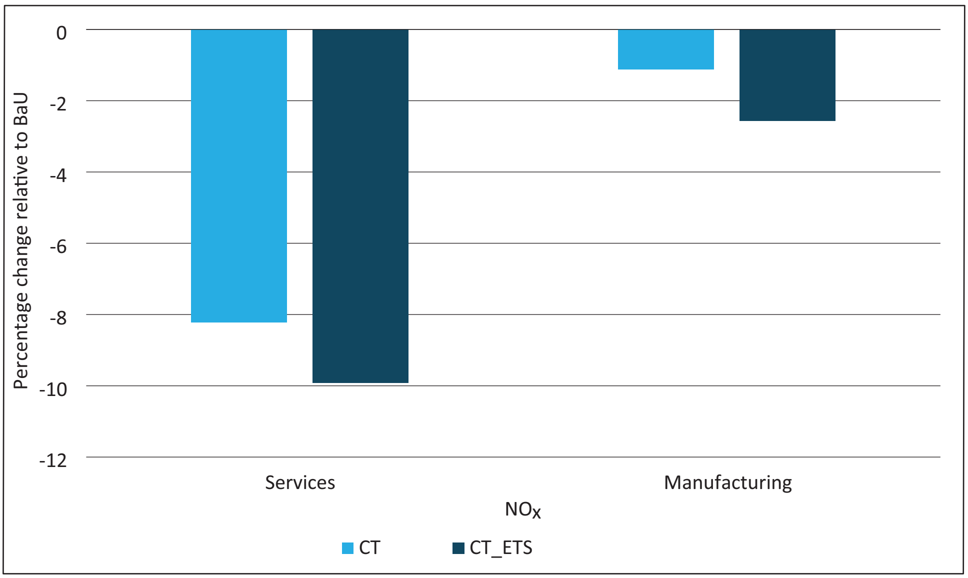
There is a small further reduction in NMVOC (24 per cent) and NH_3 (13 per cent) emissions in the CT_ETS scenario relative to the CT scenario. Under the CT scenario, the largest percentage reductions in NMVOC are from the agricultural and manufacturing sectors as well as households. The agricultural sector is completely covered by the carbon tax, whilst 21 per cent of the manufacturing sector is covered by the carbon tax (see Appendix B). As such, when the carbon tax is increased, both these sectors and households use less fossil fuels, thereby reducing NMVOC emissions. Under the CT_ETS scenario, there is a further reduction in emissions, mainly driven by the manufacturing sector. However, a key source of NMVOC emissions is from the production of spirits (Environmental Protection Authority, 2021). These emissions are difficult to reduce under decarbonisation policies. The main source of NH_3 emissions is the agriculture sector, and thus, this is the driver behind the reductions in the CT and CT_ETS scenarios. Whilst this sector is not covered by the EU ETS, the economic downturn in the CT_ETS scenario leads to a further reduction in agricultural output and associated emissions.

4.2 Sector Results

Focussing first on the services and manufacturing sectors, there is a reduction in all air pollutants under the CT scenario and the CT_ETS scenario. Since the patterns across all air pollutants are very similar across these sectors, only NO_x is shown in Figure 2. Emissions in the services sector are generally covered by the carbon tax, with only 3.2 per cent of the health and social services subsector covered by the EU ETS, as shown in Appendix B. Since burning carbon commodities also releases air pollutants, when the prices of these commodities increase there is a switch away from them; thus, co-emitted air pollutants are reduced. When both the carbon tax and the EU ETS price are increased, the dampening effects on the economy reduce demand for all goods, including carbon-intensive commodities, thereby further reducing related air pollutant emissions.

Emissions in the manufacturing sector fall in a large part under the EU ETS. However, in the CT scenario, air pollutant emissions from manufacturing still decrease, as shown in Figure 2. This is due to the interconnection of production sectors across the economy, which is captured in the CGE setting. Though the increased carbon tax does not directly affect most of the manufacturing sector, its production is affected as the inputs that the manufacturing sector uses and the firms and households demanding manufactured goods are impacted by carbon taxation, and there is an overall dampening effect on the economy. Hence, the CT scenario has indirect impacts on the manufacturing sector, resulting in lower air pollution. The reduction in NO_x emissions relative to BaU is more than doubled in the CT_ETS scenario compared to the CT scenario, as the bulk of manufacturing emissions are subject to the EU ETS price.

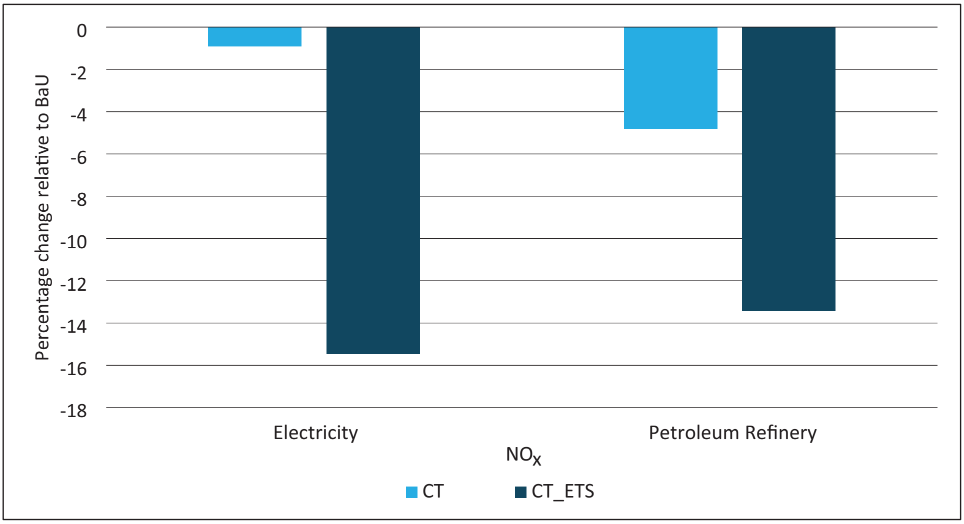
Figure 2: Percentage Change in NO_x Emissions for the Services and Manufacturing Sectors in 2040 Relative to BaU



Source: Authors' calculations.

Since the electricity and petroleum refinery sectors are fully covered by the EU ETS, an increase in the EU ETS price results in an even larger reduction in air pollutants than in the CT scenario. Like the manufacturing sector, there is a reduction in air pollutant emissions even in the CT scenario. The results are consistent across pollutants (NO_x, SO_x, NMVOC, NH_3, $PM_{2.5}$ and PM_{10}), so only NO_x is shown in Figure 3. This reduction in air pollutants is driven by the secondary impacts from firms and households limiting their demand for electricity and petroleum products. The reduction is much larger for the petroleum refinery sector than for the electricity sector. This is due to sectors and households switching from carbon-intensive petroleum products to electricity, which is relatively less carbon-intensive. This dampens the negative effect of an overall decrease in electricity demand and increases the reduction in petroleum product demand. This further reduction is greatest in the electricity sector as there is increased switching from non-renewable sources of electricity generation to renewable sources, particularly wind.

Figure 3: Percentage Change in NO_x Emissions for the Electricity and Petroleum Refinery Sectors in 2040 Relative to BaU

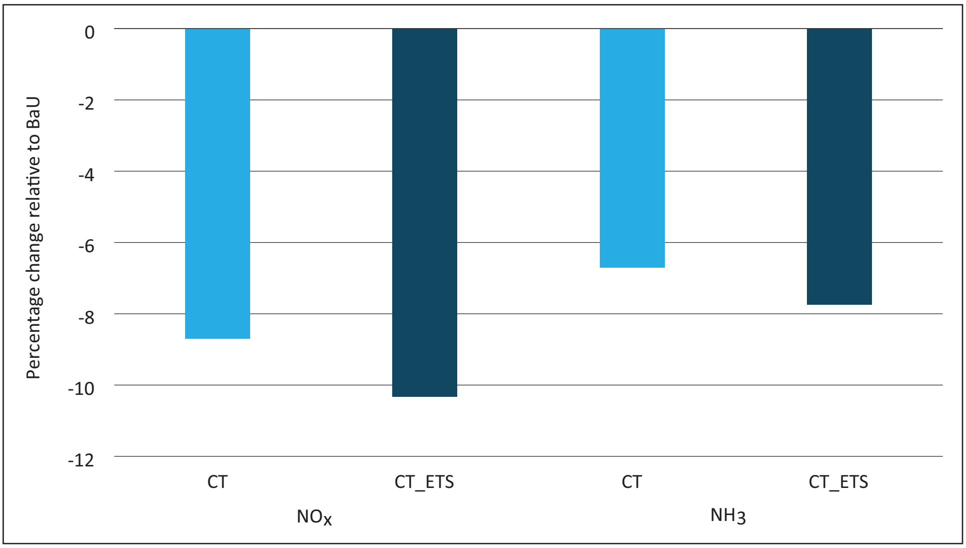


Source: Authors' calculations.

Whilst there are differences between sectors as shown above, there are also differences in air pollutants within a sector. The aggregate transport sector emits 36 per cent of total NO_x emissions and 0.3 per cent of total NH_3 emissions in Ireland in the BaU scenario in 2040. This is because the primary inputs to the transport sector are fossil fuels, and these release large volumes of NO_x and small volumes of NH_3 when they are used. As such, there is a larger percentage reduction of NO_x emissions than NH_3 emissions in both the CT and CT_ETS scenarios in the transport sector, as shown in Figure 4.

The transportation sector consists of several subsectors, namely land transportation, water transportation, aviation and other transportation and storage. This aggregate sector is mainly covered by the carbon tax; thus, there is a significant reduction in both air pollutants in the CT scenario. However, since the air transportation subsector emissions are fully covered by the ETS, emission reduction is five times larger in the CT_ETS scenario compared to the CT scenario in this subsector. This further reduces aggregate transport sector emissions when the ETS price is also increased. Concerning NH_3 emissions in this scenario, the land transportation and private car transport subsectors see a slight further reduction; the aviation, water transport and other transport and storage subsectors do not emit NH_3.

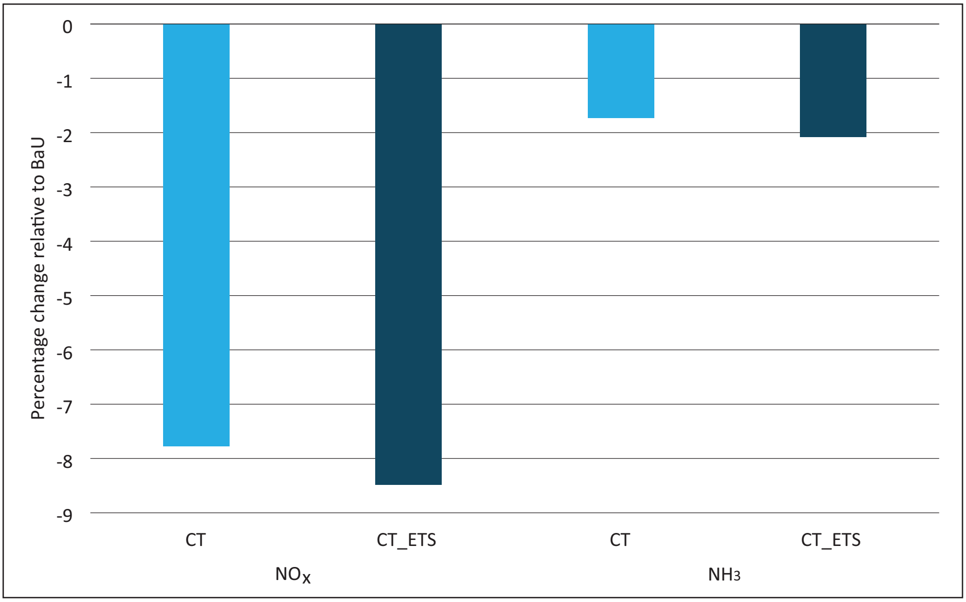
Figure 4: Percentage Change in NO_x and NH_3 Emissions for the Transport Sector in 2040 Relative to BaU



Source: Authors' calculations.

The agriculture sector emits only 6 per cent of total NO_x emissions and 46.7 per cent of total NH_3 emissions. As such, one may expect a larger percentage reduction in NH_3 than in NO_x emissions in these scenarios. However, this is not the case because the main contributors of NH_3 emissions in the agriculture sector are not directly subject to either the carbon tax or the EU ETS. These contributors are manure management from dairy and non-dairy cattle and fertiliser application. The only mechanisms by which the carbon tax or EU ETS can affect NH_3 emissions are either directly through changes in the fossil fuels (which emit small amounts of NH_3) used by the agriculture sector or indirectly through a reduction in agricultural output. The main source of the reduction in NH_3 emissions is a decrease in agricultural output, whilst the main source of the reduction in NO_x emissions is a decrease in fossil fuel and input use. Since the CT and CT_ETS scenarios directly decrease fossil fuel usage, it makes sense that the percentage of NO_x emission reduction relative to BaU is higher for the CT and CT_ETS scenarios than for NH_3.

Figure 5: NO_x and NH_3 Emissions for the Agriculture Sector in 2040 Relative to BaU

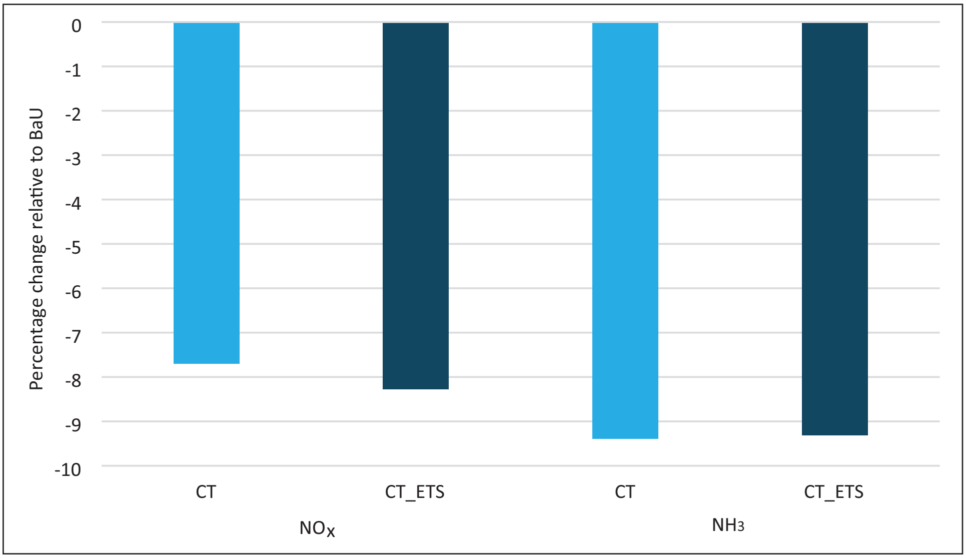


Source: Authors' calculations.

Household emissions are only from the use of fossil fuels. In the BaU scenario, coal was the source of 8 per cent of household NO_x emissions and 34 per cent of household NH_3 emissions. Additionally, peat was the source of 7 per cent of NO_x and 29 per cent of NH_3 household emissions. When the carbon tax is increased, households reduce relatively more coal and peat than any other fossil fuel. Since these fuels make up a larger proportion of NH_3 than NO_x emissions, the percentage reduction in NH_3 emissions relative to BaU is larger for NH_3 emissions, as seen in Figure 6.

When the EU ETS price increases, households experience a further decrease in NO_x emissions, but a relative increase in other air pollutants compared to the CT scenario shown in Figure 6. Whilst the residential sector is not covered by the ETS, it is affected by the dampening effect of increased EU ETS prices on economic output, which results in households consuming fewer goods. As such, they reduce their consumption of most fossil fuels, which reduces emissions. However, there is also a switch away from electricity and petroleum products to peat products as the former two sectors are covered by the EU ETS, whilst the latter is not. Households that have turbary rights to cut and use peat domestically switch away from these products to peat which is not produced by either of these sectors. For NO_x, the effect of the reduction in most fossil fuels and emitted pollutants dominates the slight increase in pollutants from peat usage. Thus, there is a further reduction in NO_x emissions by households compared to the CT scenario. However, for the other pollutants, the increased emissions from peat usage dominate. As such, there is a relative increase in NH_3 and other air pollutant emissions in the CT_ETS scenario compared to the CT scenario. However, these impacts are very small.

Figure 6: NO_x and NH_3 Emissions by Households in 2040 Relative to BaU



Source: Authors' calculations.

This section has shown that whilst there is a reduction in all air pollutants in the CT scenario for all sectors, the size and sign of the further impact from the increased EU ETS price varies depending on the sector and pollutant.

In all the scenarios we considered, the government is assumed to use its additional income from carbon taxes and ETS permits[1] to finance its expenditures. Although there is no explicit earmarking of carbon revenues for a specific purpose, the I3E model includes an adaptive government welfare system in which welfare transfers increase with the overall price level (CPI) and the unemployment rate. Hence, increased carbon taxation results in increased welfare transfers to

[1] Under the current EU ETS structure, Ireland receives approximately 50 per cent of the revenues generated by EU ETS permit sales to Irish firms. Of this, 30 per cent is diverted to the social welfare system.

households equivalent to approximately 30 per cent of the revenue from carbon tax, which is in line with the government's commitment to directing a fraction of carbon tax revenue to social welfare payments (Department of the Taoiseach, 2020). As the government has no clear plan for further revenue recycling (RR), we believe this best replicates the current policy setting. However, one may argue that the results presented here are the outcome of additional taxation rather than an environmental tax reform, and the implications of various RR schemes should be discussed to complete this analysis.

As is well known from the related literature,[2] RR schemes not only aim to boost the economy (efficiency) but also to improve income distribution (equity), thereby achieving a fairer share of the burden of an environmental tax reform across different households. As this paper does not focus on the efficiency-equity implications of carbon pricing, the results of de Bruin and Yakut (2024) are used to draw conclusions about the potential implications of an RR scheme. All RR schemes in combination with a carbon tax lead to lower CO_2 emissions reductions than the case of no revenue recycling, i.e. lessening the implications of the carbon tax. This is driven by increases in economic activity and disposable income, especially when the RR scheme targets households directly by reducing the wage or sales tax rate or increasing transfers to households. This impact, however, is small, resulting in a reduction of emissions from 15.8 per cent to between 13.2 and 15.3 per cent depending on the RR scheme chosen. The same effect would be expected for other pollutants, as the RR scheme will generate more favourable economic conditions, boosting production and emissions of all pollutants. On the other hand, the relative impacts of an RR scheme on different pollutants will be based on the RR design. If the carbon tax revenue is directed to support sectors by lowering production or corporate tax rates, the carbon tax would be much less efficient for the main investors, e.g. pharma and chemicals, or heavily emitting sectors, e.g. cement or fabricated metal. An RR scheme targeting households would lead to increased pollution from sectors whose outputs are demanded more for final demand purposes.

V CONCLUSION

Policymakers around the world are facing pressure to reduce outdoor air pollution as this affects environmental quality and human health. Evidence suggests that decarbonisation policies are effective at reducing NO_x, SO_x, NMVOC, NH_3, $PM_{2.5}$ and PM_{10} emissions. However, to the authors' knowledge, such research has not compared the EU ETS and a national carbon tax.

This paper contributed to the literature by estimating the scale of abatement of NO_x, NMVOC, SO_x, NH_3, $PM_{2.5}$ and PM_{10} emissions in 2040 and the emission

[2] See Köppl and Schratzenstaller (2022) for a recent literature survey.

reductions by sector in response to increases in the carbon tax, the EU ETS and both policies. Increases in the carbon tax reduced CO_2 emissions by 6.3 per cent relative to the BaU, whilst decreasing SO_x and $PM_{2.5}$ emissions by 7.1 per cent and 8.4 per cent respectively. The reductions in the other air pollutants were lower than the reduction in CO_2 under the carbon tax. When the EU ETS price also increased, there was a further reduction in CO_2 and all air pollutants; however, this reduction was smaller than that from the carbon tax. The further reduction under the increased EU ETS was largest for SO_x emissions (86 per cent of the reduction under the CT scenario), followed by CO_2 emissions (83 per cent of the reduction under the CT scenario). The results show that combining increases in both decarbonisation policies may help reduce outdoor air pollution.

Whilst there is a reduction in all air pollutants in all sectors when the carbon tax is increased and, in most sectors, when the EU ETS price is increased, the size of this impact varies depending on the sector and pollutant.

This analysis identifies the sectors that generate the largest positive spillovers in air pollutant reductions in response to carbon price increases. The transport, services, residential and agricultural sectors had the largest reductions in NO_x and most other pollutant emissions in response to increases in the carbon tax relative to BaU. These sectors are primarily covered by the carbon tax; thus, the increased price results in a shift towards low-carbon fuels, thereby reducing air pollutant emissions. The electricity, petroleum and manufacturing sectors, which are covered by the EU ETS, experienced the largest reductions in air pollutants at higher EU ETS prices compared to the BaU scenario.

However, the decarbonisation policies had limited impacts on certain pollutants, such as NH_3, which are less impacted by changes in fossil fuel usage. As such, future research should consider including additional policies specific to these pollutants to curb air pollution. Policies reducing NH_3 emissions from non-transport agriculture should be investigated.

This study cannot distinguish regional or local differences in the impacts of outdoor air pollution within Ireland because of the nature of the I3E model. Because yearly outdoor air pollutant data are used, the model cannot detect seasonal differences in air pollutant impacts. Liu *et al.* (2021) find that in China, the ETS reduced $PM_{2.5}$ more in the summer relative to the other seasons. The emission factors used in this paper were for 2019 and were assumed to remain constant over time. Future research could consider using varied emission factors to account for technical progress and changes in emission standards over time. This study also cannot consider the effect of climate change on air pollution or the impact of air pollution on climate change, e.g. through radiative forcing or cooling. However, Lanzi and Dellink (2019) suggest that the impact of the former is limited.

Exposure to outdoor air pollution is a contributor to mortality and morbidity around the globe. As such, future research could include the impacts of changes in outdoor air pollution on future morbidity and mortality. Incorporating this into a CGE analysis will also capture the effects on labour productivity and GDP. The results from this paper confirm that outdoor air pollution can be reduced through certain decarbonisation policies and that this finding holds when the EU ETS price is increased. Moreover, this paper shows that the combination of increases in both the carbon tax and the ETS price is more effective than only increasing the carbon tax in reducing NO_x, NMVOC, SO_x, NH_3, $PM_{2.5}$ and PM_{10} emissions in Ireland.

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APPENDIX A LIST OF ACTIVITIES

Table A.1: Activities in Each Aggregate Sector with NACE Codes

I3E Activity	*Activity*	*NACE code*	*Aggregate Sector*	
A_PRA	Agriculture	1	AGR	Agriculture
A_FRS	Forestry	2	AGR	
A_FSH	Fishing	3	AGR	
A_FBT	Food, Beverage and Tobacco	10,11,12	MAN	Manufacturing
A_TEX	Textile	13,14,15	MAN	
A_WWP	Wood and Wood Products	16	MAN	
A_OIN	Other Industrial Products	17,18,33	MAN	
A_CHE	Chemical Products	20	MAN	
A_BPP	Basic Pharmaceutical Products	21	MAN	
A_RUP	Rubber and Plastic Products	22	MAN	
A_ONM	Other Non-metallic Products	23	MAN	
A_BFM	Basic Metal Manufacturing	24,25	MAN	
A_HTP	High-Tech Products	26,27,28	MAN	
A_OTM	Other Manufacturing	31,32	MAN	
A_CON	Construction	41,42,43	MAN	
A_TRE	Transportation Equipment	29,30	MAN	Manufacturing
A_WAT	Water and Sewerage	36,37,38,39	MAN	
A_OMN	Other Mining Products	5-9	MAN	
A_ELC	Conventional		ELC	Electricity
A_NGS	Natural Gas Supply		ELC	
A_WND	Wind		ELC	
A_ORE	Other Renewables		ELC	
A_PET	Petroleum	19	PET	Petroleum Refinery
A_TRD	Trade	45,46,47	SER	Services
A_ACC	Accommodation and Hotel Services	55,56	SER	
A_TEL	Telecommunication Services	61	SER	
A_FSR	Financial Services	64,65,66	SER	
A_RES	Real Estate Services	68	SER	
A_PSE	Professional Services	69,70,71,72, 73,74,75	SER	
A_ADS	Admin and Support Services	77,78,79,80, 81,82	SER	
A_OSE	Other Services	remaining services	SER	
A_PUB	Public Services	84	SER	Services
A_EDU	Education Sector	85	SER	

Table A.1: Activities in Each Aggregate Sector with NACE Codes (Contd.)

I3E Activity	*Activity*	*NACE code*	*Aggregate Sector*	
A_HHS	Health Sector	86,87,88	SER	
A_LTS	Land Transportation	49	TRP	Transportation
A_WTS	Water Transportation	50	TRP	
A_ATS	Air Transportation	51	TRP	
A_OTR	Other Transport (Storage and Postal)		52,53	TRP
A_PRV	Private car Transportation		TRP	

Source: Authors' analysis.

APPENDIX B POLLUTANT COEFFICIENTS AND SHARE OF ETS

Table B.1: Pollutant Coefficients and Share of ETS for BaU in 2040

Activity	NO_x	NMVOC	SO_x	NH_3	$PM_{2.5}$	PM_{10}	ETS Share
A_ACC	0.017	0.004	0.001	0.000	0.001	0.001	0.000
A_ADS	0.006	0.002	0.000	0.000	0.000	0.000	0.000
A_ATS	0.216	0.023	0.014	0.000	0.002	0.002	1.000
A_BFM	0.424	0.213	0.009	0.000	0.008	0.009	0.791
A_BPP	0.001	0.000	0.000	0.000	0.000	0.000	0.791
A_CHE	3.262	1.723	0.001	6.950	0.013	0.019	0.791
A_CLC	1.580	0.084	1.067	0.000	0.117	0.155	1.000
A_CON	0.009	0.003	0.003	0.000	0.018	0.280	0.000
A_EDU	0.028	0.007	0.001	0.000	0.001	0.002	0.000
A_FBT	0.037	0.945	0.005	0.000	0.001	0.001	0.791
A_FRS	0.383	0.035	0.000	0.000	0.015	0.015	0.000
A_FSH	3.899	0.095	0.001	0.000	0.058	0.058	0.000
A_FSR	0.003	0.001	0.000	0.000	0.000	0.000	0.000
A_HHS	0.015	0.004	0.000	0.000	0.000	0.001	0.031
A_HTP	0.001	0.000	0.000	0.000	0.000	0.000	0.791
A_LTS	3.930	0.353	0.004	0.013	0.233	0.397	0.000
A_NGS	0.072	0.002	0.000	0.000	0.000	0.000	1.000
A_OIN	0.008	0.160	0.000	0.000	0.000	0.000	0.000
A_OMN	0.002	4.945	0.000	0.000	0.373	3.041	0.000
A_ONM	1.887	0.180	0.419	0.000	0.477	0.738	1.000
A_ORE	0.144	0.012	0.003	0.000	0.004	0.005	1.000
A_OSE	0.020	0.004	0.003	0.000	0.002	0.002	0.000
A_OTM	0.022	0.007	0.001	0.000	0.000	0.000	0.791
A_OTR	0.011	0.002	0.002	0.000	0.001	0.002	0.031
A_PEA	0.240	0.001	0.221	0.000	0.053	0.077	0.000
A_PET	0.084	0.004	0.009	0.000	0.001	0.001	1.000
A_PRA	0.353	4.791	0.000	6.513	0.103	0.335	0.000
A_PSE	0.006	0.001	0.001	0.000	0.000	0.001	0.000
A_PUB	0.018	0.004	0.001	0.000	0.001	0.002	0.000
A_RES	0.002	0.001	0.000	0.000	0.000	0.000	0.000
A_RUP	0.027	0.005	0.005	0.000	0.003	0.004	0.000
A_TEL	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A_TEX	0.004	0.001	0.000	0.000	0.000	0.000	0.000
A_TRD	0.013	0.002	0.002	0.000	0.001	0.002	0.000
A_TRE	0.004	0.001	0.000	0.000	0.000	0.000	0.000
A_WAT	0.018	0.193	0.003	0.043	0.108	0.108	0.000

Table B.1: Pollutant Coefficients and Share of ETS for BaU in 2040 (Contd.)

Activity	NO_x	NMVOC	SO_x	NH_3	$PM_{2.5}$	PM_{10}	ETS Share
A_WND	0.004	0.000	0.002	0.000	0.000	0.000	1.000
A_WTS	7.519	0.238	0.170	0.000	0.118	0.138	0.000
A_WWP	0.006	0.001	0.001	0.000	0.001	0.001	0.000

Source: Authors' calculations.
Note: The pollutant coefficients are calculated by dividing the pollutant emissions per sector in 2040 by the output per sector in 2040. When the share of ETS is equal to 1.00 the sector is completely covered by the ETS whilst if the share is 0.00 then the sector is not covered by the ETS. The shares between 0.00 and 1.00 indicate partial coverage by the ETS in that sector.