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The healthcare costs of poor air quality in Ireland: A review of potential data sources and methods

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THE HEALTHCARE COSTS OF POOR AIR QUALITY IN IRELAND: A REVIEW OF POTENTIAL DATA SOURCES AND METHODS

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ABBREVIATIONS

ABF	Activity-based funding
AQG	Air quality guidelines
COPD	Chronic obstructive pulmonary disease
DRG	Diagnosis-related group
EEA	European Environment Agency
EPA	Environmental Protection Agency
EU	European Union
GBD	Global burden of disease
GDP	Gross domestic product
GP	General practitioner
GUI	*Growing Up in Ireland*
HIPE	Hospital In-Patient Enquiry
HPO	Healthcare Pricing Office
HSE	Health Service Executive
ICD-10	International Classifications of Disease (10th edition)
IHD	Ischaemic heart disease
ISSDA	Irish Social Science Data Archive
LOS	Length of stay
MDC	Major diagnostic classification
NO_2	Nitrogen dioxide
O_3	Ozone
PAF	Population attributable fraction
PCG	Primary caregiver
PCRS	Primary Care Reimbursement Service
$PM_{2.5}$	Particulate matter with a diameter of 2.5 micrometres or smaller
US	United States
WHO	World Health Organization

EXECUTIVE SUMMARY

Air pollution is a major risk factor for disease and premature mortality worldwide. In Ireland, fine particulate matter ($PM_{2.5}$), which originates largely from burning solid fuel for heating, and nitrogen dioxide (NO_2), derived from road transport, in particular from diesel engines, are the main contributing sources of poor air quality. In addition to the mortality and morbidity burden, air pollution also imposes a significant economic burden, in terms of healthcare costs, lost productivity, impact on agricultural crops and damage to buildings and infrastructure. In this report, we scope out the data and methods to estimate the healthcare costs of poor air quality in Ireland, focusing on three types of healthcare: emergency inpatient hospitalisations, general practitioner (GP) care and prescribed medicines dispensed in community pharmacies (community pharmacy services). As the available data in Ireland preclude a comprehensive analysis of the healthcare costs associated with poor air quality, the data and methodological approach used in this report provide a framework that can be used to inform future data collection and research studies on this issue.

The approach taken relies on a number of steps. First, it is necessary to identify the healthcare conditions that are linked to poor air quality. Published evidence from the European Environment Agency (EEA) is used to identify six risk–outcome pairs for which robust evidence for causal relationships exists:

- $PM_{2.5}$ – Asthma (age 0–14)
- $PM_{2.5}$ – Chronic obstructive pulmonary disease (COPD) (age 25+)
- $PM_{2.5}$ – Ischaemic heart disease (IHD) (age 25+)
- $PM_{2.5}$ – Stroke (age 25+)
- NO_2 – Stroke (age 25+)
- NO_2 – Asthma (age 15+).

Second, the healthcare utilisation and costs associated with these healthcare conditions are quantified and scaled up to the population level. A mixture of administrative, survey and treatment guideline data are used to quantify healthcare utilisation and costs for each type of care. Finally, an estimate of the proportion of cases (or utilisation) of a particular disease or condition that can be attributable to poor air quality is obtained. Evidence from the EEA is used to provide estimates of the proportion of particular health conditions attributable to poor air quality.

For emergency inpatient hospitalisations, the most resource-intensive risk–outcome pair is for $PM_{2.5}$ air pollution-related discharges for COPD, which accounted for an average of 9,194 bed days, and cost an average of €8.4m per annum. Across the four risk–outcome pairs that relate to $PM_{2.5}$ air pollution, emergency inpatient hospitalisations accounted for 15,565 bed days per annum, and cost an average of €15.6m. For NO_2-related emergency inpatient hospitalisations, the respective figures were 2,881 bed days and €3.1m.

For GP care, the most resource intensive risk–outcome pair relates to $PM_{2.5}$ air pollution and COPD, accounting for over 32,225 GP visits per annum at a cost of €1.8m. Overall, the four conditions causally linked to $PM_{2.5}$ air pollution accounted for a total of nearly 60,000 GP consultations per annum, at a cost of over €3.1m. Conditions linked to NO_2 air pollution (i.e., stroke and asthma in adults) accounted for 28,941 annual GP visits and cost €1.6m per annum.

For community pharmaceuticals, once again the most resource intensive risk–outcome pair relates to $PM_{2.5}$ air pollution and COPD, accounting for almost €4.4m in community pharmaceuticals costs, very closely followed by NO_2 air pollution and asthma in adults, accounting for over €4.3m. Overall, the four conditions causally linked to $PM_{2.5}$ air pollution accounted for a total of almost €7.6m in community pharmaceuticals per annum, compared to over €4.7m for the two conditions linked to NO_2 air pollution (i.e., stroke and asthma in adults).

Direct comparisons between the three types of healthcare utilisation examined in this report cannot be made due to differences in data and methodologies. Nonetheless, the results highlight that while overall contact with GP and community pharmaceutical services is far greater than for emergency inpatient hospitalisations, the much higher unit costs of emergency inpatient care are reflected in much higher overall costs.

Despite the limitations in the available data and methodological approach, the approach used in this report, while incomplete, provides a framework that can be used to inform future data collection and research studies on this issue. Future work could expand the analysis to include other types of healthcare utilisation (e.g., practice nurse visits), other risk–outcome pairs (e.g., $PM_{2.5}$ air pollution and lung cancer), and assess the sensitivity of the findings to alternative assumptions about population-attributable fractions, population prevalence and healthcare utilisation.

CHAPTER 1

Background

1.1 BACKGROUND

Air pollution is well recognised as a major risk factor for disease and premature mortality worldwide (EEA, 2022; Murray et al., 2020; Vos et al., 2020). Global assessments of ambient (outdoor) air pollution suggest that between four million and nine million deaths annually, and hundreds of millions of lost years of healthy life, can be attributed to ambient air pollution (WHO, 2021). The global burden of disease (GBD) attributable to air pollution is now estimated to be comparable with other major health risks, such as unhealthy diet and tobacco smoking, and was in the top 5 out of 87 risk factors for male and female deaths in 2019 (Murray et al., 2020).[1] As a result, air pollution is now recognised as the single largest environmental threat to public health (WHO, 2021).

Ambient air pollution is a complex mixture of particles and gases. Their concentrations and composition vary from place to place, depending on what sources are present, weather conditions and how they mix in the atmosphere (Burns et al., 2020). The European Union (EU) Ambient Air Quality Directives (currently under review) set EU air quality standards for 12 air pollutants: sulphur dioxide, nitrogen dioxide (NO_2)/nitrogen oxides, particulate matter (PM_{10}, $PM_{2.5}$), ozone (O_3), benzene, lead, carbon monoxide, arsenic, cadmium, nickel and benzo(a)pyrene. In 2021, the World Health Organization (WHO) published new air quality guidelines (AQGs) for particulate matter ($PM_{2.5}$ and PM_{10}), O_3, NO_2, sulphur dioxide and carbon monoxide following a systematic review of the latest scientific evidence on how air pollution damages human health (WHO, 2021).[2]

In Ireland, fine particulate matter ($PM_{2.5}$), which originates largely from burning solid fuel for heating, and NO_2, derived from road transport, in particular from diesel engines, are the main sources contributing to poor air quality (EPA, 2022). Although air pollution has decreased in most European countries over the past two decades, including Ireland, levels of ambient air pollution in Ireland remain above the WHO's AQGs in many cities and towns (EPA, 2022, 2023). For example, in 2023,

1 The GBD methodology has a risk factor hierarchy. Level 1 risk factors are behavioural, environmental and occupational, and metabolic; level 2 risk factors include 20 risks or clusters of risks (e.g., air pollution); level 3 includes 52 risk factors or clusters of risks; and level 4 includes 69 specific risk factors (e.g., ambient particulate matter). Counting all specific risk factors and aggregates computed in the GBD for 2019 yields 87 risks or clusters of risks. In the GBD methodology, air pollution is a level 2 risk, comprised of particulate matter air pollution (level 3) and O3 pollution (level 3). Particulate matter pollution is further comprised of ambient particulate matter pollution (level 4) and household particulate matter pollution (level 4) (Murray et al., 2020a). However, it is important to note that, to date, GBD estimates are limited to PM2.5 and O3. Other common pollutants such as NO2 and sulphur dioxide are not yet included and, therefore, these figures based on exposure to PM2.5 and O3 are likely to underestimate the full health toll from air pollution (WHO, 2021).

2 For example, the WHO updated guidelines for PM2.5 are: annual average of 5 µg/m3 (previous limit was 10) daily average of 15 µg/m3 (previous limit was 25).

80 out of 101 $PM_{2.5}$ monitoring stations exceeded the new WHO daily AQG for $PM_{2.5}$ and 79 out of 101 stations exceeded the new WHO annual AQGs (EPA, 2024). In Ireland, the current Clean Air Strategy commits to the achievement of the final WHO AQG values by 2040 (Government of Ireland, 2023).[3]

As noted, air pollution is now well recognised as a major risk factor for disease and premature mortality worldwide. The greatest health damage from ambient air pollution is caused by chronic exposure to particulate matter, in particular to $PM_{2.5,}$ which increases the risk of heart diseases, stroke, lung cancer and many respiratory diseases including asthma, bronchitis, chronic obstructive pulmonary disease (COPD) and respiratory infections (Brook et al., 2010; Cohen et al., 2017; OECD, 2016, 2020a; Pimpin et al., 2018). Air pollution exposure may increase the incidence of, and mortality from, a larger number of diseases and conditions than those currently considered, such as cognitive impairment and dementia (Ailshire and Crimmins, 2014; Peters et al., 2019; Weuve et al., 2012; Wood et al., 2022), and type 2 diabetes (Murray et al., 2020). There is also a growing evidence base linking air pollution (particularly $PM_{2.5}$) with poorer mental health and wellbeing, including depression and anxiety (Braithwaite et al., 2019; Lyons et al., 2024; Power et al., 2015), suicide (Gładka et al., 2021), bipolar disorder (Hao et al., 2022) and life satisfaction (Orru et al., 2016). Aguilar-Gomez et al. (2022) survey the growing literature within economics that has begun to investigate the causal effects of air pollution on numerous 'non-health' outcomes, such as worker productivity, school performance, decision-making and even crime.

Air pollution may also exacerbate existing health conditions; for example, it can worsen the prognosis of pneumonia patients (Yee et al., 2021). Certain population subgroups are particularly vulnerable to the effects of air pollution, such as children and older people (Neidell, 2004; Nhung et al., 2017). In addition, for a given level of air pollution, those in more disadvantaged socioeconomic positions may be more susceptible to the negative health consequences of air pollution; this is due to pre-existing health conditions, poorer housing conditions, etc. (EEA, 2018; OECD, 2020a).

In addition to the mortality and morbidity burden, air pollution also imposes a significant economic burden, in terms of healthcare costs, lost productivity, impact on agricultural crops, and damage to buildings and infrastructure (OECD, 2020a; WHO, 2021). In this report, we focus on the healthcare costs of poor air quality in Ireland, focusing on three types of healthcare: emergency inpatient hospitalisations, general practitioner (GP) care and prescribed medicines dispensed in community pharmacies (community pharmacy services). As described below, the available data in Ireland preclude a comprehensive analysis of the

3 There are four interim targets (IT) identified (IT1, IT2, IT3, IT4) for each pollutant. For example, for annual PM2.5, IT3 is 15 µg/m3 and IT4 is 10 µg/m3. The Clean Air Strategy commits to achieving the interim WHO AQG IT3 targets by 2026, and the IT4 targets by 2030.

healthcare costs associated with poor air quality, but the data and methodological approach used in this report, while incomplete, provide a framework that can be used to inform future data collection and research studies on this issue.

1.2 PREVIOUS RESEARCH

Using an impact pathway approach linking data on air pollutant emissions, concentrations of key pollutants, impacts on health and crop yields and economic costs, the Organisation for Economic Co-operation and Development (OECD) estimate that the total welfare losses from ambient air pollution ($PM_{2.5}$ and ground-level ozone) in the EU-27 in 2017 amounted to €601bn, or approximately 4.9 per cent of gross domestic product (GDP). While the majority (88 per cent) of the welfare losses were accounted for by premature mortality, healthcare costs amounted to €15bn (or 2.5 per cent of the total welfare losses). Healthcare costs related to the cost of treating lung cancer, cardiovascular disease and respiratory disease due to high concentrations of $PM_{2.5}$ and ozone (OECD, 2016). In Ireland, the healthcare costs were estimated at €0.15bn, or 0.06 per cent of GDP (OECD, 2016, 2020a).[4] A similar analysis conducted for the European Public Health Alliance estimated that the social costs associated with poor air quality in Dublin amounted to 1.4 per cent of GDP in 2018 (de Bruyn and de Vries, 2020).[5]

A recent analysis of the global economic costs of $PM_{2.5}$ in 2019 conducted by the World Bank, using mortality and morbidity data from the GBD study, found that the global health cost of mortality and morbidity caused by exposure to $PM_{2.5}$ air pollution (both ambient and household) in 2019 was $8.1 trillion, equivalent to 6.1 per cent of global GDP. In Ireland, the cost of ambient air pollution was estimated at $4.4m in 2019 (World Bank, 2022). Using a human capital approach to evaluate the cost of various forms of pollution on economic growth and societal development, Fuller et al. (2022) found that the cost in the EU-15 in 2019 was approximately 0.5 per cent of GDP, and that it had fallen since 2000, reflecting pollution control policies, the outsourcing of polluting industries, and reductions in death rates.[6,7]

In England, it was estimated that the total health and social care costs of $PM_{2.5}$ in 2017 came to £41.2m (based on data where there is robust evidence for an association between $PM_{2.5}$ and health and social care service utilisation), increasing to £76.1m when diseases are included where the evidence is associative or

4 Caution must be exercised in making international comparisons of data using GDP as the denominator for Ireland, as GDP figures for Ireland are heavily influenced by the activities of global multinational companies locating in Ireland (Wren and Fitzpatrick, 2020).

5 Pollutants considered included PM2.5, PM10, O3 and NO2.

6 In the human capital approach, the economic losses associated with deaths due to pollution can be valued by the output lost when a person dies prematurely (i.e., the human capital approach), or by using the value per statistical life (i.e., what people would pay for small risk reductions that sum up to one statistical life) (Fuller et al., 2022).

7 The pollutants considered were ambient ozone, ambient particulate matter, lead exposure, occupational carcinogens, occupational PM, gases and fumes.

emerging (Pimpin et al., 2018; Public Health England, 2018). They examined primary care visits, prescriptions, secondary care (inpatient and outpatient) visits and social care. Asthma, chronic obstructive pulmonary disease (COPD), coronary heart disease, stroke, type 2 diabetes and lung cancer were included within the model based on estimates of associations between exposure to the pollutants and risk of developing the diseases; these estimates were obtained from meta-analyses of prospective cohort studies. Low birth weight and dementia were also included, although the evidence was less well established for these conditions.

A model employed by the United States (US) Environmental Protection Agency, BenMAP-CE, is used to inform the regulatory impact analyses for policy initiatives such as air quality standards. The model uses air quality and population data, baseline rates of mortality and morbidity, concentration-response estimates, and unit cost values to quantify the number and value of air pollution-attributable cases of premature death and disease (e.g., hospital admissions for respiratory and cardiovascular conditions) in the US. Administrative claims data from US private health insurers are used to identify the population with diseases related to poor air quality (principally respiratory and cardiovascular disease), their incremental healthcare utilisation and associated costs. The results also indicate the importance of accounting for non-hospital types of care, and conditions other than respiratory and cardiovascular disease; for example, including the costs of additional services would increase the health care costs by 43.2 per cent for respiratory patients (from just over USD$50,000 per patient per annum to nearly USD$75,000 (Birnbaum et al., 2020)).

While not focused specifically on air pollution, many of the techniques used in cost of illness studies are common to the approaches used to quantify the economic costs of air pollution in the studies reviewed above. Cost of illness studies require the identification, measurement and valuation of all resources (e.g., healthcare, informal care, work absence, etc.) related to a particular disease. The output, expressed in monetary terms, is an estimate of the total burden of a particular illness to society (Connolly et al., 2014). A study conducted for the Asthma Society of Ireland estimated that the annual direct and indirect costs of asthma in Ireland in 2017 were €472m, with direct costs associated with hospital care, primary care and medications accounting for 57 per cent of total costs, and indirect costs (absenteeism and premature mortality) accounting for 43 per cent of the total costs (Asthma Society of Ireland, 2019).[8] However, cost of illness analyses in Ireland have been hampered severely by data challenges, including the absence of data on population prevalence for specific health conditions and on many aspects of

8 However, much of the data on prevalence and healthcare utilisation for children were derived from an online convenience sample of Asthma Society of Ireland members who have asthma (or who have children with asthma), and the healthcare utilisation estimates did not account for utilisation not related to asthma.

healthcare utilisation such as informal care (Connolly et al., 2014; Sharma et al., 2022; Smith et al., 2010).

Using individual-level data, a large body of evidence has assessed the association between air pollution and healthcare (usually hospital) utilisation. A common approach is the use of daily time-series data on outcomes, such as hospitalisations, linked with contemporaneous and lagged levels of pollution and potential confounding variables, such as weather (Anderson et al., 2003a; Carugno et al., 2016; Chen et al., 2022; Dominici et al., 2006; Liu et al., 2018; Xu et al., 2016; Zanobetti and Schwartz, 2006; Zhou et al., 2023).[9] While less common, some studies have also examined other aspects of healthcare utilisation using the time-series approach, such as general practice visits for upper respiratory tract infections (Tam et al., 2014) and lower respiratory tract infections (Hajat et al., 2001), and outpatient visits for asthma (Li et al., 2010). In Ireland, Clancy et al. (2002) and Dockery et al. (2013) used this approach to examine the impact of the so-called 'smoky coal bans' on mortality and hospitalisations during the 1990s.[10]

An alternative approach is the use of cohort data that follow individuals over time and compare pollution measures aggregated over time with health outcomes (and healthcare utilisation) (Gan et al., 2013; Wood et al., 2022). Both the time-series and cohort approaches have been criticised, as ambient air pollution is not randomly assigned across the population; this has led to an increasing interest in quasi-experimental techniques to isolate exogenous changes in pollution. (See Alexander and Schwandt (2022), Brook et al. (2010), Deryugina et al. (2019), Lleras-Muney (2010), Moretti and Neidell (2011), Neidell (2004, 2009) and Ward (2015) for good examples.) A recent quasi-experimental analysis of the extension of smoky coal bans to smaller towns in Ireland over the period 2010–2018 found that the bans were associated with significant reductions in the incidence of chronic lung disease among the older population, but with non-significant effects on all-cause mortality (Lyons et al., 2023). With both time-series and cohort approaches, the challenge lies in making inferences at a population level about broader health impacts and quantifying those health impacts in monetary terms.

9 See Adar et al. (2014), Yee et al. (2021), Zheng et al. (2015) and Zhu et al. (2020) for meta analyses, and Brook et al. (2010a) for an overview of studies examining cardiovascular mortality and hospitalisations.

10 The two studies found divergent results for cardiovascular mortality. Dockery et al. (2013) found that respiratory mortality decreased significantly, by 17 per cent, after the 1990 ban (confirming the earlier study by Clancy et al., 2002) and, to a lesser extent, after the 1995 and 1998 bans. However, unlike the earlier study, they did not find a reduction in total or cardiovascular mortality after either the 1990 ban or the later bans. The authors concluded, 'we now believe the previous analyses (Clancy et al. 2002) overestimated the Dublin ban's effects on mortality rates for those causes with substantial long-term trends, that is, total and cardiovascular mortality.' Analyses of the hospital admissions data at that time were hampered by substantial underreporting issues and the absence of data from a reference population to account for long-term background trends. Regular reporting of hospital admissions began in 1990; no data were available before the 1990 coal ban in Dublin, and only limited amounts of data were available before the 1995 and 1998 bans.

1.3 RESEARCH OBJECTIVES

In this context, the purpose of this report is to scope out potential data sources and methods to assess the healthcare costs of poor air quality in Ireland, focusing on three elements of healthcare: emergency inpatient hospitalisations, GP care and prescribed medicines dispensed in community pharmacies. Quantifying the potential impact of air pollution on healthcare costs is important for future policy and resource planning, and for targeting of mitigation measures and public health campaigns (Pimpin et al., 2018; World Bank, 2022). Ideally, population disease registers and linked administrative healthcare utilisation and cost data would be available in order to identify the population diagnosed with health conditions that are linked to poor air quality, their healthcare utilisation and associated costs. In the absence of such data, we use a mixture of administrative and survey data on healthcare utilisation and costs, supplemented with data on the burden of ill-health attributed to air pollution for specific conditions with causal links to air pollution (e.g., asthma) to assess the healthcare utilisation and costs associated with treating conditions that are linked with poor air quality in Ireland. Our approach is similar to that used in cost-of-illness studies, in which the costs to the healthcare system (or society at large) of a particular disease are quantified. Due to data deficiencies, we focus here on the direct healthcare costs for three important elements of healthcare utilisation: emergency inpatient hospitalisations, GP care and prescribed medicines dispensed in community pharmacies. Expenditure on these services amounted to €2.14m, €1.01m and €2.27m respectively in 2019 (Keegan et al., 2020; Walsh et al., 2021).[11] The data and methodological approach used in this report, while incomplete, provide a framework that can be used to inform future data collection and research studies on this issue.

The strength of our approach is that it does not rely on the availability of the data used in the studies summarised above, such as linked high-frequency data on air pollution concentrations and healthcare utilisation. In Ireland, while the number of air quality monitors is now at 116 (much increased from just a few years ago) (EPA, 2023), the challenge lies in linking these data to appropriate high-frequency spatially-coded administrative data on healthcare utilisation and costs. Low monitor coverage may also mean that there may be significant variation in local air pollution concentrations within the area covered by a single monitoring station. In addition, the time-series approach can only identify the short-term effects of air pollution, while cohort-based approaches largely focus on the longer-term impacts. Moreover, these types of studies cannot account for other differences between areas (unrelated to air pollution) that may account for differences in healthcare utilisation and costs, e.g., levels of socioeconomic deprivation. Previous research has also highlighted the difficulty in attributing ambient air pollution data

11 Expenditure on GP care includes expenditure by private patients (i.e., those without a medical or GP visit card), while expenditure on community pharmacy and emergency in-patient care refers to public expenditure only. The figure for emergency in-patient expenditure refers to 2018.

to individuals; in particular, personal exposure will also depend on indoor pollution as well as on individual behaviour (mobility and time spent outdoors) (Koehler et al., 2019; Lleras-Muney, 2010). Our approach, using a mixture of administrative and survey data on healthcare utilisation and costs, supplemented with data on the burden of ill-health attributed to air pollution for specific conditions with causal links to air pollution (e.g., asthma), circumvents many of these types of issues.

The remainder of the report is structured as follows: Chapter 2 describes the data and methodology in greater detail; Chapter 3 presents the empirical results; and Chapter 4 discusses the results and implications for future data collection and research efforts.

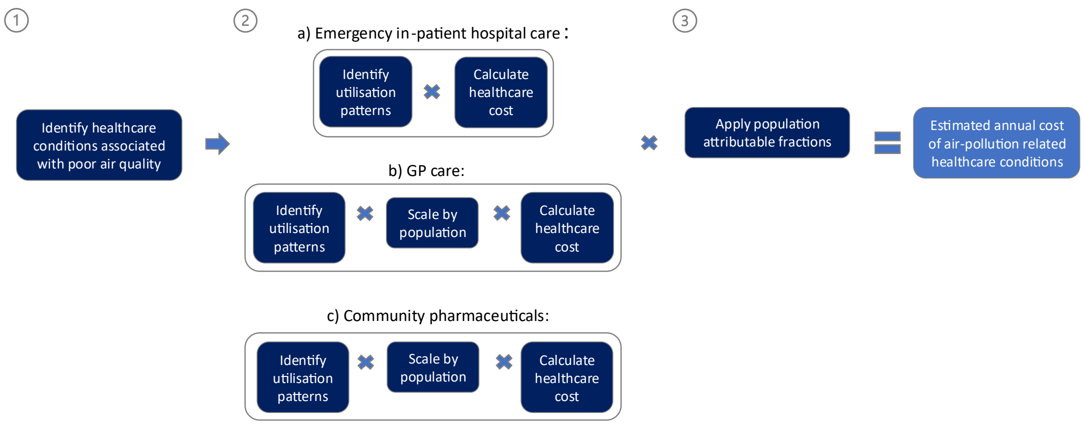
CHAPTER 2

Data and methodology

2.1 OVERVIEW OF APPROACH

In this chapter, we provide an overview of the data and methods used to quantify the healthcare costs associated with poor air quality for a) emergency inpatient hospitalisations, b) general practitioner (GP) care and c) prescribed medicines dispensed in community pharmacies (hereafter referred to as 'community pharmaceuticals'). These three types of healthcare service are chosen primarily due to data availability, but also to illustrate the use of different data and methodological approaches. Figure 2.1 provides an overview of the approach. In all cases, specific information is required. First, it is necessary to identify the healthcare conditions that are linked to poor air quality. Second, the healthcare utilisation and costs associated with these healthcare conditions need to be quantified and scaled up to the population level. Finally, an estimate of the proportion of cases (or utilisation) of a particular disease or condition that can be attributable to poor air quality needs to be obtained. Evidence from the international literature is used to identify health conditions with causal links to poor air quality (and estimates of the proportion of diagnoses attributable to poor air quality), while a variety of administrative and survey data sources and published literature are used to gather information on healthcare utilisation, costs and population prevalence.

FIGURE 2.1 OVERVIEW OF THE APPROACH



This approach is taken because Ireland has no comprehensive national disease register (HIQA, 2022), and the absence of a unique patient identifier means that it is difficult to link data on utilisation and costs across different service types.[12] In the absence of such data, we use a mixture of administrative and survey data on healthcare utilisation and costs, supplemented with data on the burden of ill-health attributed to air pollution for specific conditions with causal links to air pollution (e.g., asthma), to assess the healthcare utilisation and costs associated with treating conditions that are linked with poor air quality in Ireland. The data and methodological approach used in this report, while incomplete, provide a framework that can be used to inform future data collection and research studies on this issue.

The following sections provide further details on the data and methods used to derive the data necessary in order to quantify the emergency inpatient, GP and community pharmaceutical costs of poor air quality in Ireland. Section 2.2 focuses on the identification of healthcare conditions with causal links to air pollution, while Section 2.3 describes the data on healthcare utilisation and costs that are collated for each of our three types of healthcare (emergency inpatient, GP and community pharmaceuticals). Section 2.4 provides an overview of the process by which the proportion of cases attributable to poor air quality is derived.

2.2 IDENTIFICATION OF HEALTH CONDITIONS ASSOCIATED WITH POOR AIR QUALITY

We rely on research from the European Environment Agency (EEA) to identify health conditions associated with poor air quality. The EEA research estimates the morbidity-related health burden associated with exposure to key air pollutants – fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2) and ozone (O_3) – for 41 European countries in 2019 (Kienzler et al., 2022). The full report considered ten risk–outcome pairs for which evidence for robust causal relationships exists. The identification of the risk–outcome pairs was derived by considering published epidemiological evidence on the links between risk and outcome for each risk–outcome pair, with a further assessment of the quality of the evidence base (i.e., only studies for which causal evidence of associations was strong were included). In this report, we focus on six of the risk–outcome pairs that relate to long-term impacts of $PM_{2.5}$ and NO_2 on circulatory and respiratory diseases (see Table 2.1). Circulatory and respiratory disease are also the health outcomes for which the broader evidence base on the links between air pollution and health is most

12 The Health Identifiers Act (2014) established the Individual Health Identifier, assigning a unique number to every person who has contact with Ireland's health and care services, but implementation has been slow (Walsh et al., 2021). The Health Information Bill (2023) aims to develop an information system that will allow this identifier to link health records securely and efficiently for relevant purposes such as health service planning and research. However, it is unclear when this Bill will be enacted (see https://www.gov.ie/en/publication/f3faa-health-information-bill-2024/ for further details).

developed (Anderson et al., 2003b; Brook et al., 2010; Murray et al., 2020; OECD, 2020b).

TABLE 2.1 RISK–OUTCOME PAIRS FOR CIRCULATORY AND RESPIRATORY DISEASES RELATED TO AIR POLLUTION

Risk–outcome pair	ICD-10-AM code
$PM_{2.5}$ Asthma (age 0–14)	J45–J46
$PM_{2.5}$ COPD (age 25+)	J40–J44; J47
$PM_{2.5}$ IHD (age 25+)	I20–I25
$PM_{2.5}$ Stroke (age 25+)	I60–I69
NO_2 Stroke (age 25+)	I60–I69
NO_2 Asthma (age 15+)	J45–J46

Source: Kienzler et al. (2022).
Notes: All outcomes for $PM_{2.5}$ and NO_2 were considered as associated with long-term exposures to those pollutants. In Ireland, the ICD-10-AM classification system is used to classify diagnoses in the acute hospital system. ICD-10-AM codes are organised into 22 chapters, each of which relates to the main underlying disease category concerned. For example, respiratory diseases are coded to chapter 'J', with further disaggregation to a three-character code to identify specific diagnoses (e.g., asthma is identified using the code 'J45'). ICD-10-AM refers to the 10th edition of the International Statistical Classification of Diseases and Related Health Problems, Australian modification.

2.3 HEALTHCARE UTILISATION AND COSTS

In this section, we describe the data that are used to quantify the healthcare utilisation and costs associated with the healthcare conditions identified in Table 2.1, namely asthma (for those aged 0–14 and 15+), chronic obstructive pulmonary disease (COPD) (for those aged 25+), ischaemic heart disease (IHD) (for those aged 25+) and stroke (for those aged 25+). Section 2.3.1 describes the data and costing methods for emergency inpatient hospital care, while Sections 2.3.2 and 2.3.3 describe the data and costing methods for GP care and community pharmaceuticals, respectively.

2.3.1 Emergency inpatient hospital care

Healthcare utilisation

The data on hospital care is sourced from the Hospital In-Patient Enquiry (HIPE) database. As explained in greater detail below, we focus on emergency inpatient hospital care. HIPE is a health information system designed to collect clinical and administrative data on acute public hospitals in Ireland, covering day and inpatient (elective, emergency and maternity) discharges for all public hospitals. A HIPE discharge record is created when a patient is discharged from (or dies in) a hospital. This record contains administrative, demographic and clinical information for a discrete episode of care. An episode of care begins at admission to the hospital as a day patient or inpatient and ends at discharge from (or death in) that hospital.

For each discharge, a principal diagnosis and up to 29 secondary diagnoses are recorded. The HIPE dataset codes clinical information using the International Statistical Classification of Disease and Related Health Problems, Australian modification (ICD-10-AM),[13] the Australian Classification of Health Interventions and the Australian Coding Standards (ACS).[14] ICD-10-AM codes are organised into 22 chapters, each of which relates to the main underlying disease category concerned. For example, respiratory diseases are coded to chapter 'J', with further disaggregation to a three-character code to identify specific diagnoses (e.g., asthma is identified using the code 'J45').

The Healthcare Pricing Office (HPO) provided the authors with a data file of all HIPE discharges with a principal or secondary diagnosis of circulatory (I00–I99) or respiratory (J00–J99) diseases over the period 2016 to 2021.[15] We make several adjustments to this data file in order to derive a discharge-level dataset of diagnoses related to asthma, COPD, IHD and stroke. First, we focus only on discharges with a principal diagnosis of asthma, COPD, IHD or stroke; e.g., a discharge with a principal diagnosis of cancer with a secondary diagnosis of asthma is excluded. Second, we exclude the last two years (2020 and 2021) of the data as public hospital activity was severely affected by the COVID-19 pandemic during that period. This exclusion also ensures that a consistent clinical coding system (eighth revision of ICD-10-AM) is used for the period 2016–2019. Third, we focus on emergency inpatient discharges only – i.e., those admitted for elective care as a day patient or for maternity care are excluded.[16] Fourth, we exclude HIPE discharges with a length of stay (LOS) of over 365 days and those in hospitals with very few circulatory or respiratory discharges.[17] Finally, we exclude a very small number of discharge records with incomplete information. This results in a final sample size of 464,639 discharges over the four-year sample period 2016–2019. To put these figures in context, this represents just over 25 per cent of all emergency inpatient discharges over the period 2016–2019 (HPO, 2020). To smooth out year-on-year fluctuations in activity, we use the data on the full four-year period 2016–2019 to derive an annual average of the number of discharges for each condition, as illustrated in Table 2.2.

13 At the start of 2020, the classification used to code clinical information in Ireland was updated from the eighth edition (in use since 1 January 2015) to the tenth edition.

14 The use of ICD-10-AM, the Australian Classification of Health Interventions and the Australian Coding Standards are complemented by the Irish Coding Standards; these are revised as required to reflect changing clinical practice and ensure the classification and its application are relevant to the Irish healthcare system (HPO, 2022).

15 In ICD-10-AM, a series of ICD codes account for conditions 'caused' by problems related to the physical environment (e.g., air, noise, soil pollution, etc.). For example, there is a specific diagnostic code for 'exposure to air pollution' (Z58.1), although it is rarely used (just 14 diagnoses over the period 2016–2021 included Z58.1 as a diagnosis), and no discharges were assigned this code as a principal diagnosis.

16 We do not account for those who visit emergency departments but who are not admitted to hospital, as there is no diagnostic data available on the reason for emergency department attendances in Ireland (Brick and Keegan, 2020).

17 We exclude hospitals in which the number of discharges is less than the one percentile of observations per hospital over the period 2016–2019. These are likely to be specialised hospitals (e.g., orthopaedics, maternity) that would not typically treat circulatory or respiratory patients.

TABLE 2.2 HIPE EMERGENCY INPATIENT DISCHARGES FOR CIRCULATORY AND RESPIRATORY DISEASES

Healthcare condition	Total discharges 2016–2019	Annual average discharges
Asthma (age 0–14)	6,112	1,528
COPD (age 25+)	60,975	15,244
IHD (age 25+)	46,448	11,612
Stroke (age 25+)	28,276	7,069
Asthma (age 15+)	9,688	2,422

Source: Authors' analysis.
Notes: While there are six risk–outcome pairs (see Table 2.1), there are five unique healthcare conditions (stroke is associated with both $PM_{2.5}$ and NO_2 air pollution).

Costs

To analyse the healthcare costs of air pollution-related emergency inpatient hospital discharges, we rely on the diagnosis-related group (DRG) classification scheme. This scheme enables the disaggregation of discharges into homogenous groups, which undergo similar treatment processes and incur similar levels of resource use (such as staff, equipment and overheads) (HPO, 2022). The first step in the assignment of a discharge to a DRG is the classification of discharges by major diagnostic category (MDC). There are 23 MDCs reflecting major systems of the body, e.g., MDC 4 represents diseases of the respiratory system. Within MDC, cases are further partitioned into surgical, medical and other categories,[18] and by complexity (Bane, 2015). In 2019, there were 807 DRGs in use (HPO, 2020).

Costs for each DRG are available from the price lists set by the Health Service Executive (HSE) as part of the activity-based funding (ABF) initiative. The ABF system determines funding to hospitals based on the number and mix of patients that they treat. In an ABF scheme a hospital receives a payment for each patient encounter. The exact payment for a given encounter depends on the type and complexity of the individual case (Bane, 2015). As the cost of care in emergency departments is currently not included in the ABF system, and as all emergency inpatients will have been processed via an emergency department, and thereby incur hospital costs prior to their inpatient hospital stay, we apportion the average emergency department cost (€298 per emergency department attendance in 2018, uprated to 2023 prices) (Keegan et al., 2020) to all air-pollution-related hospitalisations in this analysis. We use data from the ABF system for 2021, and update values to 2023 prices using the Consumer Price Index.

18 The DRGs are identified by a four-character code. The first character in the code is alphabetic and refers to the MDC that the DRG belongs to. The second and third characters are numeric and identify whether the DRG is surgical, medical or other. The fourth character identifies the complexity level associated with the DRG (Bane, 2015).

An additional indicator of resource use, bed days, can also be calculated for each health condition. Bed days are defined as the sum of the length of stay for all discharges in each risk–outcome pair.

2.3.2 GP care

For GP care, the process for quantifying the costs associated with each risk–outcome pair is more complicated than for emergency inpatient hospitalisations. The absence of a comprehensive administrative dataset like HIPE that records diagnostic and associated healthcare utilisation and cost information means that we must rely on survey data to generate estimates of the total annual number of GP visits for each risk–outcome pair, Census of Population data to generate population-level estimates, and published literature to obtain information on GP unit costs of care.

Healthcare utilisation

To calculate the annual number of GP visits for consultations associated with poor air quality, we rely on two population surveys: the Healthy Ireland survey for the 15+ population and the *Growing Up in Ireland* (GUI) survey for the 0–14 population.

Healthy Ireland

The Healthy Ireland survey is an annual cross-sectional survey conducted by the Department of Health. It includes a core set of questions on health, healthcare utilisation and healthcare behaviours, as well as demographic and socioeconomic characteristics. Additional modules on particular issues (e.g., sleep) are fielded in different waves. To date, eight waves of the survey have been completed, in the following time periods: 2014–2015 (wave 1); 2015–2016 (wave 2); 2016–2017 (wave 3); 2017–2018 (wave 4); 2018–2019 (wave 5); 2020–2021 (wave 7); 2021–2022 (wave 8); and 2022–2023 (wave 9).[19] Waves 1 through 5 were conducted face-to-face, while waves 7 through 9 were administered over the phone. The survey includes a sample of approximately 7,500 people, with each wave representative of the population aged 15 and older living in Ireland. The Department of Health provided the authors with access to all waves of the Healthy Ireland survey. We used waves 1–2 and 4–5 to ensure a consistent survey administration mode (face-to-face). Wave 3 was omitted as it does not include questions on GP service utilisation.

In order to identify the health conditions with causal links to air pollution (i.e., asthma, COPD, IHD and stroke), we access information collected on health conditions using the following question:

19 Wave 6 (started in 2019) was not completed due to the COVID-19 pandemic.

> 'Have you suffered from any of the following conditions in the past 12 months?'[20]

Participants were presented with a card listing various conditions, including asthma, COPD, IHD and stroke. We then derived an estimate of the relevant population with each condition (e.g., asthma age 15+) using data on age groups from Census 2022 (see Table 2.3).

TABLE 2.3 POPULATION WITH CIRCULATORY AND RESPIRATORY DISEASES

Healthcare condition	Proportion (%)	Estimated population (n)
Asthma (age 0–14)	7.2	73,379
COPD (age 25+)	2.5	85,642
IHD (age 25+)	5.2	180,660
Stroke (age 25+)	1.4	48,396
Asthma (age 15+)	6.7	276,808

Notes: The proportions are derived as an average of the proportion (in each age range) who report the relevant health condition across Healthy Ireland waves 1, 2, 4 and 5. These proportions are then combined with Census 2022 figures on the number of individuals aged 0–14, 15+ and 25+ (https://data.cso.ie/table/F1002) to derive an estimate of the relevant population who report suffering from each condition. For asthma (age 0–14), see the text on GUI below.

In waves 1, 2, 4 and 5, participants were asked about their GP visiting behaviour:

> 'When was the last time you consulted a GP or family doctor on your own behalf? (This includes home visits and phone consultations but excludes nurse-only consultations).'

Possible responses to this question included 'less than 12 months' and 'more than 12 months'. Those who reported that they had consulted a GP or family doctor less than 12 months ago were then asked the following question:

> 'How often in the last four weeks did you consult a GP on your own behalf, excluding nurse-only consultations?'

An annual number of GP visits per respondent was then derived, by multiplying monthly visits by 13 to estimate annual GP visits.[21]

Not all GP visits accessed by one individual with a particular condition will be due to that condition; a person with asthma could also visit the GP for diagnosis and treatment of another, unrelated, condition. For that reason, we pooled the data across waves and used regression analysis to calculate the marginal (additional)

20 In waves 4 and 5, the question wording changed to, 'Do you currently have any of the following conditions that has been confirmed by a medical diagnosis?', and the response categories (and ordering) changed slightly – see Appendix A for further details.

21 Those who last visited their GP more than 12 months ago (or visited in the last 12 months but not in the last 4 weeks) are assumed to have no annual GP visits.

number of GP visits for each health condition. For each health condition, we estimate a linear regression of the annual number of GP visits, controlling for wave (year), age, sex, medical card status and multimorbidity. Multimorbidity is proxied by the number of additional health conditions cited by the respondent (e.g., if a respondent with asthma also indicates that they suffer from COPD, they are given the value 1 for this variable).[22] For each health condition, the estimated population with each condition in Table 2.3 is then multiplied by the average annual number of marginal GP consultations to derive a population-level estimate of the average annual number of GP consultations for each health condition (Table 2.4).

Growing Up in Ireland

Growing Up in Ireland (GUI) is a longitudinal study that follows the progress of two distinct cohorts of children and young people: Cohort ’98 and Cohort ’08.[23] Cohort ’98 comprises over 8,500 young people born in 1998 who were first surveyed at the age of nine. Cohort ’08 comprises over 11,000 children born in 2008, first surveyed at nine months old. Both cohorts have been followed up every two to three years, with six waves of data collection completed to date for Cohort ’98 and seven waves of data collection completed for Cohort ’08.[24]

All waves for Cohort ’98 and Cohort ’08 were made available to the authors through the Irish Social Science Data Archive (ISSDA). As children and young people were surveyed at different ages and time periods in GUI, it is challenging to derive an estimate of: a) the relevant population with asthma among those aged 0–14; and b) the average annual number of GP visits for those aged 0–14. We rely on the most up-to-date information and, for that reason, use the younger Cohort ’08. For Cohort ’08, waves 1 to 6 correspond with the ages of 9 months, 3 years, 5 years, 7 years, 9 years and 13 years. Since asthma cannot be easily diagnosed in children under 2 years of age (Asthma Society of Ireland, 2019), we omit wave 1. We also omit wave 4 (age 7), as it was administered via a postal survey and did not ask any healthcare-related questions, and wave 6 (age 13), which did not ask directly ask about asthma and which was administered via telephone.[25] Therefore, in this report, we use waves 2 (3 years), 3 (5 years) and 5 (9 years) from Cohort ’08 to derive an estimate of a) the relevant population with asthma and b) GP visiting rates among those aged 0–14.

We use the information in GUI to identify the average GP utilisation associated with asthma in children and young people aged 0–14. In each wave, the child’s primary caregiver (PCG) was asked questions about the study child’s health. We

22 Full regression results are available in Appendix B.
23 A new birth cohort, Cohort ’24, will begin data collection later in 2024.
24 See https://www.growingup.gov.ie/ for further details. For both cohorts, a shorter online COVID survey was also carried out in December 2020 (but this did not collect information on GP visiting behaviour).
25 Ideally, we would have used wave 2 (age 13) of the ’98 Cohort to infer asthma diagnoses and GP visiting rates for those in early adolescence; however, the questionnaire did not ask directly about asthma (and was also collected in 2011, over 10 years ago).

derive an indicator for ‘asthma’ based on responses to two questions as follows. First, the PCG is asked:

> ‘Does <child> have any longstanding illness, condition or disability?’

If the answer was ‘yes’, the PCG was then asked:

> ‘What longstanding illness, condition or disability does <child> have?’

The PCG was presented with a card that lists various conditions, including asthma. We then derived an estimate of the 0–14 years population with asthma using data on age groups from Census 2022 (see Table 2.3).

In waves 2, 3 and 5 of Cohort ’08, the PCG was asked about the child’s GP visiting behaviour, using the following question:

> ‘In the last 12 months, how many times have you seen or talked on the telephone with a general practitioner about <child’s> physical or emotional health?’

As not all GP visits for a child with asthma will be due to that condition (e.g., a child with asthma could also visit the GP for diagnosis and treatment of another, unrelated, condition), we use regression analysis to calculate the marginal (additional) number of GP visits for asthma. For each health condition, we estimate a linear regression of the annual number of GP visits, controlling for age (wave), sex, medical card status and multimorbidity.[26] For each health condition, the estimated population with asthma in Table 2.3 is then multiplied by the average annual number of GP consultations to derive a population-level estimate of the average annual number of GP consultations (see Table 2.4).

26 The full regression results are shown in Appendix B.

TABLE 2.4 GP VISITS FOR POPULATION WITH CIRCULATORY AND RESPIRATORY DISEASES

Healthcare condition	Estimated population (n)	Marginal GP visits	Population-level GP visits
Asthma (aged 0–14)	73,379	2.03	149,084
COPD (aged 25+)	85,642	4.76	407,909
IHD (aged 25+)	180,660	2.75	497,136
Stroke (aged 25+)	48,396	3.68	178,096
Asthma (aged 15+)	276,808	2.04	564,430

Notes: See Table 2.3 for details on how the population estimates are derived, and Appendix B for full regression results, which inform the estimates of marginal GP visits per annum.

Cost

Information on the unit costs of GP care are sourced from a published analysis of the unit costs of a comprehensive range of non-acute healthcare services over the period 2016–2019 (Smith et al., 2021). Two estimates of GP unit costs are provided, reflecting the different financing systems for GP care in Ireland. Those with access to a medical card or GP visit card ('public' patients) are entitled to free GP appointments, for which the GP is reimbursed by the Primary Care Reimbursement Service (PCRS). For those without a medical or GP visit card ('private' patients), the patient pays the full out-of-pocket cost. In 2019, it was estimated that the unit cost of a public GP visit was €46,[27] while the unit cost of a private GP visit was €50 (Smith et al., 2021). We uprate these values to 2023 prices using the Central Statistics Office's Consumer Price Index. Using data from GUI and Healthy Ireland on the proportion of those with each health condition who have a medical/GP visit card, we can derive an average GP unit cost per health condition (see Table 2.5).

TABLE 2.5 GP UNIT COSTS FOR CIRCULATORY AND RESPIRATORY DISEASE

Healthcare condition	% with a medical/GP visit card	Average GP unit cost (€)
Asthma (aged 0–14)	53.1	54.86
COPD (aged 25+)	63.5	54.38
IHD (aged 25+)	62.6	54.43
Stroke (aged 25+)	66.2	54.26
Asthma (aged 15+)	50.5	54.98

Source: Authors' calculations.

2.3.3 Community pharmaceuticals

In order to estimate the healthcare costs of community pharmaceuticals prescribed for the treatment of the conditions listed in Table 2.1, we adopt an alternative bottom-up costing methodology. We do this because there is no population-representative data on community pharmaceutical use that can be linked to disease diagnoses. In addition, while the PCRS collects data on all

27 An alternative estimate of €49 is also derived, but this includes the cost of services that are publicly funded (e.g., childhood immunisations) and that are available to all residents, not just those with medical or GP visit cards.

community pharmaceuticals dispensed under the community drug schemes, those who pay out-of-pocket for community pharmaceuticals are excluded. We conducted a literature search to identify the relevant pharmaceutical treatment guidelines for each health condition, used population numbers from Healthy Ireland and GUI (Table 2.3) to derive the relevant population, and then used cost data from the PCRS to derive an annual community pharmaceutical treatment cost for each healthcare condition.

Medication utilisation was estimated based on treatment recommendations in applicable clinical guidelines. Applicable guidelines were identified by conducting a search for the most recent version of guidelines that applied to Ireland covering each of the included conditions. A base case of typical treatment was defined based on treatment recommendations for each condition. In the case of stroke and IHD, the recommendations that apply in general for these conditions were used. In the case of asthma and COPD, where treatment varies by step or group based on classification and severity of the condition, the recommendation that applies to the starting step of treatment (asthma, step 2) and the most prevalent group (COPD, group B) was adopted.

Where specific medications were recommended at a specified dosage, these were included in the typical treatment. Where no dosage was specified, the product licence (summary of product characteristics) for Ireland was consulted and the specified dosage indicated for the condition was used if available; alternatively, the World Health Organization's (WHO) defined daily dosage was used (a measure to assess drug utilisation across populations). Where recommendations related to a drug class, rather than a specific drug, a specific medication was selected based on guidance from the HSE, either via the Medicines Management Programme's Prescribing and Cost Guidance (inhaled medications for asthma and COPD), or the Medicines Management Programme's Preferred Drug initiative. Any dosage recommendations from this guidance were used in the absence of other recommendations, followed by the product licence recommendation, and the WHO defined daily dosage. Where a combination of medications was recommended in the guideline, as was the case for management of asthma and COPD, the HSE recommended combination product (i.e., one inhaler containing more than one medication/drug) was selected. In other cases, where no specific product recommendation exists, the product at the specified dosage with the lowest reimbursement cost per the HSE PCRS was selected.

The cost for each product was assigned as the reimbursement cost for a one-month supply for oral dosage forms such as tablets or one inhaler per month for inhaled medicines, plus a dispensing fee and multiplied by 12 to obtain an annual cost.[28]

Several alternative complex scenarios were examined. First, the base case was adjusted for medications that are recommended to be used on an as needed/as required basis (pro re nata). Instead of including the cost of one dispensing per month, this was adjusted to include a dispensing 75 per cent of the time, recognising that some patients will still require monthly dispensing, while others may require dispensing every second month or less frequently. Next, a more complex case was developed for each condition. For IHD and stroke, additional recommendations that apply in certain circumstances or to certain patients were incorporated; rather than assuming all patients with this condition received the standard treatment, it assumed a proportion of patients received alternative treatment (for example regarding stroke, replacing antiplatelet treatment with anticoagulant treatment, which is recommended for the estimated 33 per cent of patients with both this condition and atrial fibrillation). For asthma and COPD, rather than assuming that all patients were treated as per the recommendations for the starting step or most common group, the treatment recommendations for each step/group were costed, and a weighted average was used based on the prevalence of each asthma step/COPD stage reported in the literature in other countries. In the case of asthma for children, different recommendations apply to those aged 0–5 years and 6–11 years, so these were costed separately, and then a weighted average was used for asthma in children based on the relative proportion of these age groups in the Irish population according to the 2022 Census. Last, the complex case was also adjusted for pro re nata medications. See Table C1 in Appendix C for details of the inputs into each case for each conditions, and Table C2 for the total cost of each case for each condition.

28 The reimbursement cost was calculated using the National Centre for Pharmacoeconomics' recommendation from their Guidelines for Inclusion of Drug Costs in Pharmacoeconomic Evaluations of €5.48 as the mean dispensing fee for medications dispensed on state drug schemes in 2018.

TABLE 2.6 COMMUNITY PHARMACEUTICAL TREATMENT PLANS FOR CIRCULATORY AND RESPIRATORY DISEASE

Healthcare condition	Recommended treatment cost per annum
Asthma (aged 0–14)	€262
COPD (aged 25+)	€649
IHD (aged 25+)	€473
Stroke (aged 25+)	€339
Asthma (aged 15+)	€358

Source: Authors' calculations.

2.4 IDENTIFICATION OF DISEASE BURDEN ATTRIBUTABLE TO POOR AIR QUALITY

In the previous sections, we have outlined: a) how the list of health conditions with causal links to poor air quality were identified; and b) how the associated population prevalence, healthcare utilisation and costs were derived. However, only a fraction of the healthcare utilisation (and associated costs) of a particular health condition can be attributed to poor air quality. We use published estimates of the population attributable fraction (PAF) for each of the six risk–outcome pairs used in our analysis. The PAF represents the share of the environmental burden of disease attributable to the relevant environmental exposure (e.g., $PM_{2.5}$), and reflects the proportion of the outcome (disease) that could be averted if the exposure was eliminated (Matthay et al., 2021). It is a function of the relative risk associated with a particular exposure and is expressed as: $PAF = \frac{P_e(RR-1)}{(1+P_e)RR'}$, where P_e is the population exposed and RR is the relative risk estimate. Table 2.7 documents the PAFs for each of the six risk–outcome pairs.[29]

TABLE 2.7 POPULATION ATTRIBUTABLE FRACTIONS FOR POOR AIR QUALITY RISK–OUTCOME PAIRS

Risk–outcome pair	PAFs
1. $PM_{2.5}$ Asthma (aged 0–14)	0.075
2. $PM_{2.5}$ COPD (aged 25+)	0.079
3. $PM_{2.5}$ IHD (aged 25+)	0.011
4. $PM_{2.5}$ Stroke (aged 25+)	0.049
5. NO_2 Stroke (aged 25+)	0.023
6. NO_2 Asthma (aged 15+)	0.044

Source: Kienzler et al. 2022.

29 For each risk–outcome pair, a range of estimates are provided (low, mean, high) that reflect the uncertainty in the underlying parameters; we rely on the mean estimate.

2.5 SUMMARY

This chapter provides an overview of the data and methods required to derive estimates of the healthcare costs of healthcare conditions with causal links to air pollution, namely, asthma, COPD, IHD and stroke. Due to data issues, three broad types of healthcare were considered: emergency inpatient hospitalisations, GP care and community pharmaceuticals. The data and methods used to derive estimates of annual healthcare utilisation and costs for each service type illustrate a range of different approaches, each with their own strengths and weaknesses. In the chapter that follows, we present and discuss the results on costs.

CHAPTER 3

Results

3.1 INTRODUCTION

This chapter presents the results of the analysis of the annual costs of care for healthcare conditions linked to poor air quality, for three broad types of healthcare: a) emergency inpatient hospitalisations; b) general practitioner (GP) care; and c) community pharmaceuticals. As described in the previous chapter, evidence from the international literature was used to identify health conditions with causal links to poor air quality (and estimates of the proportion of diagnoses attributable to poor air quality). A variety of administrative and survey data sources and published literature were used to gather information on healthcare utilisation, costs and the relevant populations.

3.2 EMERGENCY INPATIENT HOSPITALISATIONS

Table 3.1 presents the results of the analysis of the annual costs (expressed in 2023 prices) of emergency inpatient care. An alternative metric of emergency inpatient hospital resource use – bed days – is also presented. For information, Table D1 in Appendix D presents additional data, including annual discharges, cost and bed days for all discharges in each risk–outcome pair (i.e., not just those related to air pollution), and the respective population attributable fractions (PAFs).

TABLE 3.1 ANNUAL COST AND BED DAYS OF EMERGENCY INPATIENT CARE ASSOCIATED WITH POOR AIR QUALITY

Risk–outcome pair	Annual discharges	Annual cost	Annual bed days
$PM_{2.5}$ Asthma (aged 0–14)	115	€407,151	203
$PM_{2.5}$ COPD (aged 25+)	1,204	€8,393,987	9,194
$PM_{2.5}$ IHD (aged 25+)	128	€1,067,859	728
$PM_{2.5}$ Stroke (aged 25+)	346	€5,746,361	5,440
NO_2 Stroke (aged 25+)	163	€2,697,271	2,553
NO_2 Asthma (aged 15+)	107	€416,469	328

Source: Authors' calculations.

The most resource-intensive risk–outcome pair is for $PM_{2.5}$ air pollution-related discharges for chronic obstructive pulmonary disease (COPD), which accounted for an average of 9,194 bed days, and cost an average of €8.4m per annum. Emergency inpatient hospitalisations for stroke that can be attributed to $PM_{2.5}$ air pollution accounted for an average of 5,440 bed days, and cost an average of €5.8m per annum. Other risk–outcome pairs (e.g., hospitalisations for asthma for children aged 0–14) accounted for much smaller shares of total resources. Across the four risk–outcome pairs that relate to $PM_{2.5}$ air pollution, emergency inpatient hospitalisations accounted for 15,565 bed days per annum, and cost an average of €15.6m. For nitrogen dioxide (NO_2) related emergency inpatient hospitalisations, the respective figures were 2,881 bed days and €3.1m. To put these figures in context, in 2019, total expenditure on acute hospital services in Ireland (emergency and elective inpatient, as well as day patient and outpatient, care) amounted to €6.8bn (HSE, 2020), and total emergency inpatient bed days amounted to 2.8m (HPO, 2020).

The variation in total costs across risk–outcome pairs reflects differences in the number of discharges, the PAF, length of stay (LOS), diagnosis-related groups (DRGs) and associated activity-based funding (ABF) costs for each risk–outcome pair. For bed days, resource use for each risk–outcome pair is a function of the PAF, the number of discharges and the average LOS. For example, while a similar share of hospitalisations for asthma for children aged 0–14 and hospitalisations for COPD for adults aged 25+ are estimated to be attributable to PM2.5 air pollution (7.5 and 7.9 per cent respectively; see Table 2.7), the combination of shorter average LOS and fewer discharges means that the total bed days for asthma hospitalisations for children aged 0–14 are considerably fewer than for COPD discharges for adults aged 25+. Similarly, the higher share of asthma hospitalisations attributable to air pollution among children aged 0–14 (compared with adults aged 25+) means that total costs for the treatment of hospitalisations for asthma for children aged 0–14 and for adults aged 15+ are broadly similar, despite the fact that fewer children are hospitalised for asthma overall than adults.

3.3 GP CARE

Table 3.2 presents the results of the analysis of the annual costs (expressed in 2023 prices) of GP care, while Table D2 in Appendix D presents additional data, including annual GP visits for all discharges for each risk–outcome pair (i.e., not just those related to air pollution), and the respective PAFs.

TABLE 3.2 ANNUAL COST OF GP CARE ASSOCIATED WITH POOR AIR QUALITY

Risk–outcome pair	Annual GP visits	Annual cost (€)
$PM_{2.5}$ Asthma (aged 0–14)	11,181	613,417
$PM_{2.5}$ COPD (aged 25+)	32,225	1,752,542
$PM_{2.5}$ IHD (aged 25+)	5,468	297,631
$PM_{2.5}$ Stroke (aged 25+)	8,727	473,494
NO_2 Stroke (aged 25+)	4,096	222,252
NO_2 Asthma (aged 15+)	24,835	1,365,431

Source: Authors' calculations.

As for emergency inpatient hospital care, the most resource intensive risk–outcome pair relates to $PM_{2.5}$ air pollution and COPD, accounting for over 32,225 GP visits per annum at a cost of €1.8m. Overall, the four conditions causally linked to $PM_{2.5}$ air pollution account for a total of nearly 60,000 GP consultations per annum, at a cost of over €3.1m. Conditions linked to NO_2 air pollution (i.e., stroke and asthma in adults) accounted for 28,941 annual GP visits and cost €1.6m per annum. To put these figures in context, it was estimated that there were 18.8m GP consultations in Ireland in 2019, with a total expenditure of €875.5m (Walsh et al., 2021).

3.4 COMMUNITY PHARMACEUTICALS

Table 3.3 presents the results of the analysis of the annual costs (expressed in 2023 prices) of community pharmaceuticals (see Table D3 in Appendix D for additional data, including the relevant PAFs).

TABLE 3.3 ANNUAL COST OF COMMUNITY PHARMACEUTICALS ASSOCIATED WITH POOR AIR QUALITY (BASE CASE)

Risk–outcome pair	Annual cost (€)
$PM_{2.5}$ Asthma (aged 0-14)	1,441,897
$PM_{2.5}$ COPD (aged 25+)	4,390,951
$PM_{2.5}$ IHD (aged 25+)	939,974
$PM_{2.5}$ Stroke (aged 25+)	803,906
NO_2 Stroke (aged 25+)	377,344
NO_2 Asthma (aged 15+)	4,360,280

Source: Authors' calculations.

The most resource intensive risk–outcome pair relates to $PM_{2.5}$ air pollution and COPD, accounting for almost €4.4m in community pharmaceuticals costs. This is very closely followed by NO_2 air pollution and asthma in adults, accounting for over €4.3m. Overall, the four conditions causally linked to $PM_{2.5}$ air pollution account for a total of almost €7.6m in community pharmaceuticals per annum, compared to over €4.7m for the two conditions linked to NO_2 air pollution (i.e., stroke and asthma in adults).

Table D4 in Appendix D presents the results for the base case scenarios accounting for 'as needed' use of medicines, and the more complex treatment cases, with and without 'as needed' use. For $PM_{2.5}$ and COPD, the annual costs ranged from €3.9m to €4.2m across these alternative scenarios, whereas for NO_2 and asthma in adults, the range was €3.3m to €5.3m. The total annual cost for $PM_{2.5}$ linked conditions ranged from €7.2m to €7.9m, while for NO_2 linked conditions the total annual cost ranged from €3.6m to €5.8m.

3.4 SUMMARY

In this chapter, estimates of the annual emergency inpatient, GP and community pharmaceutical costs for the treatment of six risk–outcome pairs were presented. The range of estimates reflects not only differences in the costs of each healthcare type, but also differences in the underlying data and methods used to derive the estimates, with each type of healthcare service using different data and methods. Direct comparisons between types of healthcare are difficult to make, as the underlying data and methodology differ. However, it is clear that while the intensity of resource use for each health condition for GP and community pharmaceutical care is much greater than for emergency inpatient hospital care (in terms of annual number of consultations/discharges), emergency inpatient hospital care is much more expensive in terms of annual cost to the healthcare system.

The next chapter summarises the main results, outlines the strengths and limitations of the different costing approaches, and makes a number of recommendations for future data collection and research activities that could help to refine and further develop future estimates of the healthcare costs of air pollution-related conditions in Ireland.

CHAPTER 4

Summary and discussion

4.1 SUMMARY OF MAIN FINDINGS

Although air pollution has decreased in most European countries over the past two decades, including Ireland, levels of ambient air pollution in Ireland remain above the World Health Organization's (WHO) air quality guidelines (AQGs) in many cities and towns (EPA, 2022, 2023). There have been some assessments of the mortality burden associated with ambient air pollution in Ireland (EEA, 2019, 2022; Goodman et al., 2023),[30] and the global burden of disease (GBD) network publishes periodic assessments of the mortality and morbidity burden of (ambient and household) air pollution (Murray et al., 2020). However, a lack of evidence remains on the broader healthcare costs associated with ambient air pollution in Ireland. Quantifying the potential impact of air pollution on healthcare costs is important for future policy and resource planning, and for targeting of mitigation measures and public health campaigns (Pimpin et al., 2018; World Bank, 2022).

In this report, we described the data and methods available to estimate the healthcare costs of air pollution in Ireland, focusing on three important types of healthcare utilisation: emergency inpatient hospital care; general practitioner (GP) care; and community pharmaceuticals. We used a mixture of administrative and survey data on healthcare utilisation and costs, supplemented with data on the burden of ill-health attributed to air pollution for specific conditions with causal links to air pollution (e.g., asthma) to assess the healthcare utilisation and costs associated with treating conditions that are linked with poor air quality in Ireland.

While direct comparisons between the three types of healthcare utilisation examined in this report cannot be made, due to differences in data and methodologies, a number of key findings can be identified. For emergency inpatient hospital care, $PM_{2.5}$ and chronic obstructive pulmonary disease (COPD) is the most resource-intensive risk–outcome pair, reflecting a relatively high population attributable fraction (PAF), number of emergency hospital discharges and cost complexity. The same is also true for GP and community pharmaceutical care, and while overall contact with GP and community pharmaceutical services is far greater than for emergency inpatient hospitalisations, the much higher unit costs of emergency inpatient care are reflected in much higher overall costs.

30 Using data for 2019, Goodman et al. (2023) estimate that approximately 1,700 premature deaths (680 from cardiovascular disease) per annum in Ireland can be attributable to exposure to PM2.5. These premature mortality estimates for PM2.5 are higher than those published by the EEA or the GBD study, which ranged from 535 to 1,300 (EEA, 2019, 2022; Murray et al., 2020a). This reflects the authors' use of updated dose response functions based on growing research evidence that exposure to PM2.5 is more harmful than previously thought.

4.2 LIMITATIONS

As with any analysis using a variety of data sources and methods, there are inevitable strengths and limitations. Ideally, population disease registers and linked administrative healthcare utilisation and cost data would be available in order to identify the population diagnosed with health conditions that are linked to poor air quality, their healthcare utilisation and associated costs. In the absence of such data, we used a mixture of administrative and survey data on healthcare utilisation and costs, supplemented with data on the burden of ill-health attributed to air pollution for specific conditions with causal links to air pollution (e.g., asthma) to assess the healthcare utilisation and costs associated with treating conditions that are linked with poor air quality in Ireland.

The analysis focused on three important elements of healthcare utilisation in Ireland: emergency inpatient care; GP care; and community pharmaceuticals. Other types of care were omitted due to an absence of data. For example, Hospital In-Patient Enquiry (HIPE) collects data on day patient and in-patient discharges in public hospitals only, which necessarily omits other hospitalisations (e.g., emergency department visits, outpatient visits and attendances in private hospitals) that may also be attributable to air pollution. For primary care, we focused only on GP care, but individuals may also consult practice nurses (or other community healthcare professionals) for treatment. The public–private mix in healthcare financing and delivery in Ireland further complicates the analysis. For example, regarding the analysis of community pharmaceutical costs, a bottom-up costing methodology was adopted; this was due to the absence of a comprehensive population-representative database of community pharmaceutical use or suitable survey data on reported pharmaceutical use or that are linked to administrative pharmacy claims data. Such sources would likely provide a more accurate estimate, reflecting true treatment patterns rather than assuming that all patients receive recommended treatment, while also capturing intermittent medication use (e.g., for treating infections or exacerbations due to their condition).

While administrative data (such as from HIPE) ensure that the relevant population and healthcare utilisation associated with a particular health condition are easily identified (using ICD-10-AM diagnostic codes), survey data (such as from Healthy Ireland and *Growing Up in Ireland* (GUI)) rely on self-reported information on diagnoses and healthcare utilisation (often with differences in question wording and response categories over time). However, for both emergency inpatient and GP care, it is possible that the estimates both overestimate and underestimate healthcare utilisation associated with a particular condition; for example, the HIPE analysis focused on primary diagnoses only, while survey data estimates of utilisation from Healthy Ireland and GUI are likely not controlling adequately for healthcare utilisation associated with other health conditions. A key difficulty arose in generating estimates of the relevant population with a particular health condition for the analyses of GP and community pharmaceutical costs – in both cases, the relevant population refers to those who self-reported that they 'suffered' from the condition over the previous 12 months (which reflects both population prevalence and incidence).

Finally, as the evidence base for the harmful effects of air pollution is most robust for circulatory and respiratory diagnoses, the analysis in this report focused on these conditions. However, there is emerging evidence of the harmful effects of ambient air pollution on other aspects of physical and mental health (see Chapter 1), an issue that could be incorporated into future analyses. While we use PAF estimates from the European Environment Agency (EEA) to estimate the share of discharges within each risk–outcome pair attributable to the various air pollutants, there is a wide variety of PAF estimates in the available literature.[31] In addition, with the data available to us, it is not possible to distinguish the short- and long-term effects of exposure to air pollution on healthcare utilisation. For instance, for a diagnosis such as asthma, symptoms can arise from contemporaneous exposure (as quickly as one hour of exposure), from cumulative exposure over several days, or several days after exposure (Neidell, 2009). In addition, if people respond to higher pollution levels by increasing avoidance behaviour, then the estimated effect of pollution on health and healthcare utilisation can be biased downwards, and the full cost of pollution exposure will, therefore, be underestimated (Moretti and Neidell, 2011).[32]

4.3 CONCLUSIONS

Despite these limitations, the data and methodological approach used in this report, while incomplete, provide a framework that can be used to inform future data collection and research studies on this issue. Future work could expand the analysis to include other types of healthcare utilisation (e.g., practice nurse visits), other risk–outcome pairs (e.g., $PM_{2.5}$ air pollution and lung cancer), and assess the sensitivity of the findings to alternative assumptions about PAFs, population prevalence and healthcare utilisation.

31 See Box 2.5 in OECD (2020a) for a good discussion of the implications of differences in PAF estimates for differences in estimates of the mortality burden of air pollution across Europe.

32 Indeed, Neidell (2004, 2009) show how individuals respond to 'smog alerts' in California by reducing outdoor interactions, with the result that the estimated effects of O3 concentrations on hospitalisation rates for children and older people in particular are biased downwards.

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APPENDIX A

Healthy Ireland health condition questions

FIGURE A1 WAVE 1 (2015) CONDITION CARD

Q.4 Have you suffered from any of the following conditions in the past 12 months?
SHOW CARD Q.4

Asthma (allergic asthma included)
Chronic bronchitis, chronic obstructive pulmonary disease (COPD), emphysema
Heart Attack or chronic consequences of heart attack
High blood pressure
A stroke or the chronic consequences of stroke (cerebral hemorrhage or cerebral thrombosis)
Arthrosis (excluding arthritis)
Arthritis
Lower back disorder or other chronic back defects
Neck disorder or other chronic neck defects
Diabetes
Allergy, such as rhinitis, hay fever, eye inflammation, dermatitis, food allergy or other (allergic asthma excluded)
Cirrhosis of the liver
Urinary incontinence or problems in controlling the bladder
Kidney problems
Depression
None of these

FIGURE A2 WAVE 2 (2016) CONDITION CARD

Q.4 Have you suffered from any of the following conditions in the past 12 months?
SHOW CARD Q.4

Asthma (allergic asthma included)
Chronic bronchitis, chronic obstructive pulmonary disease (COPD), emphysema
Heart Attack or chronic consequences of heart attack
High blood pressure
A stroke or the chronic consequences of stroke (cerebral hemorrhage or cerebral thrombosis)
Arthrosis (excluding arthritis)
Arthritis
Lower back disorder or other chronic back defects
Neck disorder or other chronic neck defects
Diabetes
Allergy, such as rhinitis, hay fever, eye inflammation, dermatitis, food allergy or other (allergic asthma excluded)
Cirrhosis of the liver
Urinary incontinence or problems in controlling the bladder
Kidney problems
Depression
None of these

FIGURE A3 WAVE 4 (2018) CONDITION CARD

Q.4 Do you currently have any of the following conditions that has been confirmed by a medical diagnosis?

SHOW CARD B3

Chronic lung disease such as chronic bronchitis or emphysema	
Asthma	
Arthritis (including osteoarthritis, or rheumatism)	
Osteoporosis, sometimes called thin or brittle bones	
Cancer or a malignant tumour (including leukaemia or lymphoma but excluding minor skin cancers)	
Parkinson's disease	
Any emotional, nervous or psychiatric problems, such as depression or anxiety	
Alcohol or substance abuse	
Alzheimer's disease	
Dementia, organic brain syndrome, senility	
Serious memory impairment	
Stomach ulcers	
Varicose Ulcers (an ulcer due to varicose veins)	
Cirrhosis, or serious liver damage	
High blood pressure or hypertension	
Angina	
A heart attack (including myocardial infarction or coronary thrombosis)	
Congestive heart failure	
Diabetes or high blood sugar	
A stroke (cerebral vascular disease)	
Ministroke or TIA	
High cholesterol	
A heart murmur	
An abnormal heart rhythm	
Any other heart trouble (specify)	
DK	
RF	
None of these	

FIGURE A4 WAVE 5 (2019) CONDITION CARD

Q.4 Do you currently have any of the following conditions that has been confirmed by a medical diagnosis?

SHOW CARD B3

Chronic lung disease such as chronic bronchitis or emphysema	
Asthma	
Arthritis (including osteoarthritis, or rheumatism)	
Osteoporosis, sometimes called thin or brittle bones	
Cancer or a malignant tumour (including leukaemia or lymphoma but excluding minor skin cancers)	
Parkinson's disease	
Any emotional, nervous or psychiatric problems, such as depression or anxiety	
Alcohol or substance abuse	
Alzheimer's disease	
Dementia, organic brain syndrome, senility	
Serious memory impairment	
Stomach ulcers	
Varicose Ulcers (an ulcer due to varicose veins)	
Cirrhosis, or serious liver damage	
High blood pressure or hypertension	
Angina	
A heart attack (including myocardial infarction or coronary thrombosis)	
Congestive heart failure	
Diabetes or high blood sugar	
A stroke (cerebral vascular disease)	
Ministroke or TIA	
High cholesterol	
A heart murmur	
An abnormal heart rhythm	
Any other heart trouble (specify)	
Don't Know	
Refused	
None of these	

APPENDIX B

GP regression estimates

TABLE B1 0–14 ASTHMA FROM *GROWING UP IN IRELAND*

GP annual	Coefficient	Std. err.	t	P>t	[95% conf. interval]	
Asthma	2.03	0.056	36.02	0.00	1.921	2.142
Gender	-0.23	0.027	-0.86	0.00	-0.076	0.029
Age	-0.26	0.005	-45.36	0.00	-0.269	-0.247
Medical card	0.29	0.019	15.46	0.00	0.258	0.332
Additional conditions	0.65	0.059	10.90	0.00	0.533	0.768
Cons	2.98	0.035	83.98	0.00	2.909	3.049

TABLE B2 15+ ASTHMA FROM HEALTHY IRELAND

GP annual	Coefficient	Std. err.	t	P>t	[95% conf. interval]	
Asthma	2.04	0.198	10.29	0.00	1.651	2.428
Gender	-1.22	0.099	-12.24	0.00	-1.415	-1.025
Age	0.06	0.003	23.51	0.00	0.059	0.070
Medical card	1.14	0.102	11.16	0.00	0.942	1.343
Additional conditions	4.61	0.374	12.33	0.00	3.874	5.338
Wave	-0.04	0.032	-1.35	0.177	-0.105	0.019
Cons	1.32	0.176	7.51	0.00	0.978	1.669

TABLE B3 25+ COPD FROM HEALTHY IRELAND

GP annual	Coefficient	Std. err.	t	P>t	[95% conf. interval]	
COPD	4.76	0.405	11.25	0.00	3.969	5.557
Gender	-1.09	0.106	-10.35	0.00	-1.305	-0.889
Age	0.07	0.004	20.15	0.00	0.061	0.075
Medical card	1.15	0.109	10.56	0.00	0.939	1.368
Additional conditions	3.27	0.407	8.02	0.00	2.467	4.062
Wave	-0.06	0.034	-1.78	0.075	-0.127	0.006
Cons	1.13	0.208	5.41	0.00	0.718	1.554

TABLE B4 25+ HEART ATTACK FROM HEALTHY IRELAND

GP annual	Coefficient	Std. err.	t	P>t	[95% conf.	interval]
Heart attack	2.75	0.286	9.52	0.00	2.129	3.332
Gender	-1.16	0.106	-10.92	0.00	-1.369	-0.952
Age	0.07	0.003	18.98	0.00	0.058	0.072
Medical card	1.14	0.109	10.37	0.00	0.921	1.350
Additional conditions	4.29	0.381	11.28	0.00	3.551	5.045
Wave	-0.11	0.034	-3.11	0.002	-0.173	-0.04
Cons	1.43	0.211	6.77	0.00	1.015	1.842

TABLE B5 25+ STROKE FROM HEALTHY IRELAND

GP annual	Coefficient	Std. err.	t	P>t	[95% conf.	interval]
Stroke	3.68	0.539	6.84	0.00	2.631	4.745
Gender	-1.13	0.106	-10.64	0.00	-1.339	-0.923
Age	0.07	0.003	20.34	0.00	0.006	0.076
Medical card	1.17	0.109	10.66	0.00	0.953	1.382
Additional conditions	4.62	0.383	12.06	0.00	3.869	5.372
Wave	-0.07	0.034	-2.16	0.00	-0.139	-0.006
Cons	1.18	0.208	5.65	0.00	0.769	1.587

APPENDIX C

Community pharmaceutical treatment guidelines

TABLE C1 COMMUNITY PHARMACEUTICALS TREATMENT SCENARIOS WITH COST INPUTS

Condition	Recommended agent	Actual product	Monthly cost price	Cost basis	Annual cost (incl. dispensing fee)	Source of product choice
Asthma (aged 6–14)	Global Initiative for Asthma (GINA) 2024 guideline					
Base case	Step 2: Low dose maintenance ICS	Flixotide evohaler 50mcg	7.57	1xinhaler	156.6	MMP Guidance Inhaled Medicines for COPD
	Step 1–5: Reliever short-acting beta agonist as needed	Ventolin Evohaler 100 mcg. 200 Dose Aerosol	2.53	1xinhaler	96.12	Lowest cost generic
	Step 1–5: Spacer device annually	Volumatic spacer device	3.34	1xinhaler	8.82	Lowest cost generic
Complex case	Step 1: Low dose maintenance ICS as needed	Flixotide evohaler 50mcg	7.57	1xinhaler	156.6	MMP Guidance Inhaled Medicines for COPD
	Step 1: Reliever short-acting beta agonist as needed	Ventolin Evohaler 100 mcg. 200 Dose Aerosol	2.53	1xinhaler	96.12	Lowest cost generic
	Step 3: Low dose ICS-LABA	Bufomix easyhaler 80/4.5	24.35	1xinhaler	357.96	MMP Guidance Inhaled Medicines for COPD
	Step 4: Medium dose ICS-LABA	Bufomix easyhaler 160/4.5	25.06	1xinhaler	366.48	MMP Guidance Inhaled Medicines for COPD
	Step 5: High dose ICS-LABA	Bufomix easyhaler 320/9	25.06	1xinhaler	366.48	MMP Guidance Inhaled Medicines for COPD
Asthma (aged 0–5)	Global Initiative for Asthma (GINA) 2024 guideline					
Base case	Step 2: Low dose maintenance ICS	Flixotide evohaler 50mcg	7.57	1x inhaler	156.6	MMP Guidance Inhaled Medicines for COPD

TABLE C1 (CONTD.) COMMUNITY PHARMACEUTICALS TREATMENT SCENARIOS WITH COST INPUTS

Condition	Recommended agent	Actual product	Monthly cost price	Cost basis	Annual cost (incl. dispensing fee)	Source of product choice
	Step 2–4: Reliever short-acting beta agonist as needed	Ventolin Evohaler 100 mcg. 200 Dose Aerosol	2.53	1xinhaler	96.12	Lowest cost generic
	Step 1–5: Spacer device annually	Volumatic spacer device	3.34	1xinhaler	8.82	Lowest cost generic
Complex case	Step 1: Reliever short-acting beta agonist as needed	Ventolin Evohaler 100 mcg. 200 Dose Aerosol	2.53	1xinhaler	96.12	Lowest cost generic
	Step 3: Double low dose ICS	Flixotide Evohaler 50mcg	7.57	2xinhaler	313.2	MMP Guidance Inhaled Medicines for COPD
	Step 4: Step 3 plus Leukotriene receptor agonist	Montelair 4mg chewable tabs	5.04	28x4mg	126.24	Lowest cost generic
COPD	Global Initiative for Chronic Obstructive Lung Disease (GOLD) 2024 guideline					
Base case	All groups: Short acting beta agonist (rescue)	Ventolin Evohaler 100 mcg. 200 Dose Aerosol	2.53	1xinhaler	96.12	Lowest cost generic
	Group B: LABA + LAMA combination	Anoro Ellipta	40.62	1xinhaler	553.2	MMP Prescribing Tips and Tools Inhaled Medicine for COPD
Complex case	Group A: Bronchodilator – LABA or LAMA	Incruse Ellipta or	29.22	1xinhaler	416.4	MMP Prescribing Tips and Tools Inhaled Medicine for COPD
		Oxis Turbohaler 12mcg	20.11	1xinhaler	307.08	MMP Prescribing Tips and Tools Inhaled Medicine for COPD
	Group E: LABA + LAMA combination	Anoro Ellipta	40.62	1xinhaler	553.2	MMP Prescribing Tips and Tools Inhaled Medicine for COPD
	Alt Group E: LABA/LAMA/ICS (56%)	Trelegy Ellipta	53.35	1xinhaler	705.96	MMP Prescribing Tips and Tools Inhaled Medicine for COPD
Ischaemic heart disease	2019 ESC Guidelines for the diagnosis and management of chronic coronary syndromes					
Base case	Short-acting nitrate spray	Glytrin spray (lower cost)	4.2	1x200 dose	116.16	Lowest cost generic

TABLE C1 (CONTD.) COMMUNITY PHARMACEUTICALS TREATMENT SCENARIOS WITH COST INPUTS

Condition	Recommended agent	Actual product	Monthly cost price	Cost basis	Annual cost (incl. dispensing fee)	Source of product choice
	Beta-blockers	Preferred drug – bisoprolol, DDD 10mg	2.24	28x10mg	92.64	HSE PDI
	Dihydropyridine calcium channel blocker	Nifedipine/amlodipine DDD 5mg	1.51	28x5mg	83.88	HSE PDI
	Aspirin 75mg		1.03	28x75	78.12	Lowest cost generic
	Statin	Preferred drug – atorvastatin 20mg	3.02	28x20mg	102	HSE PDI
Complex case	Addition of clopidogrel 75mg (6 months post-stent – 87%)[1]	Clopidogrel 75mg	3.91	28x75mg	56.34	Lowest cost generic
	Anticoagulant instead of aspirin (if atrial fibrillation – 12%)[2]	Apixaban Mylan DDD 5mg bd	24.71	56x5mg	362.28	HSE PDI
Stroke	National Clinical Guideline for Stroke for the UK and Ireland					
Base case	Calcium channel blocker based on likely age of onset (55+)	Amlodipine DDD 5mg	1.51	28x5mg	83.88	HSE PDI
	High intensity atorvastatin	Atorvastatin 80mg	6.35	28x80mg	141.96	HSE PDI
	Clopidogrel	Clopidogrel 75mg	3.91	28x75mg	112.68	Lowest cost generic
Complex case	Proportion on ACE inhibitor instead of calcium channel blocker (21%)[3]	Ramipril DDD 2.5mg	1.96	28x2.5mg	89.28	HSE PDI
	Proportion not on statin (27.1%)[4]					
	Proportion on anticoagulant instead of antiplatelet (33.4%)[5]	Apixaban Mylan DDD 5mg bd	24.71	56x5mg	362.28	HSE PDI
Asthma (aged 15+)	Global Initiative for Asthma (GINA) 2024 guideline					
Base case	Step 2: Low dose ICS+formoterol as needed	Bufomix easyhaler 80/4.5	24.35	1xinhaler	357.96	MMP Guidance Inhaled Medicines for COPD

TABLE C1 (CONTD.) COMMUNITY PHARMACEUTICALS TREATMENT SCENARIOS WITH COST INPUTS

Condition	Recommended agent	Actual product	Monthly cost price	Cost basis	Annual cost (incl. dispensing fee)	Source of product choice
Complex case	Step 1: Low dose ICS+formoterol as needed	Bufomix easyhaler 80/4.5	24.35	1xinhaler	357.96	MMP Guidance Inhaled Medicines for COPD
	Step 3: Low dose ICS+formoterol	Bufomix easyhaler 80/4.5	24.35	1xinhaler	357.96	MMP Guidance Inhaled Medicines for COPD
	Step 4: Medium dose ICS+formoterol	Bufomix easyhaler 160/4.5	25.06	1xinhaler	366.48	MMP Guidance Inhaled Medicines for COPD
	Step 5: Step 4 plus LAMA	Elkira Genuair	33.12	1xinhaler	463.2	MMP Guidance Inhaled Medicines for COPD

Notes: ACE: Angiotensin converting enzyme, ICS: inhaled corticosteroid, HSE: Health Service Executive, LAMA: long-acting muscarinic antagonist, LABA: long-acting beta agonist, MMP: Health Service Executive Medicines Management Programme, PDI: Preferred Drug Initiative. DDD=Defined daily dosage.

1 https://doi.org/10.1007/s00392-021-01931-x
2 https://doi.org/10.1093/eurheartj/ehad556
3 https://doi.org/10.1161/STROKEAHA.120.031659
4 https://doi.org/10.1161/STROKEAHA.122.040536
5 https://doi.org/10.1161/STROKEAHA.114.006070.

TABLE C2 TOTAL ANNUAL COMMUNITY PHARMACEUTICALS COST FOR BASE CASE AND COMPLEX CASE FOR EACH CONDITION

Case	Total annual cost	Total annual cost with as needed use	Proportion in each stage or step	Reference
Asthma (aged 0–14)				
Base case	261.54	232.72	0.543 aged 6–14 0.457 aged 0–5	https://data.cso.ie/table/FY006A
Complex case	324.87	291.89		
Asthma (aged 6–14)				
Base case	261.54	228.69		
Step 2	261.54	228.69	0.29	https://doi.org/10.1016/j.jacig.2024.100227
Complex case	347.22	306.72		
Step 1	261.54	189.54	0.29	
Step 3	462.90	438.87	0.29	
Step 4	471.42	447.39	0.065	
Step 5	471.42	447.39	0.065	
Asthma (aged 0–5)				
Base case	261.54	237.51		
Step 2	261.54	237.51	0.29	https://doi.org/10.1016/j.jacig.2024.100227
Complex case	298.31	274.28		
Step 1	104.94	80.91	0.29	
Step 3	418.14	394.11	0.29	
Step 4	544.38	520.35	0.13	
COPD				
Base case	649.32	625.29		
Group B	649.32	625.29	0.54	https://doi.org/10.1164/rccm.202209-1774OC
Complex case	608.34	581.19		
Group A	457.86	433.83	0.29	
Group E	734.87	692.50	0.17	

TABLE C2 (CONTD.) TOTAL ANNUAL COMMUNITY PHARMACEUTICALS COST FOR BASE CASE AND COMPLEX CASE FOR EACH CONDITION

Case	Total annual cost	Total annual cost with as needed use	Proportion in each stage or step	Reference
Ischaemic heart disease				
Base case	472.80	443.76		
Complex case	555.92	526.88		
Stroke				
Base case	338.52			
Complex case	384.55			
Asthma (aged 15+)				
Base case	357.96	268.47		
Step 2	357.96	268.47	0.261	https://doi.org/10.1080/02770903.2021.1897834
Complex case	439.37	366.71		
Step 1	357.96	268.47	0.345	https://doi.org/10.1038/s41533-023-00338-7
Step 3	357.96	357.96	0.189	
Step 4	724.44	634.95	0.194	
Step 5	1187.64	1098.15	0.012	

APPENDIX D
Additional data

TABLE D1 ADDITIONAL DATA (EMERGENCY INPATIENT HOSPITAL CARE)

Risk–outcome pair	Total annual discharges	Total annual cost	Total annual bed days	Average LOS	PAF	Annual air pollution-related discharges	Annual air pollution-related total cost	Annual air pollution-related bed days
$PM_{2.5}$ Asthma (aged 0-14)	1,528	€5,428,678	2,703	1.8	0.075	115	€407,151	203
$PM_{2.5}$ COPD (aged 25+)	15,244	€106,252,997	116,381	7.6	0.079	1,204	€8,393,987	9,194
$PM_{2.5}$ IHD (aged 25+)	11,612	€97,078,053	66,225	5.7	0.011	128	€1,067,859	728
$PM_{2.5}$ Stroke (aged 25+)	7,069	€117,272,665	111,017	15.7	0.049	346	€5,746,361	5,440
NO_2 Stroke (aged 25+)	7,069	€117,272,665	111,017	15.7	0.023	163	€2,697,271	2,553
NO_2 Asthma (aged 15+)	2,422	€9,465,206	7,453	3.1	0.044	107	€416,469	328

Sources: Kienzler et al. (2022) and authors' calculation.
Notes: The PAFs refer to the mean PAFs reported in Kienzler et al. (2022).

TABLE D2 ADDITIONAL DATA (GP CARE)

Risk–outcome pair	Population (n)	Total annual GP visits	Total annual GP costs	PAF	Annual air pollution-related GP visits	Annual air pollution-related total GP costs
$PM_{2.5}$ Asthma (aged 0–14)	73,379	149,084	€8,099,636	0.075	11,181	€613,417
$PM_{2.5}$ COPD (aged 25+)	85,642	407,909	€22,184,077	0.079	32,225	€1,752,542
$PM_{2.5}$ IHD (aged 25+)	180,660	497,136	€27,057,400	0.011	5,468	€297,631
$PM_{2.5}$ Stroke (aged 25+)	48,396	178,096	€9,663,143	0.049	8,727	€473,494
NO_2 Stroke (aged 25+)	48,396	178,096	€9,663,143	0.023	4,096	€222,252
NO_2 Asthma (aged 15+)	276,808	564,430	€31,032,520	0.044	24,835	€1,365,431

Sources: Kienzler et al. (2022) and authors' calculations.
Notes: The PAFs refer to the mean PAFs reported in Kienzler et al. (2022).

TABLE D3 ADDITIONAL DATA (COMMUNITY PHARMACEUTICALS)

Risk–outcome pair	Population (n)	Total annual community pharmaceutical cost	PAF	Annual air pollution-related total community pharmaceutical cost
$PM_{2.5}$ Asthma (aged 0-14)	73,379	€262	0.075	1,441,897
$PM_{2.5}$ COPD (aged 25+)	85,642	€649	0.079	4,390,951
$PM_{2.5}$ IHD (aged 25+)	180,660	€473	0.011	939,974
$PM_{2.5}$ Stroke (aged 25+)	48,396	€339	0.049	803,906
NO_2 Stroke (aged 25+)	48,396	€339	0.023	377,344
NO_2 Asthma (aged 15+)	276,808	€358	0.044	4,360,280

Sources: Kienzler et al. (2022) and authors' calculations.
Notes: The PAFs refer to the mean PAFs reported in Kienzler et al. (2022).

TABLE D4 ADDITIONAL DATA (COMMUNITY PHARMACEUTICALS)

Risk–outcome pair	Population (n)	Total annual community pharmaceutical cost			PAF	Annual air pollution-related total community pharmaceutical cost		
		As required use scenario	Complex scenario	Complex scenario with as required use		As required use scenario	Complex scenario	Complex scenario with as required use
$PM_{2.5}$ Asthma (age 0–14)	73,379	€233	€325	€292	0.075	€1,282,298	€1,788,613	€1,607,000
$PM_{2.5}$ COPD (age 25+)	85,642	€625	€608	€581	0.079	€4,228,574	€4,113,557	€3,930,882
$PM_{2.5}$ IHD (age 25+)	180,660	€444	€556	€527	0.011	€882,343	€1,104,917	€1,047,286
$PM_{2.5}$ Stroke (age 25+)	48,396	€339	€385	€385	0.049	€803,906	€912,991	€912,991
NO_2 Stroke (age 25+)	48,396	€339	€385	€385	0.023	€377,344	€428,547	€428,547
NO_2 Asthma (age 15+)	276,808	€268	€439	€367	0.044	€3,264,120	€5,346,823	€4,469,896

Sources: Kienzler et al. (2022) and authors' calculations.
Notes: The PAFs refer to the mean PAFs reported in Kienzler et al. (2022).

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