ASSESSMENT OF THE HEALTH IMPACTS AND COSTS ASSOCIATED WITH INDOOR NITROGEN DIOXIDE EXPOSURE RELATED TO GAS COOKING IN THE EUROPEAN UNION AND THE UNITED KINGDOM

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Assessment of the health impacts and costs associated with indoor nitrogen dioxide exposure related to gas cooking in the European Union and the United Kingdom

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This publication is the result of the research conducted to assess the health impacts and costs associated with the levels of air pollution, specifically NO_2, observed indoors in homes that use gas cooking appliances in the European Union and the United Kingdom. It also evaluates the potential health impact and economic cost reduction associated with the implementation of policy recommendations aimed at using cleaner energy for cooking. The report has been prepared by a work team directed by Dr Juana Maria Delgado-Saborit and formed by researchers, Dr Àurea Cartanyà Hueso, Professor Arne Risa Hole, Dr Paula Carrasco Espí, Dr Ana Esplugues Cebrián, Dr Marisa Estarlich Estarlich and Professor Ferran Ballester Díez.

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LIST OF ACRONYMS

ALRI	Acute Lower Respiratory Infection
C_6H_6	Benzene
CI	Confidence Interval, gives information on the lower and higher level of risk of a health effect occurring that researchers are confident that is associated with a given gradient of air pollution exposure.
CO	Carbon monoxide
CO_2	Carbon dioxide
COPD	Chronic Obstructive Pulmonary Disease
CRF	Concentration-Response Function. It is the mathematical function that describes the association between an exposure and the health effect. Provides information related to the extent of the increase/decrease in a health outcome upon the increase/decrease in the level of exposure.
DALYs	Disability-Adjusted Life Years, a unit that represents the loss of one year of full health. It could be either because of premature death or because of the loss of a year of healthy life due to disability
EEA	European Environment Agency
EU	European Union
H_2CO	Formaldehyde
HIA	Health Impact Assessment
HR	Hazard Rate
I/O	Indoor to Outdoor ratio, the ratio between the concentration measured indoors (i.e. inside a building) and the concentration measured outside of the building, in the ambient air.
N_2O	Nitrous oxides
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
NUTS	Nomenclature of territorial units for statistics, which sets the spatial boundaries of a territory that is used for analysis.
OECD	Organisation for Economic Co-operation and Development
OR	Odds Ratio, a measure of the odds of an event happening in the population exposed to a risk factor compared to the odds of the event happening in those not exposed to the risk factor.

PAF	Population Attributable Fraction, measured the proportion of disease or death that can be attributed to a specific factor or hazard
PM$_{2.5}$	Particulate Matter with a diameter of 2.5 micrometres or less
PWEL	Population-Weighted Exposure Level. A concentration averaged across an area, that gives more weight to those areas with higher population compared to areas with little amount of population.
RR	Risk Ratio, provides the ratio of the probability of an event happening in the population exposed to a risk factor versus the probability of the event happening to those not exposed to the risk factor.
SD	Standard Deviation, gives an indication of the dispersion of the data collected.
UI	Uncertainty Interval
USA	United States of America
UK	United Kingdom of Great Britain and Northern Ireland
VSL	Value of a Statistical Life
VOLY	Value of a Life Year
VSLY	Value of a Statistical Life Year
WHO	World Health Organization
YLL	Years of Life Lost, takes into account the age at the time that the premature death occurs and the frequency of a premature death occurring

RESEARCH IN CONTEXT

What is known?

Gas cooking appliances are a significant source of household air pollutants, including NO_2, which is a harmful gas with known health effects. Gas hobs are present in 33% of European Union households and in 54% of households in United Kingdom (UK). The share of gas cooking is even larger in several EU countries (e.g, Italy, Netherlands, Romania, Hungary) reaching more than 60%.

Presence of gas cooking at home and exposures to NO_2 have been associated with childhood asthma, premature mortality and other health outcomes in scientific studies. However, little information is available as regards the exposure of the European population to gas cooking NO_2 emissions in their households and their impact on health at the population level.

What this study adds to the knowledge?

This study has calculated the first map of indoor NO_2 concentrations in households according to cooking appliance for the European population. The annual concentrations inside the households of more than half of the countries exceeded the heath guideline for NO_2 proposed by WHO in 2021 [5]. The estimation of NO_2 concentrations indoors allowed calculating the first estimate of premature mortality and years of life lost in Europe associated with exposure to indoor NO_2 emitted from gas cookers. It also provided the first ever estimate of the number of overall asthma cases linked to the presence of gas cookers at home. Finally, it has also calculated the value of paediatric asthma cases related with presence and exposure to gas cooking emissions, including exposures to the toxic gas NO_2. The extent of the impact is expected to be larger than currently estimated as other pollutants known to be emitted by gas cookers, and health effects associated to these pollutants could not be included in the health impact assessment due to lack of data.

What are the implications of all available evidence?

Presence of gas cookers at home and exposure to NO_2 from gas cooking appliances produces far more health impacts in the European population than previously thought, including premature deaths and asthma in the overall population. Policy makers should develop policies that would help the population to reduce their exposure to the harmful emissions associated with gas cooking. Consumers should consider other cleaner alternatives for cooking, budget permitting, which could be incentivized by the government using tax rebates or subsidies to promote the change. Information campaigns could contribute to raise awareness and stress the importance of adequately ventilating whilst cooking with gas appliances to reduce the exposure of the population to the harmful pollutants emitted by gas appliances.

1. EXECUTIVE SUMMARY

Exposure to air pollution is one of the main threats to global health. Traffic, industrial activities and residential heating are the main sources of air pollutants outdoors [6]. Nonetheless, people spend more time indoors than outdoors. Therefore, interests on the sources contributing to air pollution exposure indoors and their impact on health has gain traction.

Gas cooking appliances are a significant source of indoor air pollutants, releasing NO_2 during the combustion process, which contributes to increased levels of NO_2 exposures indoors. On the contrary, electric hobs do not contribute NO_2 indoors as no combustion takes place in the process. Thus, households that use gas cookers are exposed to higher NO_2 concentrations and exceed air quality guidelines more often than households that cook with electric appliances. In addition, NO_2 concentrations measured indoors in gas cooking households are higher than outdoors, as observed is several studies [7, 8].

According to Eurostat data [1], gas cooking remains a prevalent practice in Europe (33% of European households in 2022). However, its usage varies greatly by country, with Norway relying solely on electricity, whereas gas appliances are used in 74% of Italian households. In addition, gas hobs are more frequently used in urban areas than in rural locations. On the other hand, a declining trend on the usage of gas cookers has been observed both in urban and rural areas across Europe.

Gas cooking has been associated with a several health effects, such as a higher risk of pneumonia and chronic obstructive pulmonary disease (COPD) in children and adults, compared to electric cooking [9]. Several studies suggest an association between gas cooking and childhood asthma, although the strength of the evidence is debated [9, 10]. Some studies suggest potential links between gas cooking and other respiratory symptoms like breathlessness, cough, and bronchitis, though the evidence is less conclusive [9, 10].

In addition, several health effects have been associated with the exposure to NO_2, a gas released during gas cooking. The evidence suggests a causal link between long-term exposure to NO_2 and increased mortality risk, including all-cause, cardiovascular, and respiratory mortality [4]. NO_2 exposure has also been associated with increased risk of lung cancer mortality [11]. Several studies also suggest a potential link between short-term NO_2 exposure and increased hospital admissions due to asthma exacerbations [12-14], COPD [4] and pneumonia [9]. A limited number of studies suggest associations between chronic NO_2 exposure and increased hospital admissions [15]. Short-term exposure to NO_2 has also been linked to increased asthma symptoms in children, increased risk of night-time asthma, increased risk of missed school days due to asthma and increase wheeze [16]. Likewise, several studies have identified that chronic NO_2 exposure is associated with current and lifetime asthma, but evidence is less conclusive [10]. The strength of the association may vary depending on factors such as exposure levels, duration of exposure, and individual susceptibility.

Given that gas cooking is an important source of air pollution indoors, that gas cooking is prevalent in many European countries and that there are a number of health effects associated with exposure to gas cooking emissions, it is crucial to assess the health impacts associated with gas cooking. The current study aims to estimate the health and economic impact of indoor NO_2 exposure from gas cooking in Europe and the potential benefits of transitioning to cleaner cooking fuels. The study will focus on mortality - premature mortality and years of life lost- as well as on paediatric and total asthma cases (i.e. paediatric and adult cases).

To conduct the health impact assessment, concentration response functions (CRF) relevant to mortality [4] and asthma [9, 10] were identified from dozens of peer-reviewed meta-analysed studies. CRF are a mathematical function that describes the association between an exposure and a health effect. CRF provides information related to the extent of the increase or decrease in a health outcome upon the increase or decrease in the level of exposure. Distribution of population, percentage of population using gas cooking appliances, as well as background health rates for mortality and asthma prevalence were retrieved from governmental and institutional resources, such as Eurostat and the Global Burden of Disease databases [1, 17]. Estimates of indoor NO_2 exposure in gas and electric cooking households were calculated combining indoor-to-outdoor (I/O) NO_2 ratios with ambient NO_2 modelled data provided by the European Environment Agency (EEA) [2]. I/O NO_2 ratios were calculated for households using gas and electric cooking appliances based on the indoor and outdoor NO_2 concentrations reported in the most comprehensive and recent study conducted in 7 European countries [7]. Several I/O NO_2 ratios were derived according to cooking appliance for each of the four clusters of countries identified in the literature [18].

The population attributable fraction (PAF), i.e. the proportion of disease or death that can be attributed to gas cooking, was calculated considering the relevant risk ratios identified in the literature. These were combined with the gradient, i.e. the difference, in indoor NO_2 concentrations emitted between gas and an electric cooking, and the population in the area under study. PAFs were combined with background known health outcome rates to estimate the impact and economic cost associated to gas cooking. The cost of mortality was estimated considering the number of premature deaths associated with gas cooking and the Value of a Statistical Life (VSL, the economic value that someone would pay to avoid the death of an anonymous person). It was also combined with the number of years of life lost (YLL) due to early death or life lived with disability linked to gas cooking and the Value of a Statistical Life Year (VSLY, a similar concept to a VSL, but capturing the cost related to avoiding losing one year of life). To assess the economic costs of asthma, the estimated number of current and lifetime asthma cases linked to gas cooking was converted into disability adjusted life years (DALY) and then valued using VSLY. The DALYs represent the sum of the years of life lost to due to premature mortality and the years lived with a disability. VSL was calculated using estimates derived by standard methods developed by the Organisation for Economic Co-operation and Development (OECD) [19] and adjusted for inflation and income growth, to take into account differences among countries as regards the cost of life. VSLY were derived from VSL and remaining life expectancy.

Approximately 36,000 premature deaths and 61,000 YLL associated with exposure to NO_2 emitted during gas cooking are estimated in the EU. When data from UK and EU are combined, there are 40,000 premature deaths and 77,000 YLL. The countries with the highest burden were Italy, Poland, Romania, France and the UK. The estimated cost of premature deaths related to gas cooking in the EU and UK combined is 160 billion (EU is 143 billion) euros, with Italy incurring the highest cost (54 billion euros) as a single country. The total estimated cost of YLL in the EU is 11 billion euros, whereas the UK incurs the highest cost as a single country (3 billion euros). The countries that would benefit the most from transitioning to cleaner energy for cooking to reduce the impact on mortality associated with gas cooking emissions would be Italy, Poland, Romania, France and the UK.

The number of estimated paediatric asthma cases due to NO_2 exposure from gas cooking is approximately 25,000 cases in the EU and 41,000 cases when the UK and EU are combined. The number of estimated paediatric asthma cases associated with the presence of gas stoves is higher, estimated to be approximately 367,000 cases in the EU and 550,000 cases when the EU and UK are combined. The number of total asthma cases, which includes paediatric and adult cases, is approximately 726,000 cases in the EU and 1,055,000 cases when the EU and UK are combined. The estimated costs related to paediatric asthma associated with gas cooking are 2.6 billion euros in the EU to 4 billion euros when EU and UK are combined. The countries that would benefit the most from transitioning to cleaner sources to reduce the impact of exposure to gas cooking emissions on asthma are UK, France, Italy, Poland, Spain, the Netherlands and Romania.

Overall, gas cooking is associated with a significant burden of mortality and asthma in Europe, particularly in countries with high gas cooking prevalence.

Some limitations were identified in the current study. The NO_2 indoor concentrations estimated in this study may be underestimated. The available scientific evidence indicates that higher concentrations are generally experienced indoors than those modelled in the current study, especially in households using gas cookers. There is limited availability of data for certain health outcomes and regions, that precluded to be incorporated in the HIA. Other pollutants emitted during cooking with gas appliances were not considered in the HIA, either because indoor concentrations could not be estimated due to lack of information, or because no reliable CRF exists. Likewise, additional health effects for which not sufficiently data was available could not be included in the assessment. Some CRFs may have limitations in terms of causality and statistical significance. It is recommended to conduct further research to address data gaps, refine CRFs, and consider the impact of other pollutants and health effects in future health impact assessments.

This study has several strengths. The study has been conducted by a group of experts in exposure science [8, 20-22], epidemiology [23-26], biostatistics [27, 28] and health economy [29, 30], with prior experience in conducting health impact assessments [31-34].

This study has provided the first spatially detailed map of indoor NO_2 concentrations according to cooking fuel type in every small regional unit area (i.e. at NUTS- 3 level) for all countries in the EU and the UK. Using that map, it has calculated for the first time the health impacts and economic costs across the EU and UK associated with mortality and asthma related with exposures to NO_2 emitted from gas cookers in Europe. It has also provided for the first time an estimation of asthma cases in population of all ages related with the presence of gas cookers. Previous research included only health effects associated with paediatric asthma related to presence of gas cookers [7, 35-37], but not with population from all ages.

This study has also calculated for the first time in Europe the premature mortality and years of life lost associated with exposure to indoor NO_2 emitted from gas cookers. Only another study conducted recently such calculation in the USA [38].

One previous study assessed the societal cost from heating and cooking that represents the pollution of outdoor air from those sources in Europe [39]. However, that study focused on ambient air and could not estimate health impacts associated with indoor exposures related with gas cooking. The authors of that study acknowledged that their estimation of the total health-related costs from heating and cooking appliances was likely a considerable underestimation of the real burden associated with gas cooking [39]. Indeed, the current study estimates strongly suggest that the health costs related to indoor air pollution by cooking with gas appliances are far higher than those associated to air pollution outdoors caused by cooking and heating emissions. For instance, the mortality cost associated with NO_2 exposures for gas cooker users in the EU and UK combined calculated in this study is 160 billion euro, whilst the mortality cost related with exposure to outdoor air in the EU and the UK was estimated to be 29 million euro in that study [39].

The study assessed the impact across the EU and UK, covering the largest population ever studied so far. A previous study conducted in the US estimated the health impact and costs for mortality and paediatric asthma associated with gas cookers and their NO_2 emissions in a population of 131 million inhabitants [40]. The present study calculates the health impact and their costs for the EU and UK populations, formed by 180 million inhabitants exposed to gas stoves [41]. This study included both indoor NO_2 exposure and gas stove presence as exposure factors.

The health and economic costs associated with gas cooking in Europe are significant and far greater than previously understood. The harmful NO_2 gas, emitted during combustion in gas cooker appliances, cuts short the lives of millions of Europeans cooking on gas appliances. Premature mortality adds to the previously estimated impact on asthma from cooking with gas appliances. Transitioning to cleaner cooking fuels is essential to protect public health and reduce the burden on healthcare systems.

2. INTRODUCTION

2.1 Gas cooking as a source of indoor air pollution

Air pollution exposure is one of the top ten threats to global health [42]. Recently, research interests have focused on the impacts of indoor pollution exposures because people spend more time indoors than outdoors (approximately 90% of their time indoors) [43].

Indoor environments represent a mixture of pollutants from outdoor sources frequently produced by combustion (e.g. road traffic) or industrial activities, contaminants originated from indoor sources, related with human activities (i.e., smoking, cleaning, cooking), and emitted from furniture and building materials [44]. Another important factor of indoor air quality is ventilation, which depends on natural and mechanical ventilation (air exchange rates). Ventilation plays a role both facilitating the infiltration indoors of outdoor generated pollutants, as well as in diluting indoor generated pollutants [45].

The concentration of air pollutants indoors is partly dependent on outdoor levels. However, for some air pollutants for which indoor sources exist, indoor air concentrations are considerably higher. This is the case of NO_2, where the highest concentrations are generally measured in households using gas cookers [7], often exceeding the WHO air quality guidelines [6, 7]. This is particularly true for kitchens with poor ventilation or where extraction fume hoods are not used or are not working properly [46]. Thus, gas cooking (and heating) appliances are a significant source of household air pollutants that deserves attention.

Cooking with gas releases a mixture of hazardous air pollutants, including nitrogen dioxide (NO_2), nitrogen monoxide (NO), nitrous oxides (N_2O), carbon monoxide (CO), benzene (C_6H_6), formaldehyde (H_2CO), ultrafine particles (UFP) and $PM_{2.5}$ [38, 47-52]. Moreover, the use of gas for cooking produces emissions of two potent greenhouse gases, CO_2 and unburned methane, the last one even when cooking gas appliances are switched off [53]. Therefore, the use of gas hob for cooking has been identified as an important emission source of NO_2 indoors.

2.2 Indoor NO_2 levels associated with gas cooking

2.2.1 NO_2 concentrations related with gas cooking emissions

Cooking with gas appliances has been associated to increased concentrations of NO_2 indoors, as well as to higher exposures to NO_2 at the personal level as shown by various studies that reported higher NO_2 levels in homes that use gas hobs for cooking compared with levels measured in households that use electric hobs.

As early as in 1978, Melia et al designed an experiment to investigate differences in NO_2 concentration in kitchens with gas and with electric cookers. The results showed that NO_2 in gas kitchens was more than seven times greater than measured in electric kitchens (135.9 µg/m³compared with 17.86 µg/m³, $p < 0.05$) [54].

A study conducted across summer and winter from 1988 to 1991 in 1,400 households in Albuquerque (USA) reported that the NO_2 concentrations measured in bedrooms of children were 4-fold higher in households that used gas appliances with pilot light for cooking, with NO_2 medians ranging 25 to 43 µg/m³. The NO_2 medians measured in bedrooms from households that used electric appliances ranged 10 to 11 µg/m³ [55]. This is consistent with another study conducted in USA who measured higher concentrations in households that use gas hobs for cooking (48±34 µg/m³) than those that use electric appliances (16±17 µg/m³) [56].

An international study carried out in 1998 across 15 countries in North America, Europe and Asia measured concurrently concentrations of NO_2 indoors, outdoors and at the personal level. Use of a gas stove in the household was the most important activity increasing the concentrations of NO_2 indoors and at the personal level. Mean personal NO_2 exposure increased 67% as well as did the indoor-outdoor ratios from 0.7 to 1.2 for participants using gas stoves. NO_2 concentrations indoors were 59±31 µg/m³ in households with gas stoves, whilst concentrations were 15±10 µg/m³ in households cooking with electric hobs [57].

A large study conducted in England in 2004 measured concentrations of NO_2 in 1000 randomly selected households. They reported the highest geometric mean concentrations in households that used natural gas ovens in the kitchen (42.8 µg/m³) and the bedroom (18.2 µg/m³), followed by households that use natural gas for cooking, but not in the oven (kitchen: 22.4 µg/m³, bedroom: 12.8 µg/m³). The lowest concentrations were measured in households that did not use fossil fuel for cooking kitchen:11.5 µg/m³, bedroom: 7.9 µg/m³) [58].

In 2012, a study was carried out in England that used real-time sensors to characterise personal exposures to nitrogen dioxide in a group of non-occupationally exposed subjects [8]. The study identified commuting and cooking with gas appliances as the main contributors to peak exposures of NO_2. Delgado-Saborit (2012) reported that subjects cooking with gas hobs were exposed to an average NO_2 personal exposure of 58±114 µg/m³, whereas subjects cooking with electric appliances were exposed to lower NO_2 concentrations (35±77 µg/m³). Interestingly, that study also reported that the highest NO_2 peak exposure, as high as 1,504 µg/m³, occurred for a subject while cooking with a gas appliance [8].

Mulllen et al (2015) evaluated NO_2 concentrations in over 350 kitchens in Californian homes. They reported higher concentrations (41 µg/m³) for those households that used gas hobs for cooking compared with concentrations measured in kitchens cooking with electric appliances (12.4 µg/m³) [59].

Paulin et al (2017) studied the relation between cooking appliance use and NO_2 concentrations in a longitudinal cohort of children with asthma. The longer duration of cooking appliance use was associated with higher NO_2 concentration in a dose-dependent function [60]. They reported that each hour of cooking appliance use was associated with a 38.48 µg/m³ increase in 24-h indoor NO_2 concentration ($p<0.001$). When adjusting for confounders (season, outdoor NO_2 concentration, and window opening), each hour of cooking appliance use was associated with a 33.84 µg/m³ increase in 24-h indoor NO_2 concentration ($p<0.001$) [60].

In a recent study, Jacobs et al (2023) measured NO_2 concentrations in 250 homes across seven European countries: the Netherlands, Italy, Spain, France, Slovakia, Romania, and the UK. Households were selected according to several excluding criteria, to ensure that smoking had no influence on NO_2 concentrations indoor, and traffic emitted NO_2 had minimal influence indoors. Controlling for those important sources of NO_2 indoors, the NO_2 concentrations were lower in houses that used electric appliances for cooking compared with those that used gas-hobs in all countries. Gas-cooking homes were exposed to around twice the level of NO_2 than levels measured in households that use electric appliances for cooking. As well, homes that used gas-cooking appliances experienced levels of indoor air pollution that regularly exceeded limits regulated for outdoor environments. Moreover, in some households cooking with gas appliances, the concentrations of NO_2 experienced indoors exceeded the upper measurement limit of the sensor, peaking at around 478 µg/m³ [7].

In addition, Jacobs et al (2023) study characterised concentrations in the kitchen, the living room and in one of the bedrooms (preferably the one where children sleep, if children were present in the household). Households using gas appliances experienced higher NO_2 concentrations in the kitchen (27 μg/m³), where the gas cooker represents a source of NO_2, and decreased in the living room (23 μg/m³), with the lowest concentrations experienced in the sleeping room (18 μg/m³). In addition, when gas-cooking households spent a longer time cooking, indoor NO_2 concentrations continued to increase while the hob or oven was running. On the contrary, this not occurred in households cooking with electric hobs and ovens, and the NO_2 concentrations were similar in the kitchen, living room and bedroom (12-13 μg/m³) [7].

2.2.2 NO_2 I/O ratios in homes related with gas cooking emissions

The indoor to outdoor ratio of NO_2 concentrations differs with building type, season, and region, which may indicate different contributions of indoor and outdoor sources.

A recent review study by Hu and Zhao (2020) focused on the I/O ratio of NO_2 concentrations based on a literature search of 218 publications in Web of Science and PubMed from 40 countries [61]. The results showed that the I/O NO_2 concentration ratio differed between countries and regions (e.g. from 1.66 in Pakistan to 0.36 Portugal), thus indicating that differences exist in the indoor NO_2 source strength and ventilation. The highest I/O NO_2 concentration ratios were found for residential buildings, with cooking, smoking, and indoor combustion heating being the main indoor emission sources of NO_2. Offices were associated with relatively few indoor sources, and schools had the least number of sources emitting NO_2. For the same building type, seasonal differences in the indoor and outdoor NO_2 concentrations were mainly due to the air change rate, which was highest during the summer [61].

The review by Hu and Zhao (2020) [61] suggested that the highest I/O NO_2 ratios were measured in rural kitchens during the winter, implying large indoor sources and relatively low ventilation between the indoors and outdoors. In the same review [61] authors illustrate the I/O NO_2 concentration ratio data for different seasons. The mean ratios for buildings without indoor NO_2 sources were <1 for residential buildings (mean± standard deviation (SD), summer 0.87±0.13; winter 0.63±0.25; spring and fall 0.65±0.24). In contrast, the mean ratios were higher than one and covered a wider range of values for those cases where indoor sources exists in residential buildings (summer 1.60±1.52; winter 2.43±7.72; spring and fall 1.19±0.66).

The study by Jacobs et al (2023) measured concentrations indoors and immediately outside the home, at the façade of the building, providing useful information to calculate I/O ratios for households that use electric and gas cookers. Outdoor NO_2 concentrations were likely originating by combustion of fossil fuels for transportation and industrial activities. Indoor NO_2 concentrations were consistently higher in homes equipped with gas cooking appliances than those measured outside. NO_2 levels were on average higher in the kitchen than outdoors (27 µg/m³ vs 18 µg/m³) in gas-cooking homes, representing an average indoor to outdoor ratios (I/O) of NO_2 of 1.5. On the contrary, in households using electric hobs and ovens, average NO_2 concentrations were lower indoors, reaching an average of 13 µg/m³ in the kitchen, and higher outdoors (average concentration of 18 µg/m³ outdoors in electric-cooking households). This represents an average I/O NO_2 ratio of 0.72. These results are in agreement with several studies that report differential indoor to outdoor ratios of NO_2 concentration according to the presence of important indoor sources, such as gas cooking emissions [7].

The I/O NO_2 concentration ratio also reflects the effect of different modes of ventilation for residential buildings. For instance, in naturally ventilated buildings the mean±SD I/O NO_2 was 1.40±1.61; whereas the I/O NO_2 was 1.00±0.57 in mechanically ventilated buildings [61]. The use of cooker hoods should increase the amount of ventilation and hence reduce the I/O NO_2 ratio. In spite of this, some studies have reported little impact of the presence of cooker hoods in the home on the indoor concentrations, and hence the I/O NO_2 ratio. For instance, indoor air quality measured in the households participating in the Jacobs et al (2023) study was not affected by the presence of cooker hoods in the home [7]. In that study, households with cooker hoods (both recirculating and vented to the exterior) saw no substantial reduction in cooking-related indoor air pollution. As pointed by Jacobs et al (2023), these results shows that relying on individuals to ventilate their homes is not enough to mitigate the health risks from gas hobs and ovens [7]. Dharmage et al. (1999) reported a similar finding in Australia, where 44% of households in Melbourne did not regularly use cooker hoods for ventilation [62].

2.3 Gas cooking use across Europe

2.3.1 Gas cooking usage across European countries

Households consume energy for various purposes: heating and hot water, cooling, cooking, lighting, powering electrical appliances, and other end uses (mainly including energy uses by households outside their residences). Since 2017, Eurostat has been collecting and publishing data on household energy consumption by end use.

According to Eurostat recent survey in 2022, the residential sector accounted for 25.8% of the final energy consumption and 18.1% of the gross inland energy consumption in the EU. Cooking represents 6.3% of household energy consumption as per 2022 [1]. However, this percentage varies widely across countries (Figure 1), with the highest share of cooking energy consumption reported in Albania and Portugal (approximately 30%), and Montenegro (circa 25%) [1].

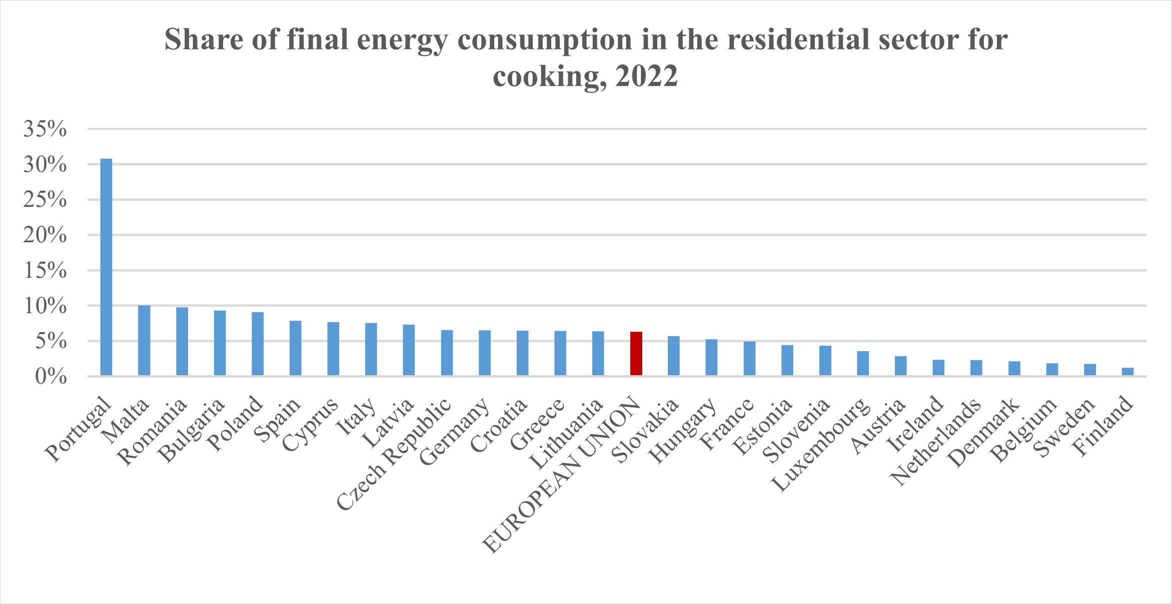

Figure 1. Share of final energy consumption in the residential sector for cooking, 2022 (Source: Eurostat 2022 [1]).

According to the Eurostat (2022), the types of energy used for cooking in Europe were solid fossil fuels (0.34%), oil and petroleum products (excluding biofuel portion) (12.28%), renewables and biofuels (3.83%), electricity (50.72%) and natural gas (32.83%) [1].

The use share of each fuel type (Figure 2) may vary by country and region, influenced by factors such as local resource availability, energy infrastructure, national energy policies and cultural preferences. The country in Europe that consumes the most electricity for cooking is Norway (100%) and the least is Romania (0.07%) and North Macedonia (0%), although in the latter, 100% of the stoves use renewable energy or biofuels [1].

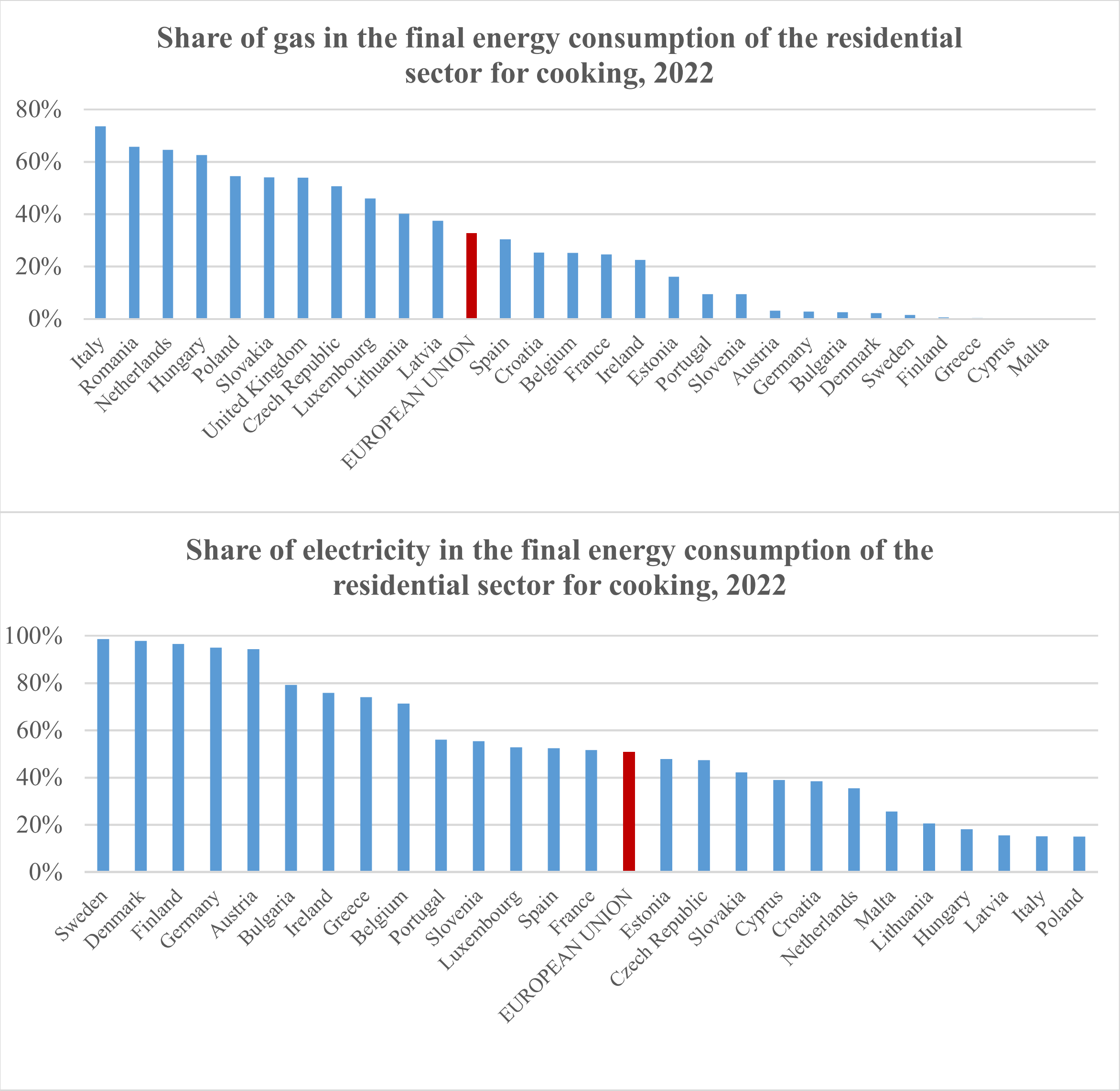

Figure 2. Share of gas (top) and electricity (bottom) fuel consumption in the final energy consumption of the residential sector for cooking, 2022 (Source: Eurostat 2022 [1])

2.3.2 Gas cooking usage urban vs rural

According to WHO estimates, in 2021, roughly two thirds (73% [UI 51-87]) of the population living in European non-high income countries were primarily cooking with gas fuels in urban locations, whereas the percentage is lower in rural areas (64% [UI 44-79]). This represents a total population exposed to gas cooking emissions in European non-high income countries of 196 [UI 136-234] million people living in urban areas and 81 [UI 56-100] million people in rural areas. Then again, estimates from 2021 imply a decrease in the use of gas cooking appliance with respect the previous decade, where 83% [UI 73-88]) and 70% [UI 58-77]) of Europeans living in urban and rural areas in non-high income countries respectively reported using gas for cooking in 2011 [5].

On the contrary, the percentage of households using electricity for cooking is quite stable, with 12% [UI 7-25] and 11% [UI 7-21] of population in European non-high income countries in urban and rural areas reporting the use of electric hobs for cooking in 2021, and 12% [UI 8-18] and 9% [UI 7-17] respectively in 2011. However, this represents a reduction in the use of electric hobs for cooking compared with data reported in 1990, where 22% [UI 12-35] and 12% [UI 4-28] of urban and rural Europeans in non-high income countries reported using electric appliances for cooking [5].

On the other hand, Eurostat [1] reports usage of gas and electric energy for cooking for all countries in the European Union. The percentage of population using gas as a main source for cooking is higher in urban than in rural areas, which might be associated to the use of other energy sources in rural areas beyond gas or electric hobs (Figure 3). A trend was also observed of an increased usage of gas cooking appliances in both urban and rural areas up until the 2005-2010 in urban areas, and 2008-2014 in rural areas, followed by a sharp decline in both areas.

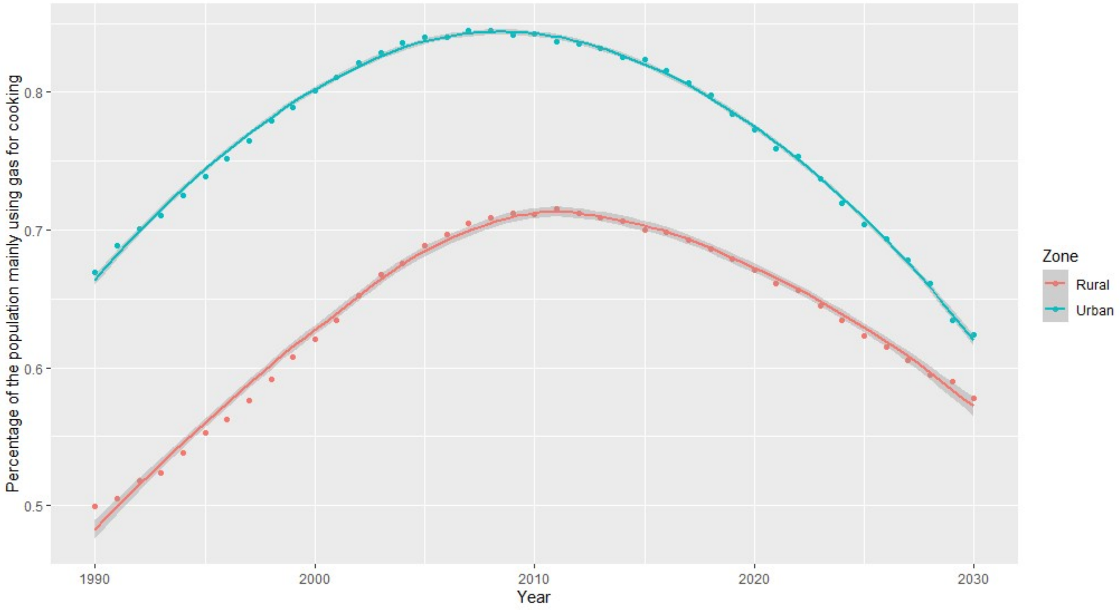

Figure 3. Percentage of the population using gas as main source for cooking (Source: Eurostat 2022 [1])

Despite the observed declining trend regarding the use of gas energy for cooking as a percentage, the total number of people mainly using gas for cooking has increased steadily, up until the 2020s, where it seems to be reaching a plateau in urban areas [1]. On the contrary, the total number of people using gas cooking appliances in rural areas is declining since 2010s (Figure 4).

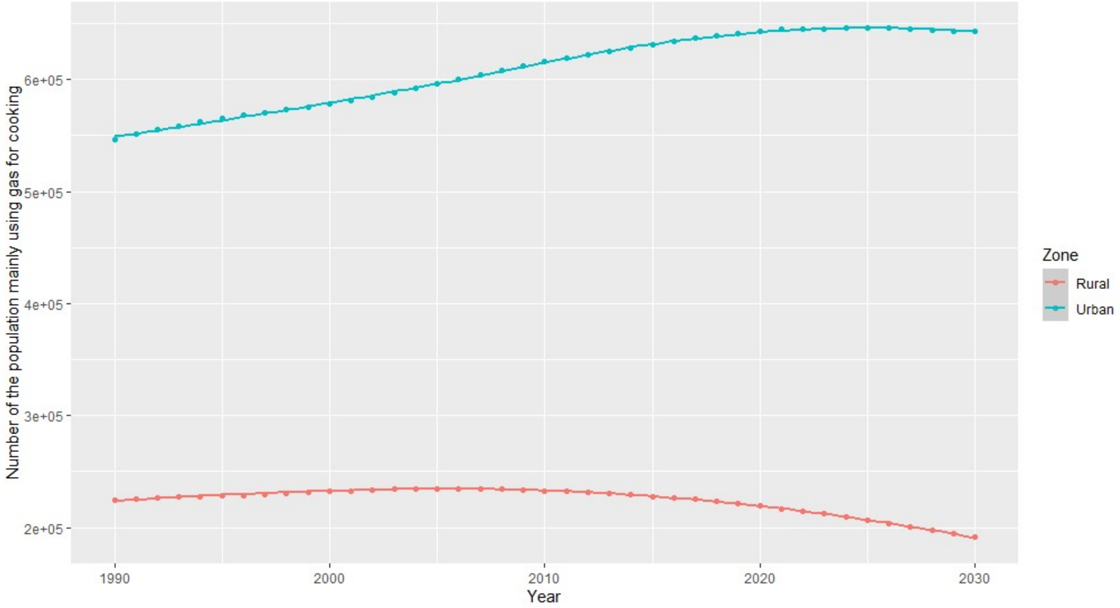

Figure 4. Number of people using gas as main source for cooking (Source: Eurostat 2022 [1])

2.4 Health effects associated with gas cooking

2.4.1 Asthma

The chemicals emitted during cooking with gas appliances have been linked with asthma onset, exacerbation of respiratory symptoms in asthmatics, bronchoconstriction and airway inflammation [53, 63]. This is especially worrying for children as they spend most of their time at home, have higher respiration rates and their lungs and immune system are still developing [64].

Lin W et al conducted a meta-analysis to synthesize the evidence available through 2013 about the association between gas cooking and asthma in children (≤18 years) [10]. The meta-analysis of 21 studies showed that children living in a home with a gas cooking stove have a 32% increased risk of asthma (current or lifetime asthma) (OR: 1.32, 95% CI: 1.18–1.48).

Subsequently, Li W et al [65] updated the review on this topic including studies in the Lin et al. meta-analysis [10] and new studies published up to 2018. A quantitative synthesis was not considered appropriate because literature, including that meta-analyzed by Lin et al [10], was limited by high heterogeneity across studies, the lack of reliable study designs (only 4 of the 22 studies used a cohort study design), and low study quality (especially with respect to exposure assessment, temporality, confounding adjustment and sample selection). So Li W et al [65] concluded that the reviewed evidence did not support causality.

A recent systematic and meta-analysis review (Puzzolo E, 2024) has summarised the health effects from cooking or heating with gas appliances compared with other more polluting fuels (e.g. wood or charcoal) and also compared with clean energy sources (eg, electricity and solar energy) including studies in child and adult populations [9]. Compared with electricity, the use of gas for cooking and heating increased the risk of asthma in children (OR: 1.09, [95%CI: 0.99, 1.19]; n=20 studies), although statistical significance was not reached. No significant association was found for asthma in adults either (OR: 1.43 [95%CI: 0.90, 2.27]; n=5 studies). However, when studies reflecting the paediatric and adult population were combined, the risk estimate had statistical significance (OR: 1.11 43 [95%CI: 1.01, 1.21]; n=26 studies).

2.4.2 Other respiratory outcomes

Lin W et al conducted a meta-analysis to synthesize the evidence available through 2013 about the association between gas cooking and wheeze in children (≤18 years) and showed no statistically significant association (OR: 1.06, 95% CI: 0.99, 1.13; n=33 studies) [10].

This association was also analyzed in the systematic review conducted by Li W et al [65] including studies published up to 2018. Thirty-three studies were found of which only 3 used a cohort design. Because of the lack of reliable study designs, high heterogeneity across studies and low study quality (especially with respect to exposure and outcome assessment, temporality, confounding adjustment) a meta-analysis was not performed. The authors concluded that the reviewed evidence available up until 2018 did not support causality [65].

A recent systematic review by Puzzolo et al (2024) showed, that compared with electricity, the use of gas for cooking or heating significantly increased the risk of pneumonia (OR: 1.26, [95%CI: 1.03, 1.53]; n=6 studies) and chronic obstructive pulmonary disease (OR: 1.15, [95%CI: 1.06, 1.25]; n=3 studies) in children and adults [9]. However, smaller non-significant effects were observed for higher-quality studies. No significant associations were found for breathlessness (OR: 0.97 [95%CI: 0.81, 1.17]; n=3 studies), cough (OR: 1.06 [95%CI: 0.96, 1.18]; n=17 studies), or wheeze (OR: 1.05 [95%CI: 0.98, 1.13] n=24 studies). On the other hand, the risk of bronchitis was significantly reduced (OR: 0.87, [95%CI: 0.81, 0.93], n=4 studies) [9].

Epidemiological evidence on gas cooking exposures on respiratory health effects in adults is limited. Recently, results from the European Community Respiratory Health Survey (ECRHS) study have been published by Pan et al (2024). The ECRHS is a multi-centre cohort study of adults that were recruited in the early 1990s (1991–1993, ECRHS I), from 56 centres across Europe and internationally, which had two follow-ups (ECRHS II in 1999–2003 and ECRHS III in 2010–2014). Data from ECRHS II and ECRHS III was used by Pan et al (2023) including a sample of 4337 adults (43.7% males) from 19 centres in 9 countries. Prevalence of gas cooking was 47.1% at ECRHS II and 37.4% at ECRHS III (range 7.2% to >80% across centres). Participants were asked about presence of respiratory symptoms in the previous 12 months, including: wheezing, shortness of breath, cough, phlegm and nasal allergies. The risk of wheezing with breathlessness (OR: 1.32; [1.00, 1.74]) and shortness of breath whilst at rest (OR: 1.38 [95%CI: 1.06, 1.79]) increased in gas versus electric cooking users. For several other symptoms, the greatest effect estimates were observed among those subjects using both gas hobs and ovens versus gas hobs only when compared to electric cookers. Differences were also found depending on the source of gas (mains versus bottled), ventilation and daily cooking duration (60 min or more versus less than 60 min). Stronger associations for several symptoms were observed for those subjects using bottled gas, those who cooked for more than 60 min per day and among those who rarely or never opened a window or door (i.e. little ventilation) compared to those who did. Stratifying results by sex and age found stronger associations in females and younger adults [66].

2.5 Health effects associated with NO_2 exposure

2.5.1 Mortality

The US Environmental Protection Agency (EPA) has conducted several assessments of the evidence of health effects associated with exposure to oxides of nitrogen [67, 68]. In the 2008 and 2016 assessment, EPA concluded that "*the evidence is suggestive of, but not sufficient to infer, a causal relationship between long-term exposure to* NO_2 *and mortality among adults*" because of inconsistency between results of US and European cohorts and difficulties of addressing confounding by co-pollutants (e.g. NO_2 and PM).

Subsequently, evidence on the association between long-term exposure to NO_2 (i.e. annual mean or multiple-year average) and overall and cause specific mortality has been summarised in several systematic reviews and meta-analyses over the last few decades with the aim of determining causal associations and establishing CRF for use in health impact and burden assessment.

In 2018, Atkinson RW et al (2018) [11] conducted a meta-analysis including studies published up to October 2016, updating previous reviews [68-71] and incorporating a wider range of causes of death. Forty eight articles were included, analysing 28 general population cohorts, and pooled *Hazard Ratios* (HRs) showed positive associations between NO_2 and all cause (1.02 [95%CI: 1.01, 1.03]; n=20 cohorts), cardiovascular mortality (1.03 [95% CI: 1.02, 1.05]; n=15 cohorts) and respiratory mortality (1.03 [95% CI: 1.01, 1.05]; n=13 cohorts) per 10 $\mu g/m^3$ increment in NO_2.

Another meta-analysis was published in 2020 [4]. It included 46 prospective and retrospective cohort studies, published up to January 2018, which had evaluated the association between long-term outdoor exposure of NO_2 and all-cause and respiratory mortality in patient and general population. A 10 µg/m^3 increase in NO_2 was associated with a high risk of mortality from all-causes (RR: 1.02 [95% CI: 1.01, 1.04]; n=24 studies included). It was also associated with a high risk of mortality from respiratory disease (RR: 1.03 [95% CI: 1.01, 1.05]; 15 studies included), COPD (RR: 1.03 [95% CI: 1.01, 1.04]; n=9 studies) and acute lower respiratory infection (ALRI) (RR: 1.06 [95% CI: 1.02, 1.10]; n=5 studies). Certainty of evidence (adapted GRADE) in the associations with mortality was rated moderate for all-causes, respiratory and ALRI and high for COPD mortality.

Most of the cohorts included in these two meta-analyses were from North America and Europe. Both highlighted high heterogeneity between studies and differences in pooled estimates in subgroups analysis especially in relation to age at recruitment, exposure assessment methods (e.g., use of land-use regression [LUR] models to estimate residential NO_2 concentrations versus area based concentration estimates) and adjustment for key confounding variables such as individual-level smoking, BMI, and socioeconomic status. For some subgroups, the HR was close to unity, with lower confidence limits below 1 [4, 11]. In addition, due to the small number of studies with multi-pollutant models and difficulties in interpreting coefficients, the evidence considering changes in risk estimates from single and multi-pollutant pollutants is limited. Therefore, pooled HRs were calculated from studies reporting results from single pollutant models and the authors recommended interpreting the results with caution as it might reflect mixtures of pollutants.

Subsequently, Huang S et al in 2021, updated the meta-analysis incorporating 6 new studies including cohorts from Asia and Oceania [12]. The pooled HR for all-cause mortality was 1.06 (95%CI: 1.04, 1.08; n=28 studies) per 10 ppb increase in annual NO_2 concentrations. The pooled HR was higher in Asia and Oceania than that in North America and Europe (HR: 1.03, 95%CI: 1.02, 1.05; n=13 studies). The pooled HRs per 10 ppb increment for cardiovascular mortality were 1.11 (95%CI: 1.07, 1.16; n=20 studies) and was higher in studies from Asia compared to the studies in North America and Europe (HR: 1.05, 95%CI: 1.00, 1.09; n=10 studies). The pooled HRs for respiratory mortality were 1.05 (95%CI: 1.02, 1.08; n=17 studies) per 10 ppb increment. Estimates from Asian studies were larger than estimates from North American and European studies (HR: 1.04, 95%CI: 0.98–1.09, n=9 studies). In addition, the sensitivity analysis pooling estimates from multi-pollutant models suggested that the effect of NO_2 on mortality might be independent of other common air pollutants.

Finally, the latest update has recently been conducted [72], including 11 new studies published since Huang et al (2021) [12]. This new meta-analysis encompassed a cohort of 220 million individuals across 18 countries in Asia, Europe, North America, and Oceania. Increase of ambient NO_2 exposure was associated with increased risk of all-cause mortality (RR: 1.03 [95% CI: 1.02, 1.05] per 10 $\mu g/m^3$ increase). The pooled RR values were significantly higher in Asia and Oceania than in North America and Europe (RR: 1.03 (95% CI: 1.01, 1.04) per 10 $\mu g/m^3$). The pooled RR value for long-term exposure to ambient NO_2 and cardiovascular mortality was 1.07 (95% CI: 1.04, 1.10) per 10 µg/m3 increase. The overall effect risk was higher in Asia than in North America and Europe (RR: 1.04 (95% CI: 1.02, 1.07) per 10 µg/m3; n=17 studies). The overall RR value for long-term exposure to ambient NO_2 and respiratory mortality was 1.03 (95% CI: 1.02, 1.05) per 10 µg/m3 increase. Pooled RR values were higher in Asia than in North America and Europe (RR: 1.03 (95% CI: 0.99, 1.06) per 10 $\mu g/m^3$; n=17 studies).

In addition to differences in combined estimates by study region, divergences were also observed according to participant age, existence of comorbidities, method of exposure measurement, year of publication and risk of bias of the studies.

2.5.2 Hospital Admissions

Linn W S et al (2000) conducted a time-series analysis to evaluate the association between NO_2 exposure and hospital admissions for cardiopulmonary diseases in individuals over 30 years residing in metropolitan Los Angeles from 1992 to 1995. Poisson regression analysis revealed a positive association between a 1 ppm increase in NO_2 concentration and the number of hospital admissions for cardiovascular diseases. Poisson regression coefficients (with standard errors) were 0.014 (0.002) $p<0.05$ (overall); 0.011 (0.005) $p<0.05$ (myocardial infarction); 0.010 (0.005) $p<0.05$ (congestive heart failure); 0.006 (0.005) $p>0.05$ (cardiac arrhythmia). Similar results were observed for hospital admissions for respiratory diseases. Poisson regression coefficients (with standard errors) were 0.007 (0.003) $p<0.05$ (overall); 0.014 (0.005) $p<0.05$ (asthma); and 0.008 (0.004) $p<0.05$) (COPD) [73].

Karr et al (2007) assessed the impact of sub-chronic and chronic exposure to NO_2 on risk of severe infant bronchiolitis requiring hospitalization. Study subjects were derived from hospital discharges in the South Coast Air Basin (n=18,595 cases) and matched each case to 10 controls (n=169,472) according to age and gestational age. No significant association was found [74].

Delfino et al (2014) in a case-crossover study of over 7,492 children ages 0-18 years in Orange County, California evaluated the relation between daily ambient NO_2 exposure at 1, 3, 5 and 7 days lags and hospital admissions and emergency department visits related to asthma from 2000 through 2008. NO_2 was significantly associated with hospital encounters only with 5- and 7-day averages [75].

Nhung NTT et al (2017) conducted a systematic review and meta-analysis of the short-term association between ambient air pollution and hospitalization of children due to pneumonia. Seventeen studies were included in the meta-analysis. Excess risk percentage per 10 ppb (18.8 $\mu g/m^3$) increase of NO_2 was 1.4% (95% CI: 0.4%; 2.4%). Associations were not substantially different between subgroups (children under five, emergency visits versus hospital admissions, income level of study location, and exposure period) [76].

Several systematic reviews and meta-analyses have summarised the evidence on short-term effects (from several hours to 7 days) of exposure to NO_2 on asthma exacerbations [16, 77, 78]. The last one published, conducted by Zheng XY et al (2021) analysed the evidence on short-term effects (from several hours to 7 days) of exposure to NO_2 on asthma exacerbations, defined as emergency room visits (including general practitioner's house calls, primary care visits) and hospital admissions [16]. Sixty-seven studies were included (48 included the data on children, 21 on adults, 14 on the elderly, and 31 on the general population) in developed and developing areas, both urban and rural. Independent analyses were carried out pertaining to the effect estimates from 24-hour concentrations and from 1-hour concentrations of NO_2. Considering emergency room visits and hospital admissions together, the pooled RR per 10 $\mu g/m^3$ increase of ambient concentration was 1.014 (95%CI: 1.008, 1.020) for average 24-hour NO_2. For the maximal 1-hour daily concentration of NO_2 the association was non-significant (pooled RR: 0.999 (95%CI: 0.966, 1.033) as per 10 $\mu g/m^3$ increase in the concentration). The strength of association did not differ significantly when stratified by the age, sex, or the type of exacerbations (emergency room visits or hospital admissions). According to the GRADE approach [79], the certainty of evidence for the associations between NO_2 (24-h) and emergency room visits or hospital admissions for asthma was high [16].

As regards chronic exposures, Delamater et al (2012) conducted an ecologic study to evaluate the relationship between asthma hospitalizations, levels of ambient NO_2, and weather conditions in Los Angeles County, California. Data from ambient monitoring stations were used to measure NO_2 exposure for all months from 2001 to 2008. Measures of temperature and relative humidity were also collected. NO_2 was significant and positively correlated with asthma hospitalizations after accounting for seasonality. One percent change in monthly average NO_2 was associated with a 0.37% (95% critical interval: 0.22, 0.52) increase in hospitalizations [80].

A recent study applying a robust multipollutant additive model assessed the associations between chronic exposure to NO_2 concentrations and hospital admissions among all 63 million fee-for-service Medicare beneficiaries aged 65 years and older living in USA between 2000 and 2016 [15]. The risk of hospital admissions with stroke increased by 0.00059% (95% CI, 0.00039–0.00075) per 1.88 $\mu g/m^3$ increase of annual NO_2. As regards atrial fibrillation, the risk of hospital admissions increased 0.00129% (95% CI, 0.00114–0.00148) per 1.88 $\mu g/m^3$ of annual NO_2 [15]..

2.5.3 Asthma

Schildcrout JS et al (2006) analysed the relationship between ambient concentrations of NO_2 and asthma exacerbations (daily symptoms and use of rescue inhalers) among 990 children in eight North American cities, during 22 months, as part of the Childhood Asthma Management Program (November 1993–September 1995) [81]. Short-term effects of NO_2 were examined using lags of up to 2 days. The outcomes studied were the dichotomous variable of any asthma symptoms versus none and the number of rescue inhaler uses. The strongest effects tended to be seen with 2-day lags, where increases of 20 ppb (37.6 $\mu g/m^3$) for NO_2 (24 hour average) were associated with asthma symptoms (OR: 1.09 [95% CI: 1.03; 1.15]) and with rate ratios for rescue inhaler use (OR: 1.05 [95% CI: 1.01, 1.09]). The study controlled for day of the week, ethnicity, family income, sensitivity to the methacholine challenge, season, temperature and humidity [81].

O'Connor GT et al (2008) followed 861 children ages 5-12 years with persistent asthma and atopy from seven US urban communities [82]. Participants recorded their daily lung function for two weeks every six months for two years. Asthma symptoms (wheeze/cough days, night-time asthma, slow play, missed school days per two-week period) data were collected every 2 months. Daily NO_2 measurements were obtained from the Aerometric Information Retrieval System. For the 10th to 90th percentile change (20.4 ppb / 38.3 µg/m^3 NO_2), positive associations with night-time asthma (OR: 1.37 [95% CI: 1.08; 1.73]), slow play (OR: 1.26 [95% CI: 1.04; 1.54]), and missed school (OR: 1.67 [95% CI: 1.18; 2.36]) over two week periods were found [82].

Lin W et al (2013) conducted a systematic review to synthesize the evidence available through 2013 about the association between indoor NO_2 exposure and asthma in children (≤18 years), including those studies reviewed previously [83]. The meta-analysis of 5 studies showed no statistically significant association (OR: 1.09, 95% CI: 0.91–1.31 for a 15-ppb increase in NO2) [10].

Li W et al (2023) [65] updated the review on this topic including studies in the Lin et al. meta-analysis [10] and new studies published up to 2018. A quantitative synthesis was not considered appropriate because literature, including that meta-analysed by Lin et al, was limited by high heterogeneity across studies, inconsistency between studies with reliable designs (10 of the 20 studies used a cohort study design), and low study quality (especially with respect to tempo-rality and confounding adjustment) [10]. The authors concluded that the reviewed evidence up to 2018 did not support causality [65].

The recent State of Global Air acknowledges that NO_2 exposure is associated with increased frequency and severity of asthma symptoms, a higher likelihood of hospitalization and that NO_2 is consistently identified as the air pollutant most strongly linked to asthma cases in children [84].

2.5.4 Other respiratory outcomes

Lin W. et al. (2013) conducted a meta-analysis to synthesize the evidence available up to 2013 regarding the association between indoor nitrogen dioxide (NO2) exposure and wheezing in children aged 18 and younger [10]. This analysis included studies previously reviewed by Hasselblad V (1992) [83]. The meta-analysis of 11 studies demonstrated a positive association between indoor NO_2 exposure and wheezing. Specifically, for every 15 parts per billion (ppb) increase in NO_2 concentration, the odds of wheezing increased by 12% (odds ratio [OR]: 1.12, 95% confidence interval [CI]: 1.04, 1.21).

Subsequently, Li W (2023) et al updated the review on this topic including studies in the Lin et al. meta-analysis [10] and new studies published up 2018 [65]. A meta-analysis was not considered appropriate given high heterogeneity across studies, the lack of consistency among studies with reliable designs (7 of the 16 studies used a cohort study design), and low study quality (especially with respect to temporality, confounding adjustment and sample selection). The authors concluded that the evidence reviewed in 2018 did not support causality [65].

Atkinson et al (2018) reviewed 20 studies reporting results between NO_2 exposure and lung cancer mortality. They identified that exposure to NO_2 was significantly associated with increased hazard ratio of lung cancer mortality (1.05 [95% CI: 1.02, 1.08]) [11].

2.6 Economic costs associated with NO_2 exposure

The economic burden of gas cooking is significant including lower life expectancies due to premature mortality associated with COPD [4]. Exposure to NO_2 emitted from gas cooking has been also associated with increased incidence of preterm birth [85], and incidence and prevalence of chronic diseases such as paediatric asthma [10], COPD [86], diabetes mellitus, and incidence of lung cancer [85, 87]. The increased chronic morbidity represents greater healthcare expenditure, and lower productivity [53, 87]. In addition, premature mortality has an important societal cost [88].

2.6.1 Societal cost of health effects related with gas cooking

The OECD (2012) described that the social cost of mortality can be expressed in terms of the VSL, which is a measure of the value a society places on avoiding the death of an unidentified person [19]. Kashtan et al. (2024) estimated that gas and propane stoves were responsible for 19,000 (95% CI: 8,500, 34,000) deaths due to long-term NO_2 exposure from gas and propane stoves in the United States [38]. Applying the VSL used by the US Environmental Protection Agency, each death linked with gas and proprane exposure represented an annual cost to society of $250 (95% CI: 75, 480) billion [36]. The same study estimated that gas and propane stoves were responsible for 200,000 (95% CI: 20, 410) current cases of paediatric asthma in the United States. Kashtan et al. (2024) calculated that the presence of a gas stove at home accounted for 3.8 % (95% CI: 0, 8%) of paediatric asthma

PAF, whereas long-term exposure to NO_2 from gas stoves was responsible for 0.09 % (95% CI: -1.33, 3 %). Applying the VSL value to asthma-induced deaths in combination with the cost of asthma-related medical costs, the use of gas and propane for cooking represented a societal cost of $1 billion (95% CI: 0, 2) in the United States [36].

Gruenwald et al (2023) also conducted an HIA to estimate the fraction of childhood asthma attributed to gas cooking emissions. They reported that 12.7 % (95% CI: 6.3, 19.3%) of current childhood asthma in the United States is attributable to gas stove use [37]. However, no economic valuation was conducted on that study.

Another measure to represent societal cost related with poor health outcomes is the DALY, which is a measure of overall disease burden and expresses the number of years lost due to ill-health, disability, or early death. That is, DALYs represents the loss of the equivalent of one year of full health [89]. In a study conducted in Australia, Knibbs et al (2018) estimated that gas cooking emissions were responsible for 12.3% (95% CI, 8.9–15.8%) of paediatric asthma population attributable fraction (in %), representing 2,756 DALYs (95% CI: 1271, 4242), or 67 DALYs per 100 000 children aged 14 years or less. They estimated that the use of range hoods vented outdoors in all Australian households would reduce the burden of paediatric asthma to 761 DALYs (95% CI: 322, 1199) [35].

Based on the 2019 health data from the International Respiratory Coalition [90], the number of DALYS lost due to asthma in the EU region was estimated at 1 million DALY and for the UK 275,000 DALYs. Societal cost of paediatric asthma related to gas cooking indoor air pollution in the EU region is estimated at 3.5 billion euro annually and 1.6 billion euro in the UK [90].

3. OBJECTIVES

The overall aim of this study is to assess the health impacts and costs associated with the levels of NO_2 observed indoors in homes that use gas-cooking appliances in the European Union and the United Kingdom and the health impact and economic cost reduction associated with the implementation of policy recommendations aimed at using cleaner energy for cooking.

The specific objectives are:

- To estimate the burden of mortality attributable to exposure to NO_2 indoors in households that use gas-cooking appliances compared to households that use cleaner cooking energy appliances in the European Union and the United Kingdom, focusing on all-cause premature mortality and years of life lost.

- To assess the economic value associated with the burden of mortality attributable to exposure to NO_2 indoors in households that use gas-cooking appliances compared to households that use cleaner cooking energy appliances in the European Union and the United Kingdom, focusing on all-cause premature mortality and years of life lost.

- To estimate the burden of paediatric and total asthma attributable to exposure to NO_2 indoors and presence of gas cookers in households that use gas-cooking appliances compared to households that use cleaner cooking energy appliances in the European Union and the United Kingdom.

- To assess the economic value associated with the burden of paediatric and total asthma attributable to exposure to NO_2 indoors and presence of gas cookers in households that use gas-cooking appliances compared to households that use cleaner cooking energy appliances in the European Union and the United Kingdom.

4. METHODOLOGY

4.1 Health Impact Assessment

4.1.1 HIA Methodology

The current HIA calculates the burden of disease attributable to the presence of gas-cooking appliances at home and to the exposure to NO_2 emitted from gas cooking appliances. It assumes a causal role of chronic NO_2 exposure on premature mortality and paediatric asthma cases, and a causal role of the presence of gas-cookers on paediatric and total asthma cases [91].

The PAF provides a measure of the public health impact of the exposure to NO_2 emitted from gas cooking appliances in the European population. The term “attributable” has a causal interpretation, and represents the estimated fraction of all cases that would not have occurred if there had been no exposure [92] to NO_2 emitted from gas cooking appliances or the household would not have had a gas cooker at home.

In this study, PAF is defined as the fraction of all cases of a given health outcome in the European population that is attributable to the exposure to NO_2 emitted from gas cooking appliances or to the presence of a gas-cooker at home. According to Equation 1 [92]:

$$PAF = \frac{\mathrm{O} - \mathrm{E}}{\mathrm{O}} \quad \text{Equation 1}$$

where O and E refer to the observed number of cases and the expected number of cases under no exposure, respectively [93]. In this case, the population under no exposure is the population not exposed to NO_2 from gas cooking appliances, who will live in households that cook with clean cooking (i.e. electric) appliances, which do not emit NO_2. The level of NO_2 indoors in not exposed households (i.e. those cooking with electric appliances) would come from external sources such as NO_2 emitted from traffic and industrial that infiltrated indoors. The population exposed refers to the population in households that cook with gas appliances, and their level of NO_2 exposure would be the addition of the NO_2 from outdoor sources infiltrated indoors, and the level of NO_2 emitted from gas cooking appliances.

Equation 1, can be rewritten as follows [94]:

$$PAF = p_c \frac{R_1 - R_0}{R_1} = \frac{\mathrm{RR} - 1}{\mathrm{RR}} \quad \text{Equation 2}$$

considering that the number of cases observed in the exposed (O) and non exposed population (E) in Equation 1 is equivalent to the risk of health outcome among the exposed (R_1) and the risk of the health outcome among the non exposed (R_0), with $RR = R_1/R_0$ being the risk ratio, multiplied by the fraction of cases exposed in the combined population (p_c).

Equation 2 can be rearranged as follows [94]:

$$PAF = \frac{p_c \times (\mathrm{RR} - 1)}{p_c \times (\mathrm{RR} - 1) + 1} \quad \text{Equation 3}$$

Equation 3 was used by Knibbs et al (2018) [35] and by Gruenwald et al (2022) [37] to estimate the PAF associated with exposure to NO_2 from gas cooking in Australia and USA respectively.

The burden of disease (BoD) attributed to the exposure to NO_2 emitted from gas cooking appliances ($BoD_{NO2\text{-}gas}$) is then calculated considering the background burden of disease (BoD_{total}) in the general population multiplied by the PAF [35].

$$BoD_{NO2-gas} = \mathrm{PAF} \times BoD_{Total} \quad \text{Equation 4}$$

The RR in Equations 2 and 3 can be replaced by rate ratios (or odds ratios, OR) when the rate ratios (or OR) approximate the corresponding risk ratio, which is generally true for rare diseases [94, 95]. According to Steenland and Armstrong (2006), incidence rates could also be used instead of risk ratios [94]. The RR applicable to the difference between the exposed concentration (C_2) and the counterfactual (C_1) concentration can be derived according to the following equation:

$$RR = {RR_0}^{[(C_2 - C_1)/\Delta C]} \quad \text{Equation 5}$$

where RR_0 is the original RR of the CRF expressed for a given ΔC increment on the concentration (e.g. every 10 µg/m^3 of NO_2), C_2 is the concentration of NO_2 in the highest exposure, in this case the NO_2 indoor levels associated with gas cooking in households, and C_1 is the NO_2 levels associated with the counterfactual (e.g. NO_2 indoors in households cooking with electric appliances).

For instance if the mortality increases 2% for each 10 µg/m^3 of NO_2 exposure, the original RR_0 would be 1.02 for an increment of 10 µg/m^3 as identified in the scientific literature [4]. To calculate the relative risk RR for a change in concentration from 25 µg/m^3 compared with a counterfactual concentration of 5 µg/m^3, according to Equation 5, the RR would be $RR = 1.02^{[(25-5)/10]} = 1.04$. If 7% of the population uses gas-cooking appliances, p_c would be 0.07 and the PAF would be 0.00282 according to Equation 3, equivalent to a population attributable percentage of 0.28%. Considering a mortality rate of 70 per 100,000 inhabitants, and a population of 2 million people, the burden of mortality in the area under study (BoD_{Total}) would be 1400 deaths per year, and the burden of mortality associated to exposure to NO_2 from gas cooking ($BoD_{NO2\text{-}gas}$) would be 4 premature deaths each year, according to Equation 5.

4.1.2 HIA Data source requirements

According to Hurley and Vohra (2010) several elements are required to conduct a HIA [96] following the Equations 1 to 4 described above. These elements include:

1. A set of pollutant-health combinations. The pollutant of interest in this study is NO_2, a characteristic gas emitted by gas cooking appliances. As regards health, this study will focus on mortality and asthma.
2. For each pollutant-health combination, a CRF is required to be able to quantify the impact. CRF expresses quantitatively the relationship between exposure to NO_2 and

the health outcome of interest, e.g. premature mortality, paediatric asthma, by means of a relationship. For instance, each 28.2 μg/m^3 increase in NO_2 exposure is associated with a 9% increase in (current and lifetime) asthma cases. The CRF is the RR, OR or Incidence rates specific for each pollutant-health outcome of interest are identified from peer-reviewed literature.

3. Background information of the population and circumstances for which the health impact is assessed. This requires knowledge of:
    a. The NO_2 concentrations indoors in households that use gas cooking in comparison with levels in households that use cleaner cooking appliances (e.g. electric hobs).
    b. The composition of the population, preferably disaggregated by age.
    c. The background rates (prevalence) of the health outcomes, i.e. the frequency of occurrence of the assessed health outcomes in the population of interest.

4.2 Concentration-response functions

4.2.1 Criteria to consider for applying concentration-response functions derived outdoors to indoor environments

Several criteria should be fulfilled to select the best CRF to be used in HIA. These include that the relationship should imply causality, in terms of calculating the impact attributable to the removal of the risk under consideration. Secondly, the CRF should not be affected by exposure to other pollutants. In this respect, those studies that evaluate the exposure in multipollutant models and find that the association remains invariable, add weight to the association and certainty that the associations observed might be causal and attributable to the exposure to the risk under consideration, in this case NO_2 exposure. Thirdly, to conduct a HIA for chronic exposures, the CRF should be derived from population studies, such as cohort studies or panel studies with chronic exposures.

As regards causality, several reviews have discussed whether the relationships observed between exposure to NO_2 or the presence of a gas cooker in the household is causally associated with the health outcome under review.

According to the External Review Draft of the 2015 ISA, the USEPA stated that long-term respiratory health effects are deemed likely to be a causal relationship. On the other hand, the U.S. EPA reviewed the weight of the evidence and considered that the association between chronic exposure to NO_2 and non-respiratory endpoints, such as cardiovascular is "suggestive, but not sufficient" [68, 97].

Li W et al [65] reviewed the studies available up to 2018 as regards gas cooking and NO_2 exposure with asthma and wheeze, as well as in children (≤18 years). They concluded that the evidence did not support causality due to high heterogeneity across studies, the small number of reliable study designs, and low study quality with respect to exposure assessment, temporality, confounding adjustment and sample selection.

A recent meta-analysis [4] concluded that associations between exposure to NO_2 with mortality was rated moderate for all-causes, respiratory and ALRI and high for COPD mortality.

A recent review by Huang S et al in 2021 included a sensitivity analysis pooling estimates from multi-pollutant models suggested that the effect of NO_2 on mortality might be independent of other common air pollutants [12].

4.2.2 Selected concentration-response functions

The current HIA evaluated the impacts of exposure to NO_2 emitted from gas cooking on mortality, as well as on paediatric asthma prevalence. Likewise, it also evaluated the impact of having a gas cooker at home with paediatric and total (paediatric and adult) asthma.

The association between exposure to NO_2 emitted from gas cooking and the health-outcome frequency is described with a CRF. The CRFs were selected from systematic reviews available in the peer-reviewed literature.

Table 1 compiles the CRF selected to conduct the HIA. The CRFs have been selected assuming that the meta-analysed risk estimates for associations between chronic NO_2 exposure and all-cause adult mortality or paediatric asthma could be extrapolated from outdoors to indoor environments.

Table 1. Health data and concentration-response relationships between chronic exposure to NO_2 or gas cooking and the selected health outcomes used in the assessment

Health Effect	**Impact Measure**	**Population**	**Odds Risk (OR), Relative risk (RR) of the dose-response relationships**	**Exposure measure**	**Reference of the dose-response relationships**
Non-accidental chronic mortality	Life years lost (YLL)	All ages	RR = 1.02 (95% CI: 1.01, 1.04)	10 µg/m^3 increase in NO_2 exposure	Huangfu and Atkinson (2020) [4] (ETC/ATNI Report 04/2020) [98]
Premature Mortality (30yrs+) deaths	Premature deaths	30-70 years old	RR = 1.008 (95% CI: 1.004,1.016)	10 µg/m3 increase in NO_2 exposure	Huangfu and Atkinson (2020) [4] (ETC/ATNI Report 04/2020) [98]
Paediatric asthma prevalence (current and lifetime)	Cases	<20 years old	RR = 1.09 (95% CI: 0.91, 1.31)	28.2 µg/m^3 (15 ppb) increase in NO_2 exposure	Lin W et al (2013) [10]
Paediatric asthma prevalence (current and lifetime)	Cases	<20 years old	OR = 1.32 (95% CI: 1.18, 1.48)	Presence of gas stoves at homes	Lin W et al (2013) [10]
Total (paediatric and adult) asthma	Cases	All ages	OR = 1.11 (95% CI: 1.01, 1.21)	Presence of gas stoves at homes	Puzzolo et al (2024) [9]

4.3 Estimation of indoor exposures to NO_2 according to cooking fuel per country

The indoor NO_2 exposures were estimated using data provided in the study conducted by Jacobs et al (2023) as regards the concentrations measured indoors at homes that use gas and electric appliances for cooking [7]. The NO_2 concentrations measured by the passive samplers during the sampling campaign in a representative room within the household, such as the living room, were selected to represent the typical indoor NO_2 concentrations within a household.

Information on geolocation, i.e. postcode centroid representative of the household, contained in the Jacobs et al (2023) database was used to estimate ambient exposures at the postcode centroid representative of the household. Thus ambient NO_2 were interpolated from the 2021 maps produced by the EEA [2].

An NO_2 indoor-to-outdoor ratio (NO_2 I/O) was calculated combining the NO_2 concentrations measured by Jacobs et al (2023) with the passive samplers indoors in the living room [2], with the NO_2 concentrations estimated at the postcode centroid representative of the household using the NO_2 2023 interpolated EEA maps [2].

To evaluate which NO_2 I/O should be used to estimate the indoor NO_2 concentrations for all the households in EU and UK, additional metadata was included in the database namely:

1. the degree of urbanicity using the Degree of Urbanization Eurostat Database according to the three classes of Urban-rural typology [99]
2. socioeconomic (SES) information, such as the SES quintile, using the population at risk of poverty or social exclusion [100]
3. the classification of the country where the household was located according one of three clusters (Eastern Europe, Southern Europe and North-Western Europe) as classified by Gregor et al (2018) EU report (Cluster A, Cluster B, Cluster C+D, respectively) [18].

An ANOVA was performed to assess if there were any differences in the NO_2 I/O according to the socioeconomic status, degree of urbanicity, country cluster and cooking appliance. Differences were only statistically significant according to cooking appliance and country cluster. Table 2 displays the NO_2 I/O calculated according to country cluster for households that use gas and electric appliances.

Table 2. Indoor to outdoor (I/O) ratio of NO_2 concentrations according to cooking appliance and country cluster calculated using indoor and outdoor data collected in real world households from 7 European countries [7].

Country cluster	Countries in cluster	NO_2 I/O for gas cooking households	NO_2 I/O for electric cooking households
Eastern Europe	Estonia, Latvia, Lithuania, Poland, Czech Republic, Slovakia, Slovenia, Hungary, Romania, Bulgaria, Turkey	1.50 ± 1.57	0.64 ± 0.34
Southern Europe	Spain, Italy, Portugal, Greece, Cyprus, Malta, Croatia	1.59 ± 1.14	0.91 ± 0.60
North West	Belgium, Denmark, Germany, Ireland, France, Luxembourg, Netherlands, Austria, Finland, Sweden	1.30 ± 0.65	0.76 ± 0.39
UK	UK	1.36 ± 1.42	0.66 ± 0.27

Based on the NO_2 concentrations and the population information at the NUTS 3 level, the population-weighted exposure level (PWEL) at the NUTS 3 level was calculated according to the following equation:

$$PWEL = \frac{\sum_i^I population_i \times NO_{2,i}}{\sum_i^I population_i} \quad \text{Equation 6}$$

Where $population_i$ is the total population in a NUTS 3 i region, $NO_{2,i}$ is the NO_2 concentration averaged over a NUTS 3 i region, and I is the total amount of NUTS 3 regions.

PWELs were averaged at the NUTS 2, NUTS 1 and country level to obtain a population-weighted exposure level at the same resolution as the background health outcome database, generally at NUTS 2 or country level, except for mortality, which was available at the NUTS 3 level.

4.4 Description of population composition

For European countries, the population composition was extracted from Eurostat. The population was described on 1 January of 2018 by broad age group, sex and NUTS 3 region (demo_r_pjanaggr3). For those cases where no population was available for 2018, data from 2017 was selected instead. This was the case for Portugal and Luxembourg. Population data was available at:

https://ec.europa.eu/eurostat/api/dissemination/sdmx/2.1/data/demo_r_pjanaggr3?format=TSV&compressed=true

The UK population was extracted from the ONS (2021) publication. It includes population estimates for 1 January 2020 as supplied to Eurostat as part of the Unified Demographic Data Collection (population, number of people) 2019. UK population is available at:

https://www.ons.gov.uk/file?uri=/peoplepopulationandcommunity/populationandmigration/populationestimates/adhocs/13079populationestimatesfor1january2020onnutsboundariesunifieddemographiccollectionforeurostat/unidemopublishing.xlsx

Population data was aggregated to calculate the population distribution in each NUTS 3, NUTS 2 and NUTS 1 region aged 0-20 years old, 0-70 years old and 20-70 years old.

4.5 Description of health outcome background rates

The background rates (prevalence) of the health outcomes, i.e. the frequency of occurrence of the assessed health outcomes in the European population are listed in Table 3.

Table 3. Health outcomes background rates

Health Effect	Impact Measure	Population	Database description	Source
Non-accidental chronic mortality	Life of years lost (YLL)	<70 years old	Years and potential years of life lost (YLL) by NUTS 2 regions of residence, 3 year average (hlth_cd_ypyll). The YLL rate is expressed per 100 000 age-standardised population under 70. 2018 YLL selected for all countries, except Portugal and Luxembourg, for which 2017 YLL were used.	https://ec.europa.eu/eurostat/api/dissemination/sdmx/2.1/data/hlth_cd_ypyll?format=TSV&compressed=true
Premature Mortality (30yrs+) deaths	Premature deaths	30-70 years old	Deaths by age group, sex and NUTS 3 region (demo_r_magec3). Premature mortality accounts for all cases of deaths from 30-70 years old	https://ec.europa.eu/eurostat/api/dissemination/sdmx/2.1/data/demo_r_magec3?format=TSV&compressed=true
Paediatric asthma prevalence	Cases	<20 years old	Paediatric asthma prevalence rate by age in WHO European Region in 2019. This is the number of new and pre-existing cases per 100,000 people. This includes all paediatric cases, both male and female, by age group	https://e.infogram.com/a3bdc20a-b81c-4147-bcc1-616051d15500?parent_url=https%3A%2F%2Finternational-respiratory-coalition.org%2Fdiseases%2Fasthma%2F&src=embed#
Adult asthma prevalence	Cases	>20 years old	Age-standardised asthma prevalence rate for the WHO European Region in 2019. This is the number of new and pre-existing cases per 100,000 people within the year. The rate is age standardised, which means it provides a weighted average that controls for differing age distributions between countries	https://infogram.com/asthma-prevalence-numbers-1hxr4zxwwrpyo6y

4.6 Description of baseline and modelling scenarios

The baseline scenario calculated the burden of disease related with indoor NO_2 exposure from gas cooking considering the current share of population that use gas appliances for cooking. This scenario considers business as usual and estimates NO_2 concentrations indoors combining an indoor-to-outdoor ratio derived from the Jacobs et al (2023) study [7] according to cooking appliance, with ambient NO_2 concentrations derived from the EEA map [2] as described in detail in Section 4.3. The number of households that have indoor NO_2 concentrations representative of gas-cooking or electric-cooking households takes into consideration the current share of households that use gas and electric appliances for cooking in the EU and UK reported by Eurostat [1].

The alternative scenario, or counterfactual value, calculated the burden of disease related with indoor NO_2 exposure considering that all households use clean methods for cooking. This implies replacing all gas cooking appliances that emit NO_2 for cleaner cooking appliances, such as electric hobs. In the alternative scenario, all NO_2 concentrations indoors have an outdoor origin and are estimated using the indoor-to-outdoor ratio measured in households that use electric appliances, derived from the Jacobs et al (2023) study [7], as described in detail in Section 4.3.

4.7 Economic valuation

4.7.1 Mortality

4.7.1.1 Premature deaths

The value of a statistical life (VSL) is a measure of the value a society places on avoiding the death of an unidentified person. VSL is based on individuals' willingness to pay for small reductions in risk, which can be elicited either via surveys in which the respondents are presented with hypothetical scenarios involving trade-offs between risk and money, or based on individuals' observed choices between, for example, risky versus less-risky jobs with different wage levels. OECD (2012) describes a very comprehensive review of the literature to estimating VSL in environmental, health and transport risk contexts, based on this approach and presents summary VSL estimates for different geographical regions [101].

To value the premature deaths due to gas cooking in economic terms we use the value of a statistical life (VSL) provided in the OECD (2012) review [101], included in the EIONET report [98]. We use the median VSL value for the EU-27 published in OECD (2012), which we first convert from 2005-USD to 2005-EUR using PPP-adjusted exchange rates for 2005, and then update to 2023-EUR by adjusting for inflation and income growth. The resulting VSL value for the EU-27 updated to 2023 is equal to 4.35 million EUR. To calculate VSL values for individual countries within the EU-27, we use the unit value transfer with income adjustment method described in OECD (2012) [101].

The economic value related to premature mortality was calculated multiplying the number of premature deaths in each country due to exposure to NO_2 from gas cooking times the 2023 country adjusted VSL value.

4.7.1.2 Years of Life Lost (YLL)

A closely related concept to VSL is the value of a statistical life year (VSLY), also known as value of a life year (VOLY). As shown in OECD (2012) this can be related to VSL using the following equation [101]:

$$VSL = \sum_t^T VSLY \cdot (1+\delta)^{-t} \qquad \text{Equation 7}$$

where T is the number of remaining life years and δ is a discount rate to reflect that life years are more valuable in the near future than in the more distant future. This equation can be used to derive VSLY values from VSL estimates, and while this is common practice, some authors note that there is limited empirical evidence supporting it [102].

To value the economic cost of the years of life lost (YLL) due to gas cooking in economic terms we estimate the value of a statistical life year (VSLY), as described in Equation 7. This is derived from the country-level 2023 updated VSL values by dividing VSL by the average remaining life expectancy at 35 years old for the relevant population, discounted by an annual rate of 4 percent [102].

The economic value related to the years of life lost due to premature mortality was calculated multiplying the number of years of life lost in each country due to exposure to NO_2 from gas cooking times the 2023 country adjusted VSLY value.

4.7.2 Asthma

The social costs of childhood asthma can be quantified in terms of disability-adjusted life-years (DALYs), which is a measure of the number of years lost due to ill-health, disability or premature death. The DALYs can be valued in monetary terms using the VSLY-approach described in section 4.7.1.2.

To value the impact of childhood asthma in economic terms we use a similar approach to the one used to value the life years lost in section 4.7.1.2. We first calculate the proportion of childhood asthma cases that are due to gas cooking, and then multiply this proportion by the DALYs lost by country due to childhood asthma from the 2021 Global Burden of Disease Study [17]. The DALYs are then valued using VSLY values derived by dividing the country-level VSL values described in section 4.7.1.1 by the average remaining life expectancy at 18 for the relevant population, discounted by an annual rate of 4 percent.

5. RESULTS AND DISCUSSION

5.1 Estimation of indoor NO_2 exposures in homes that use gas cooking

The hypothetical NO_2 concentrations indoors in a household that uses gas and electric appliances for cooking were estimated using the ambient NO_2 interpolated from the 2021 maps produced by the European Environment Agency [2] for each geolocation in Europe (Figure 5) and the corresponding NO_2 I/O according to the country cluster (Table 2). Thus, for each geolocation, an estimated indoor NO_2 concentrations representative of the NUTS 3 level geographical unit was estimated for each type of cooking appliance (i.e. gas and electric). Estimated NO_2 indoor levels are shown in (Figure 6) for households using gas appliances for cooking. Another estimation of the indoor NO_2 concentration was calculated for households using electric appliances for cooking (Figure 7).

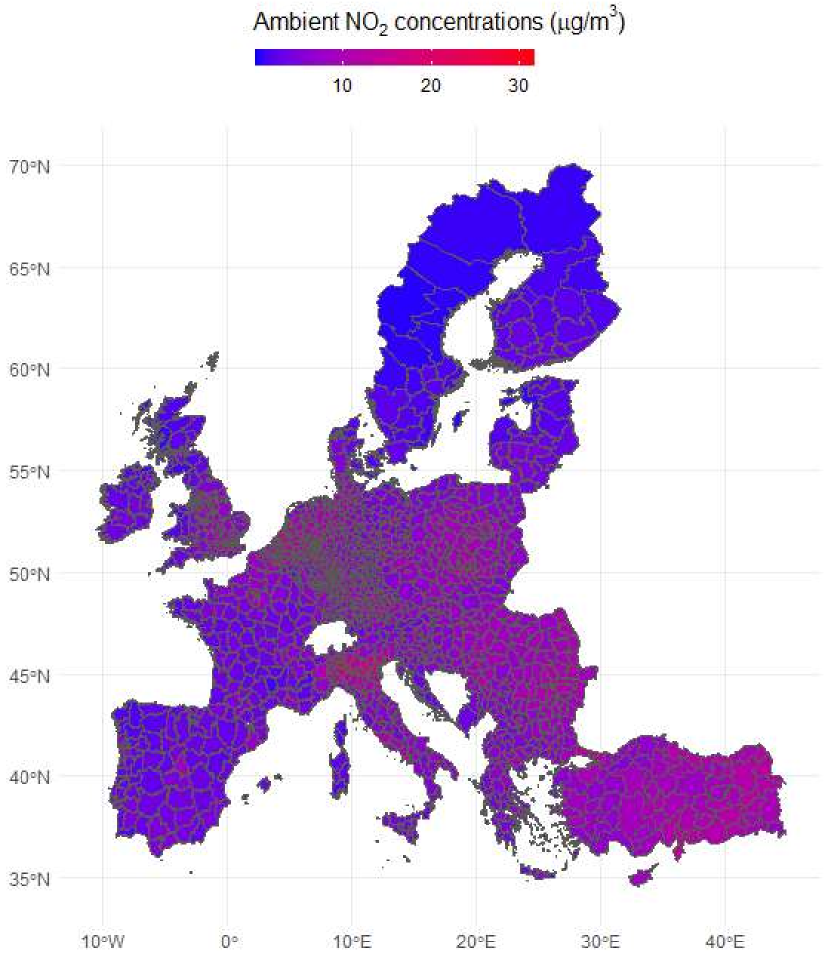

Figure 5. Ambient NO_2 concentrations ($\mu g/m^3$) interpolated from the 2021 maps produced by the European Environment Agency [2] for each geolocation in Europe for each NUT3 level [3]. Ambient NO_2 concentrations range 1.51 ± 0.72 $\mu g/m^3$ in Sweden to 10.86 ± 2.69 $\mu g/m^3$ in the Netherlands.

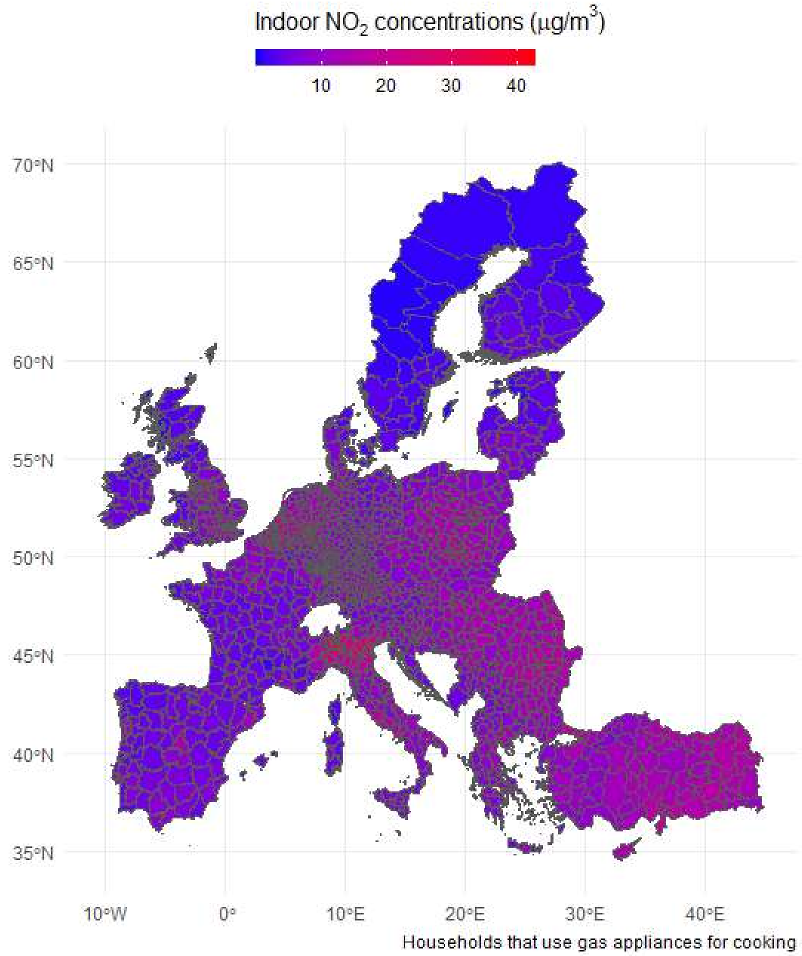

Figure 6. Indoor NO_2 concentrations (µg/m^3) in households that use gas appliances for cooking for each geolocation in Europe for each NUT3 level [3] estimated by combining information on ambient NO_2 interpolated from the 2021 maps produced by the European Environment Agency [2] and NO_2 I/O ratio according to country cluster (Table 2). Indoor NO_2 concentrations in gas-cooking households range 1.96±0.93 µg/m^3 in Sweden to 14.14±3.50 µg/m^3 in the Netherlands.

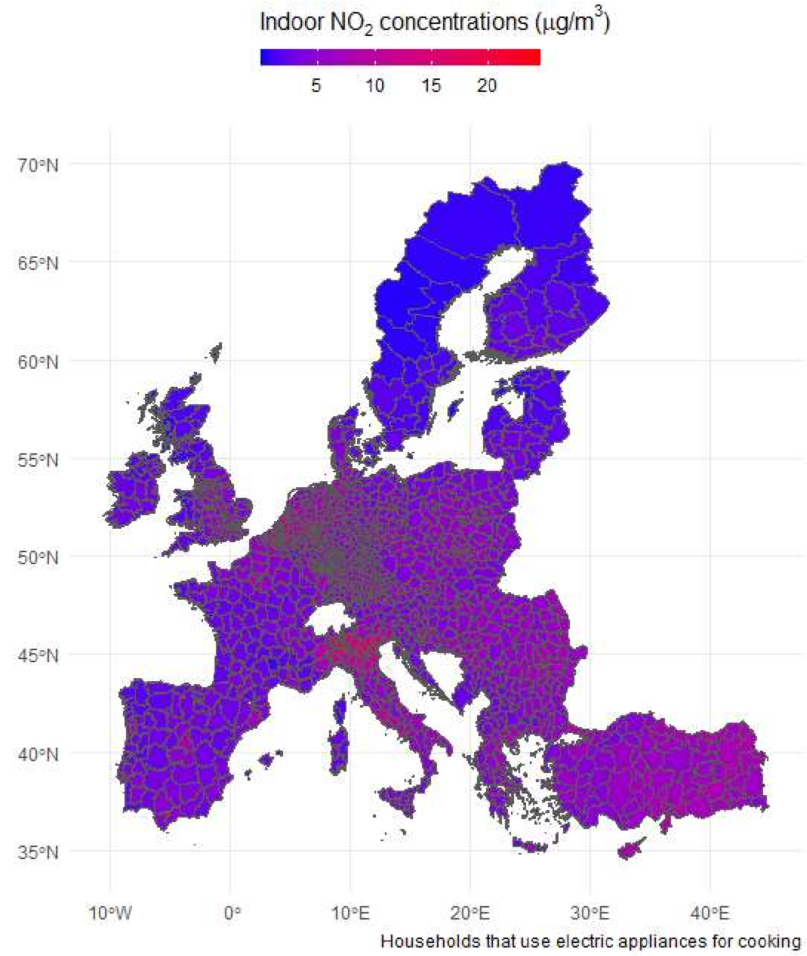

Figure 7. Indoor NO_2 concentrations (µg/m^3) in households that use electric appliances for cooking for each geolocation in Europe for each NUT3 level [3] estimated by combining information on ambient NO_2 interpolated from the 2021 maps produced by the European Environment Agency [2] and NO_2 I/O ratio according to country cluster (Table 2). Indoor NO_2 concentrations in electric-cooking households range 1.15±0.55 µg/m^3 in Sweden to 8.28±2.05 µg/m^3 in the Netherlands.

Table 4 summarises the NO_2 concentrations (µg/m^3) and PWEL (µg/m^3) averaged at the country level for ambient air, as well as the estimation for indoor air concentrations in households using gas and electric appliances for cooking.

Table 4. NO_2 concentrations (μg/m^3) in ambient air and estimated NO_2 concentrations and Population-Weighted Exposure Level (PWEL) (μg/m^3) indoors in households that cook with gas and electric appliances by country

	NO_2 Ambient		**NO_2 Indoor Gas hob**		**NO_2 Indoor Electric hob**		**PWEL NO_2 Ambient**	**PWEL NO_2 Indoor Gas hob**	**PWEL NO_2 Indoor Electric hob**
Country	**Mean**	**SD**	Mean	SD	Mean	SD			
Austria	6.88	2.17	8.96	2.83	5.25	1.66	8.92	11.61	6.80
Belgium	10.49	3.37	13.66	4.38	8.00	2.57	12.81	16.69	9.77
Bulgaria	7.93	1.51	11.95	2.28	5.14	0.98	8.56	12.91	5.56
Croatia	6.13	2.16	9.80	3.46	5.62	1.98	4.00	6.39	3.66
Cyprus	8.75	*	13.98	*	8.02	*	8.75	13.98	8.02
Czech Republic	7.89	2.15	10.74	2.93	5.26	1.44	8.47	11.53	5.64
Denmark	3.77	2.15	4.91	2.80	2.87	1.64	4.25	5.53	3.24
Estonia	2.20	0.71	3.32	1.06	1.43	0.46	2.19	3.30	1.42
Finland	2.45	1.00	3.20	1.30	1.87	0.76	2.89	3.76	2.20
France	5.56	4.26	7.24	5.55	4.24	3.25	7.35	9.57	5.60
Germany	9.54	3.42	12.42	4.46	7.28	2.61	10.87	14.15	8.29
Greece	6.47	4.84	10.33	7.73	5.92	4.43	9.74	15.57	8.93
Hungary	8.37	3.06	12.61	4.61	5.43	1.99	10.28	15.49	6.67
Ireland	4.22	1.68	5.49	2.18	3.21	1.28	4.94	6.43	3.77
Italy	8.71	4.55	13.92	7.26	7.98	4.16	10.83	17.31	9.93
Latvia	4.01	3.01	6.05	4.54	2.60	1.95	5.20	7.84	3.38
Lithuania	4.51	0.53	6.80	0.80	2.93	0.35	4.51	6.80	2.93
Luxembourg	7.55	*	9.83	*	5.76	*	7.55	9.83	5.76
Malta	4.99	2.16	7.97	3.45	4.57	1.98	6.30	10.07	5.77
Netherlands	10.86	2.69	14.14	3.50	8.28	2.05	11.82	15.39	9.02
Poland	8.74	3.02	13.18	4.54	5.67	1.96	9.39	14.15	6.09
Portugal	4.24	1.63	6.78	2.60	3.89	1.49	5.49	8.77	5.03
Romania	9.84	3.13	14.83	4.72	6.38	2.03	11.18	16.85	7.25
Slovakia	6.93	0.90	10.45	1.36	4.50	0.59	6.88	10.37	4.46
Slovenia	6.78	1.05	10.22	1.58	4.40	0.68	7.28	10.97	4.72
Spain	3.98	1.87	6.36	2.99	3.65	1.71	4.80	7.67	4.40
Sweden	1.51	0.72	1.96	0.93	1.15	0.55	1.89	2.46	1.44
United Kingdom	9.47	4.86	12.9	6.62	6.31	3.24	11.03	15.01	7.35

** SD cannot be calculated as there is only one territorial unit in each NUT level.*

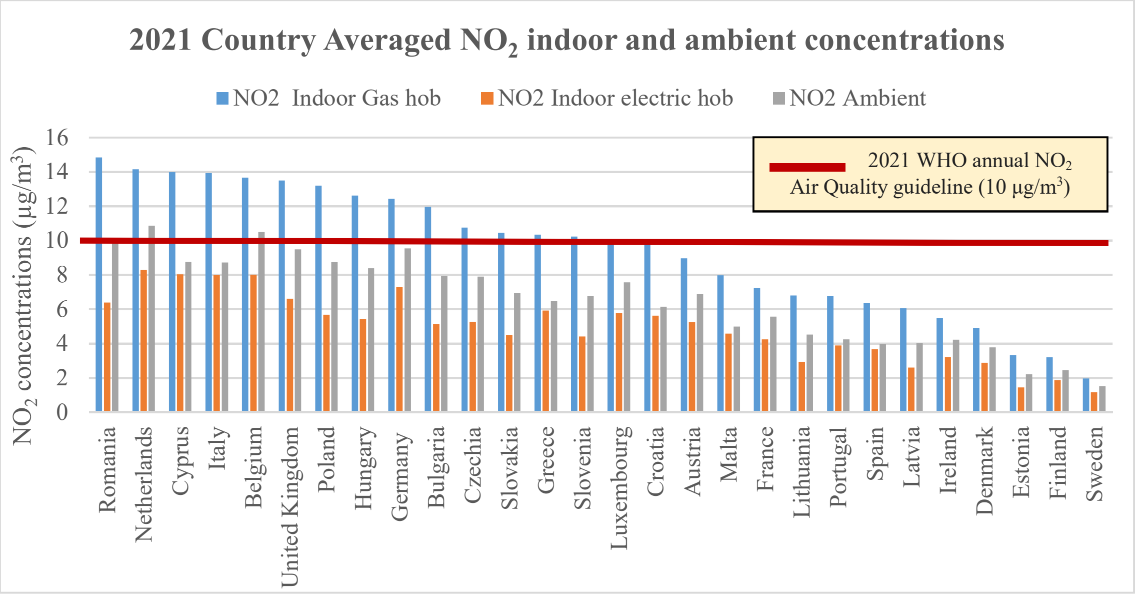

Figure 8. NO_2 concentrations (µg/m^3) in ambient air and indoors in households that use gas and electric appliances for cooking for each country estimated by combining information on ambient NO_2 interpolated from the 2021 maps produced by the European Environment Agency [2] and NO_2 I/O ratio according to country cluster (Table 2). The horizontal red line represents the 2021 WHO annual NO_2 Air Quality guideline (10 µg/m^3). Concentrations above the red line exceed the 2021 WHO annual NO_2 Air Quality guideline.

Figure 8 shows the distribution of averaged country NO_2 concentrations in ambient locations interpolated from the 2021 maps produced by the European Environment Agency [2] as well as the indoor NO_2 concentrations estimated in homes that use gas or electric appliances for cooking taking into consideration the NO_2 I/O ratios in Table 2. Only two countries (The Netherlands and Belgium) have country-averaged ambient concentrations that exceed the 2021 WHO annual NO_2 Air Quality guideline (10 µg/m^3). Considering the country-averaged estimated concentrations, estimated NO_2 concentrations in households that use gas appliances for cooking are higher than NO_2 concentrations outdoors, whereas indoor NO_2 concentrations in households that use electric appliances are lower than ambient NO_2 concentrations (Figure 8 and Table 4). In addition, country-averaged indoor concentrations of NO_2 in households that use gas cooking are higher than the 2021 WHO annual NO2 Air Quality guideline in 14 countries. These are Romania, Netherlands, Cyprus, Italy, Belgium, United Kingdom, Poland, Hungary, Germany, Bulgaria, Czech Republic, Slovakia, Greece and Slovenia. On the contrary, no exceedances are observed in the country-averaged NO_2 concentrations in households that use electric appliances.

The observed trend of higher concentrations in households that cook with gas appliances compared with households that use electric appliances is consistent with previous studies that conducted measurements in the United Kingdom [7, 8, 54] and various other European countries [7] and USA [55, 56, 59]. Nonetheless, the country-averaged indoor concentrations estimated for households that use both electric and gas appliances for cooking are lower than concentrations measured in households that use gas or electric appliances for cooking in studies conducted in several European countries [7, 8, 54], as well as in the USA [55, 56, 59, 60, 103].

The most recent comparative measurements conducted by Jacobs et al (2023) in several households in the Netherlands, Italy, Spain, France, Slovakia, Romania and UK show that the current estimated country-averaged indoor concentrations are lower than those measured in those countries in households that cook with gas and electric appliances [7]. The highest differences between NO_2 concentrations measured by Jacobs et al (2023) in the living-room of individual households that use gas appliances and the estimated country-averaged concentrations in this study were observed in Spain (33 $\mu g/m^3$ vs 6 $\mu g/m^3$). The lowest difference between measured concentrations in individual households and estimated country-averaged difference was in Slovakia (16 $\mu g/m^3$ vs 10 $\mu g/m^3$). The country-averaged concentrations estimated for households that used electricity were also lower than concentrations measured in individual households in the Jacobs et al (2023) study. Overall, the estimated difference for country-averaged estimated concentrations between households that use gas and electric cooking appliances was 2.3 times smaller (range 0.1 to 5.6) than the difference between concentrations measured in households that cook with gas and electric appliances in those seven countries. This underestimation of the likely indoor NO_2 exposure levels in European households would likely result in an underestimation of the health burden attributed to indoor NO_2 exposure from gas cooking emissions.

5.2 Mortality

5.2.1 Annual cases

The estimated number of premature deaths and years of life lost due to gas cooking by country are presented in Table 5. Figure 9 and 10 present the maps showing the distribution of estimated number of premature deaths and years of life lost due to gas cooking by country respectively.

The estimated number of premature deaths range from 0 in Cyprus and Malta, where no gas appliances are used for cooking, to 12,786 in Italy (Table 5, Figure 11), where over 70% of the population use gas appliances for cooking, according to Figure 2. Around six thousand premature deaths are estimated to occur in Poland and Romania, whereas around four thousand premature deaths are estimated to occur in France and United Kingdom due to exposure to NO_2 from gas cooking emissions. In the EU, the total number of premature deaths associated with gas cooking NO_2 emissions is 36,031, raising to 39,959 premature deaths when the EU and UK figures are combined (Table 5).

Likewise, the estimated number of years of life lost due to exposure to gas cooking emissions ranges from 0 in Cyprus and Malta, countries that do not use gas for cooking, to 15,758 in the United Kingdom (Table 5, Figure 12), in which 54% of the population uses gas appliances for cooking (Figure 2). In the EU, countries with a large share of households using gas cooking appliances (50-70%, Figure 2) such as Romania, Poland and Italy endure the highest toll with over 12,000 years of life lost (range 12,001-13,228). Overall, this represents an estimated 60,758 years of life lost in the EU and 76,541 in the EU and UK combined due to indoor exposure to NO_2 from gas cooking emissions (Table 6).

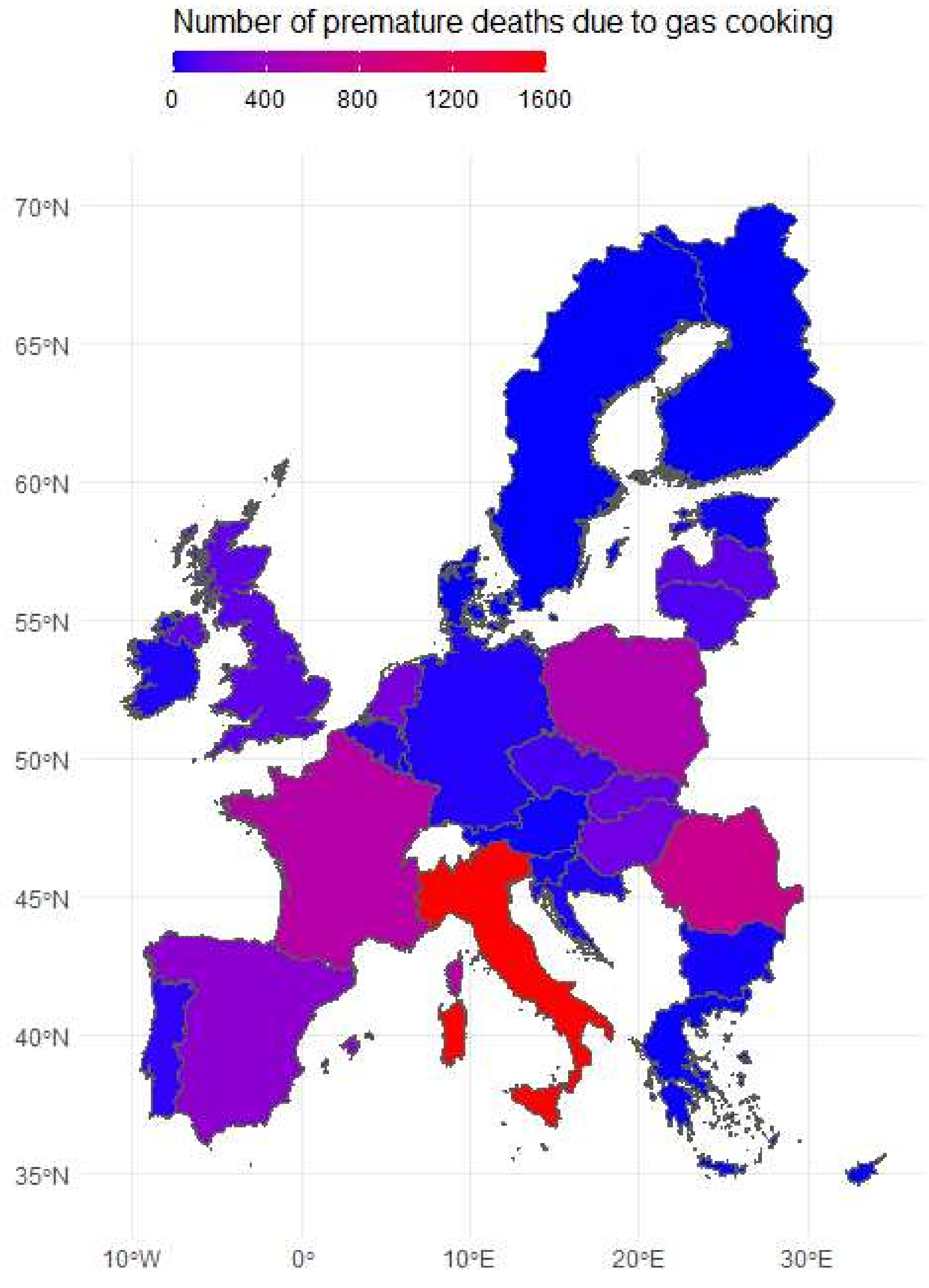

Figure 9. Estimated number of premature deaths due to exposure to NO_2 concentrations indoors in households that cook with gas appliances by country according to Huangfu and Atkinson (2020) [4] (RR = 1.008 per 10 µg/m^3 increase in NO_2 exposure). Estimated number of premature deaths range from 0 in Cyprus and Malta to 12,786 in Italy.

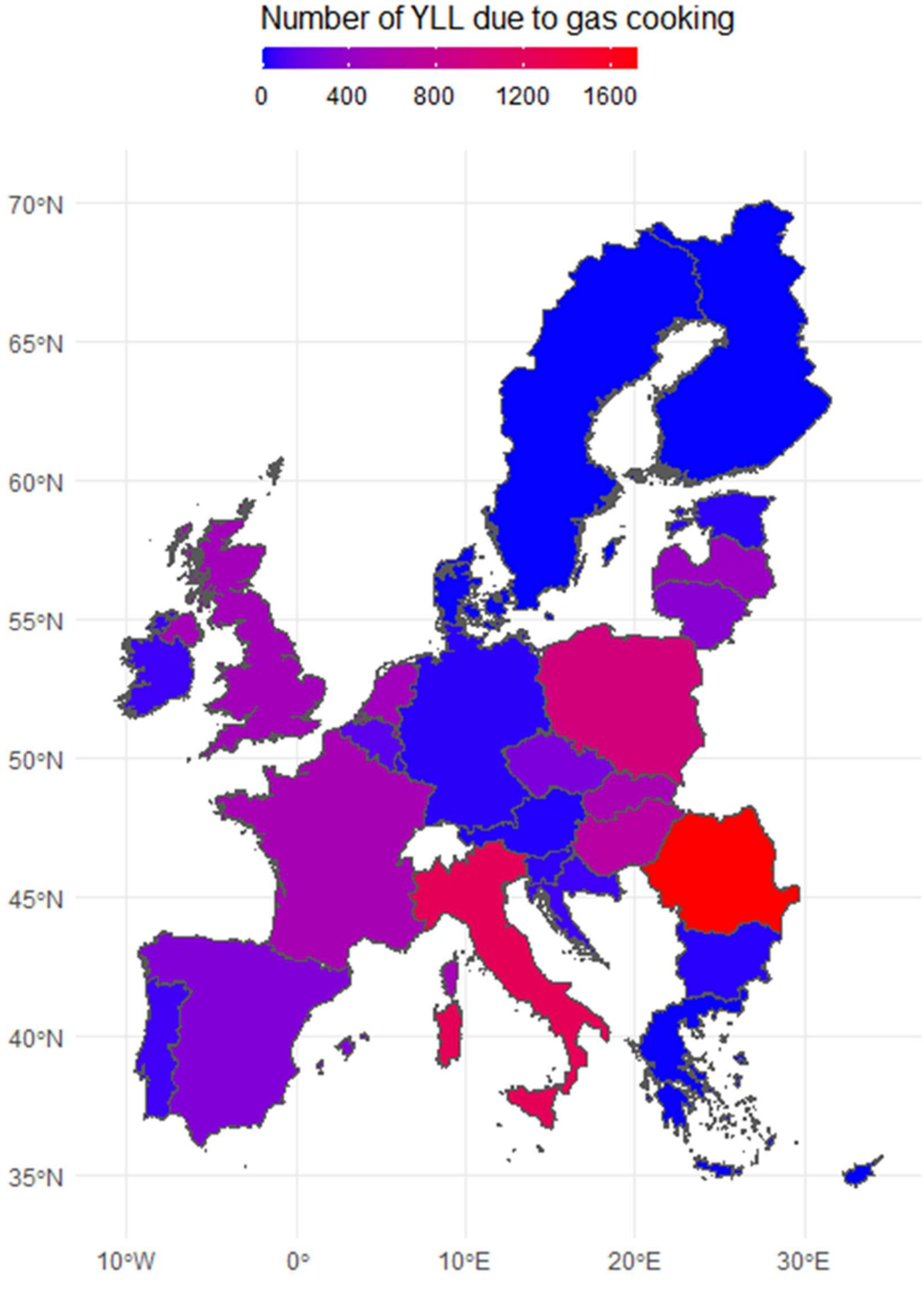

Figure 10. Estimated number of years of life lost due to exposure to NO_2 concentrations indoors in households that cook with gas appliances by country according to Huangfu and Atkinson (2020) [4] (RR = 1.02 per 10 µg/m^3 increase in NO_2 exposure). Estimated Years of Life Lost (YLL) to premature mortality or disability ranges from 0 in Cyprus and Malta to 15,758 in the United Kingdom.

Table 5. Estimated number of premature deaths and years of life lost due to exposure to NO_2 concentrations indoors in households that cook with gas appliances by country

Country	**PAF (%) Premature Deaths**	**Premature Deaths**	**PAF (%) Years of Life Lost**	**Years of Life Lost**
Austria	0.02	28	0.05	117
Belgium	0.14	218	0.34	1,152
Bulgaria	0.01	36	0.04	140
Croatia	0.05	15	0.12	57
Cyprus	0.00	-	0.00	-
Czech Republic	0.23	508	0.58	2,013
Denmark	0.00	4	0.01	18
Estonia	0.03	6	0.06	30
Finland	0.00	1	0.00	3
France	0.06	4,079	0.15	4,775
Germany	0.01	412	0.03	781
Greece	0.00	7	0.00	16
Hungary	0.39	1,295	0.97	4,805
Ireland	0.04	33	0.10	134
Italy	0.31	12,786	0.77	12,001
Latvia	0.14	133	0.35	428
Lithuania	0.13	139	0.31	535
Luxembourg	0.16	5	0.39	55
Malta	0.00	-	0.00	-
Netherlands	0.29	1,314	0.73	3,385
Poland	0.26	6,398	0.64	12,672
Portugal	0.02	105	0.05	216
Romania	0.50	5,904	1.23	13,228
Slovakia	0.33	527	0.81	1,925
Slovenia	0.05	14	0.12	66
Spain	0.08	2,062	0.21	2,224
Sweden	0.00	2	0.00	7
United Kingdom	0.30	3,928	0.73	15,758
TOTAL EU	**0.12** [(a)]	**36,031**[(b)]	**0.30**[(a)]	**60,783**[(b)]
TOTAL EU + UK	**0.13** [(a)]	**39,959**[(b)]	**0.31**[(a)]	**76,541**[(b)]

(a) Average of all Population Attributable Fraction (PAF, %); (b) Sum of all cases

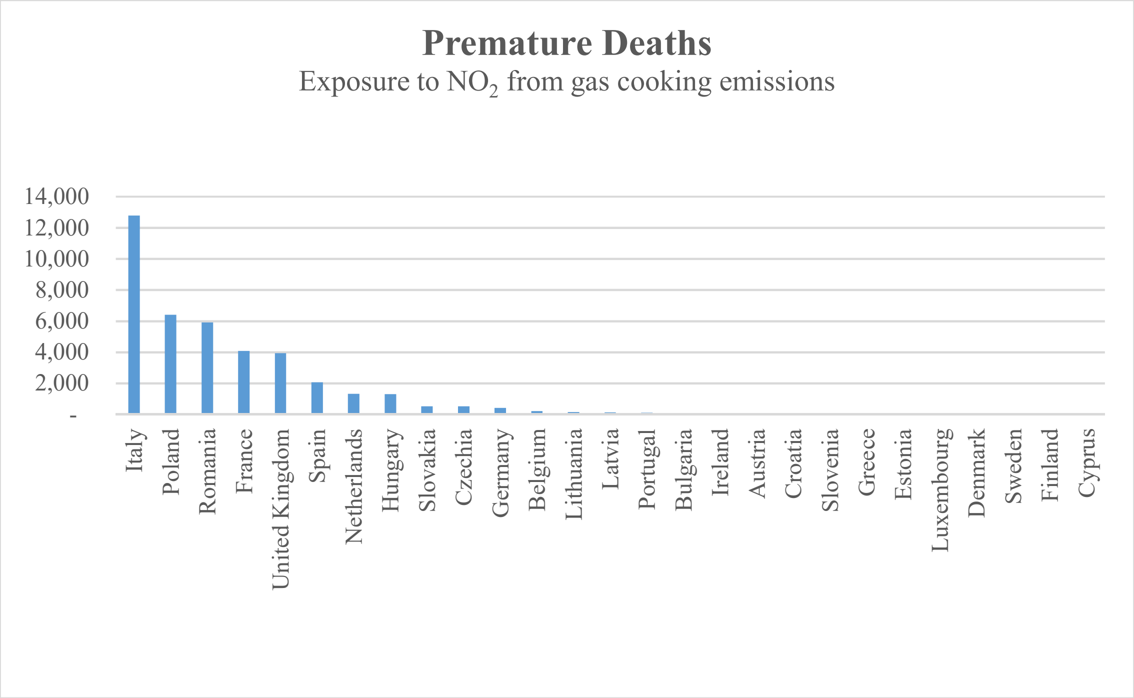

Figure 11. Ranking of estimated premature deaths due to exposure to NO_2 concentrations indoors in households that cook with gas appliances by country

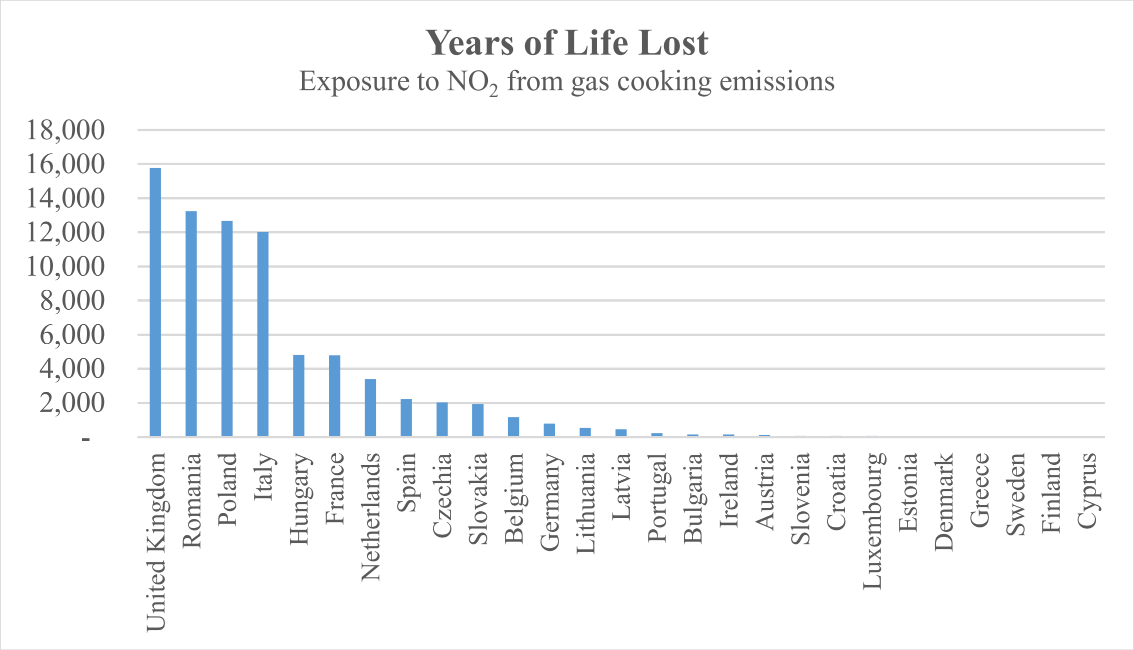

Figure 12. Ranking of estimated years of life lost due to exposure to NO_2 concentrations indoors in households that cook with gas appliances by country

5.2.2 Healthcare and Social costs

The resulting VSL and VSLY values updated for 2023 for each European country are presented in Table 6. The estimated cost of premature deaths and YLL is calculated applying the VSL and the VSLY values (Table 6) to the estimated number of premature deaths and number of YLL presented in Table 5.

The estimated cost associated with premature deaths and years of life lost due to exposure to NO_2 concentrations indoors in households that cook with gas appliances by country is presented in Table 6. The cost of premature deaths associated with exposure to NO_2 from gas cooking emissions indoors is estimated to be 142 billion euros in the EU, totalling 160 billion euro when EU and UK figures are combined. Italy is the country that endures the highest estimated cost due to the estimated premature mortality (54 billion euros), followed by Poland (24 billion euro), Romania (19 billion euro), France and the United Kingdom (18 billion euro each).

In addition, the economic burden associated with the amount of estimated years of life lost related to exposure to NO_2 from gas cooking emissions is estimated to be 11 billion euros in the EU, and 14 billion euros when UK and EU estimated costs are combined. The country with the highest estimated cost related with years of life lost is the United Kingdom (3 billion euro), followed by Italy, Poland and Romania, with an estimated cost of 2 billion euro each.

Table 6. Economic value of estimated number of premature deaths and life years lost to exposure to NO_2 concentrations indoors in households that cook with gas appliances by country. Note: all figures are in 2023-EUR million.

Country	**VSL**	**Cost of premature deaths**	**VSLY (at 35)**	**Cost of YLL**
Austria	5.07	141.44	0.231	26.96
Belgium	4.95	1,077.74	0.225	259.5
Bulgaria	2.87	103.21	0.137	19.2
Czech Republic	3.98	2,022.91	0.185	372.4
Denmark	5.42	21.05	0.248	4.45
Estonia	3.62	21.98	0.169	5.01
Finland	4.59	2.80	0.209	0.58
France	4.38	17,878.12	0.198	944.38
Germany	4.91	2,023.81	0.225	175.57
Greece	3.31	24.60	0.15	2.37
Hungary	3.65	4,730.58	0.174	835.34
Ireland	8.7	291.00	0.395	52.89
Italy	4.22	53,898.15	0.19	2,277.84
Latvia	3.34	444.60	0.16	68.57
Lithuania	3.86	537.11	0.184	98.27
Luxembourg	9.18	48.29	0.416	22.79
Netherlands	5.39	7,074.90	0.245	829.41
Poland	3.79	24,223.03	0.177	2249
Portugal	3.73	389.34	0.17	36.71
Romania	3.27	19,286.33	0.156	2,066.15
Slovenia	4.03	58.44	0.184	12.07
Spain	3.98	8,196.22	0.179	398.04
Sweden	5.16	8.05	0.234	1.55
United Kingdom	4.49	17,640.77	0.205	3,229.02
TOTAL EU	**4.58** (a)	**142,504** (b)	**0.210** (c)	**10,759** (b)
TOTAL EU+UK	**4.58** (a)	**160,144.47** (b)	**0.210** (c)	**13,988.07** (b)

(a) Average of all Value of Statistical Life (VSL); (b) Sum of cost of all countries; (c) Average of all Value

of Statistical Life Year (VSLY) (at 35).

5.3 Asthma

5.3.1 Annual cases

The estimated number of paediatric asthma cases related with NO_2 exposure from gas cooking was calculated according to the risks estimated by Lin et al (2013) [10]. This considers a risk ratio increase of 1.09 asthma cases per 28.2 $\mu g/m^3$ (15 ppb) increase in NO_2 exposure. The distribution of estimated paediatric asthma cases associated with exposure to NO_2 from gas cooking emissions by country is displayed in Figure 13.

A second calculation of paediatric asthma cases was conducted using the odds ratio (OR=1.32) estimates of paediatric asthma cases associated with the presence of gas stoves in the household according to Lin et al (2013) [10]. The geographical distribution of the estimated paediatric asthma cases linked with presence of gas stoves at home is shown in Figure 14.

Finally, the estimated number of total (i.e. paediatric and adult) asthma cases associated with the presence of gas stoves at home was calculated using the risk estimate (OR=1.11) from Puzzolo et al (2024) [9]. The geographical distribution of estimated total number of asthma cases by country is presented in Figure 15.

Table 7 presents the estimated number of paediatric and total asthma cases related with gas cooking by country.

The estimated paediatric asthma burden calculated using the risk ratio based on the indoor NO_2 exposures from gas cooking emissions [9, 10] show a wide variation across the EU and UK (Table 7 and Figure 13). The estimated number of paediatric cases related to NO_2 exposure from gas cooking emissions range from 0 in Cyprus and Malta, countries that do not use gas energy for cooking, to 15,823 paediatric asthma cases in the United Kingdom. In the EU, the countries with the highest estimated number of paediatric asthma cases due to NO_2 exposure from gas cooking are Italy (6,510 cases), Poland (4,372 cases), France (3,527 cases) and Romania (3,173 cases). Overall, this represents 25,116 estimated paediatric asthma cases in the EU due to exposure to NO_2 from gas cooking emissions. This figure increases to 40,939 estimated paediatric asthma cases when considering the estimates for the EU and UK combined.

In terms of population attributable fraction of current paediatric asthma cases associated with indoor NO_2 exposures from gas cooking emissions, PAFs ranges between nil for countries that do not use gas appliances for cooking (e.g. Malta or Cyprus) to 1.62 in Hungary, with over 60% of households using gas-cooking appliances. Overall, the average of population attributable fraction of current paediatric asthma cases associated with indoor NO_2 exposures from gas cooking emissions across European countries is 0.57%. This value is smaller than that calculated by Kashtan et al (2024) in the USA, which averages 0.91% (95% CI: -1.33, 3.0%) [36].

On the other hand, the estimated number of paediatric asthma cases calculated considering the presence or absence of gas cooking appliances at home, according to the risk estimated by Lin et al (2013) [10] is considerably higher (14 times larger) than the estimated number of paediatric cases estimated according to exposure to indoor NO_2 concentrations emitted from gas cookers. This estimate ranges from 0 cases in Malta and Cyprus, where gas is not used for cooking, to 182,203 estimated paediatric asthma cases in the UK (Figure 14, Table 7). In the EU, the countries with the largest number of estimated paediatric asthma cases according to the risk based on the presence of gas cooking appliances are France (84,084 cases), Italy (74,802 cases), Poland (49,226), Spain (36,539), Netherlands (33,177) and Romania (28,245). Overall, these figures represent 367,362 estimated paediatric asthma cases in the EU, and 549,565 estimated cases upon combining the figures of the EU and UK.

The estimates of current paediatric asthma associated with gas stove calculated in this study are larger than those reported by Kashtan et al (2024) in the USA. They estimated that 200 (95% CI: −20, 410) thousand current cases of paediatric asthma were associated with presence of gas and propane stoves [36]. As regards the estimates of the population attributable fraction of current paediatric asthma associated with gas stove estimated in this study, these range between nil for countries that do not use gas appliances for cooking (e.g. Malta or Cyprus) to 18% in the United Kingdom and Italy, with a Europe-wide average of 8% (Table 7). These values are similar to those estimated for the USA by Gruenwald et al (2022), with an average of 13% across nine states, and a range between 3% in Florida to 21% in Illinois [37]. Likewise, Knibbs et al (2018) estimated a similar population attributable fraction of paediatric asthma associated with the presence of gas stoves in Australia (12.3%; 95% CI: 8.9, 15.8%) [35]. On the other hand, Kashtan et al (2024) estimated a smaller population attributable fraction of current paediatric asthma cases associated with the presence of gas stoves in the United States (3.8%; 95% CI: 0.0, 8.0%) [36].

Finally, the estimated total number of asthma cases (paediatric and adult) were calculated based on the risk estimate associated with the presence of a gas cooking appliance in the household provided by Puzzolo et al (2024) [9] (Table 7, Figure 15). The estimated number of total asthma cases related with gas cooking ranges from 0 in countries that do not use gas cooking appliances (e.g. Malta and Cyprus) to 331,023 estimated total asthma cases in the UK. In the European Union, the country with the largest total number of estimated asthma cases associated with gas cooking is Italy (166,506 cases) followed by France (148,046), Poland (94,279 cases), Netherlands (80,045 cases), Spain (74,311) and Romania (54,402). Overall, this represents 725,863 estimated cases of asthma across all the population (paediatric and adult) associated with the presence of gas cooking appliances at home in the EU. The estimated total number of asthma cases linked with gas cooking emissions increases to over a billion cases (1,056,886) when the estimated cases from the EU are combined with those from the UK.

The number of paediatric asthma cases in children cannot be subtracted from the number of total cases of asthma (paediatric and adult) to obtain the number of asthma cases in adults attributed to gas cooking. It cannot be subtracted because both estimates were calculated using a different odds ratio. According to Lin et al (2013), the paediatric odds ratio associated with presence of gas stove is 1.32. That is, the odds of suffering asthma is 32% higher in children living in households using gas appliances for cooking than for those children living in households cooking with electric appliances. According to Puzzolo et al (2024), after systematically reviewing health studies involving children and adults, the odds of suffering asthma in all ages is 11% higher for subjects living in households with gas cookers than for those in homes with electric ones.

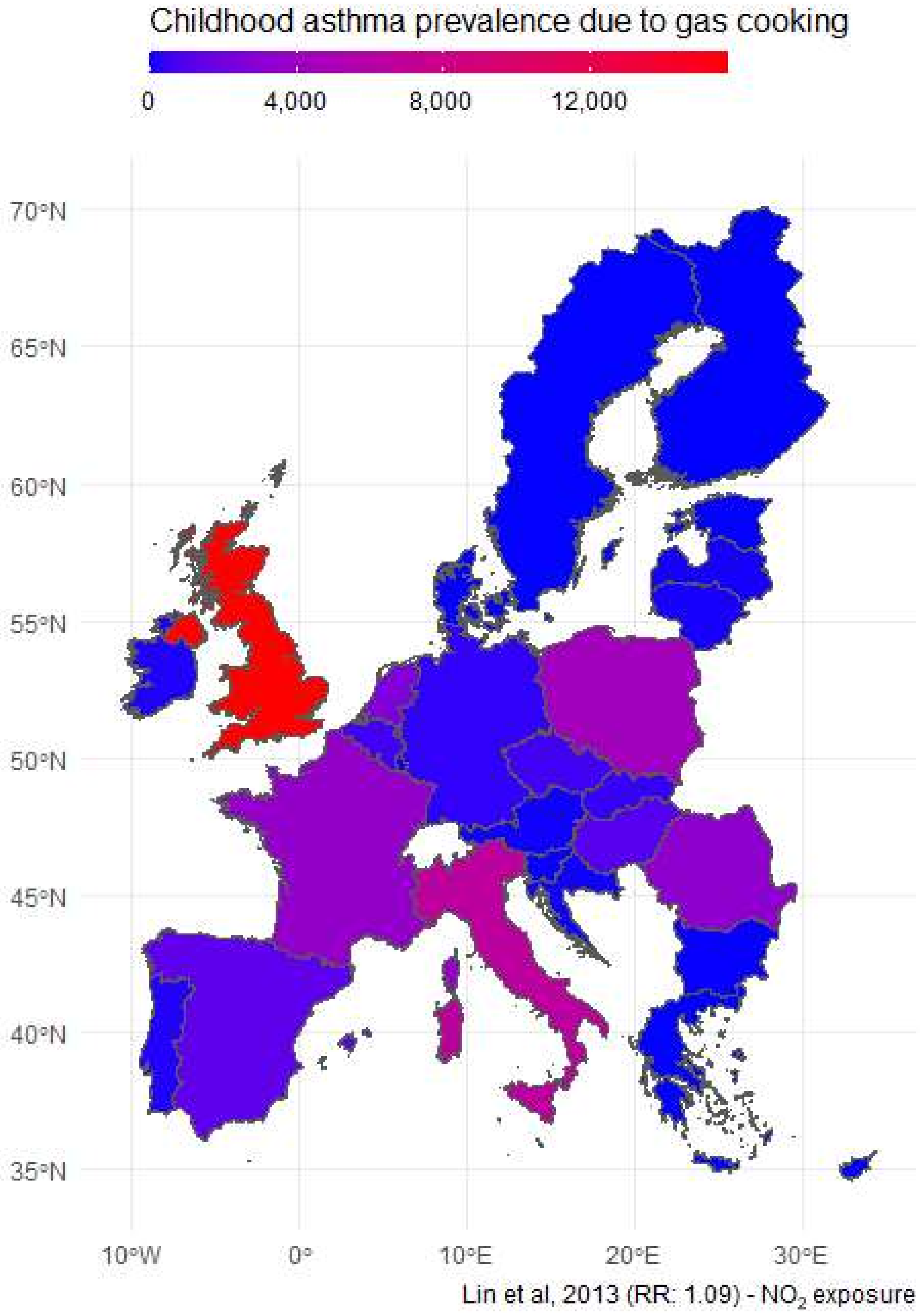

Figure 13. Estimated paediatric asthma prevalence due to exposure to NO_2 concentrations indoors in households that cook with gas appliances by country according to Lin et al (2013) (RR=1.09 per 28.2 µg/m^3 NO_2). Number of estimated asthma cases range from 0 in Cyprus and Malta to 15,823 in UK.

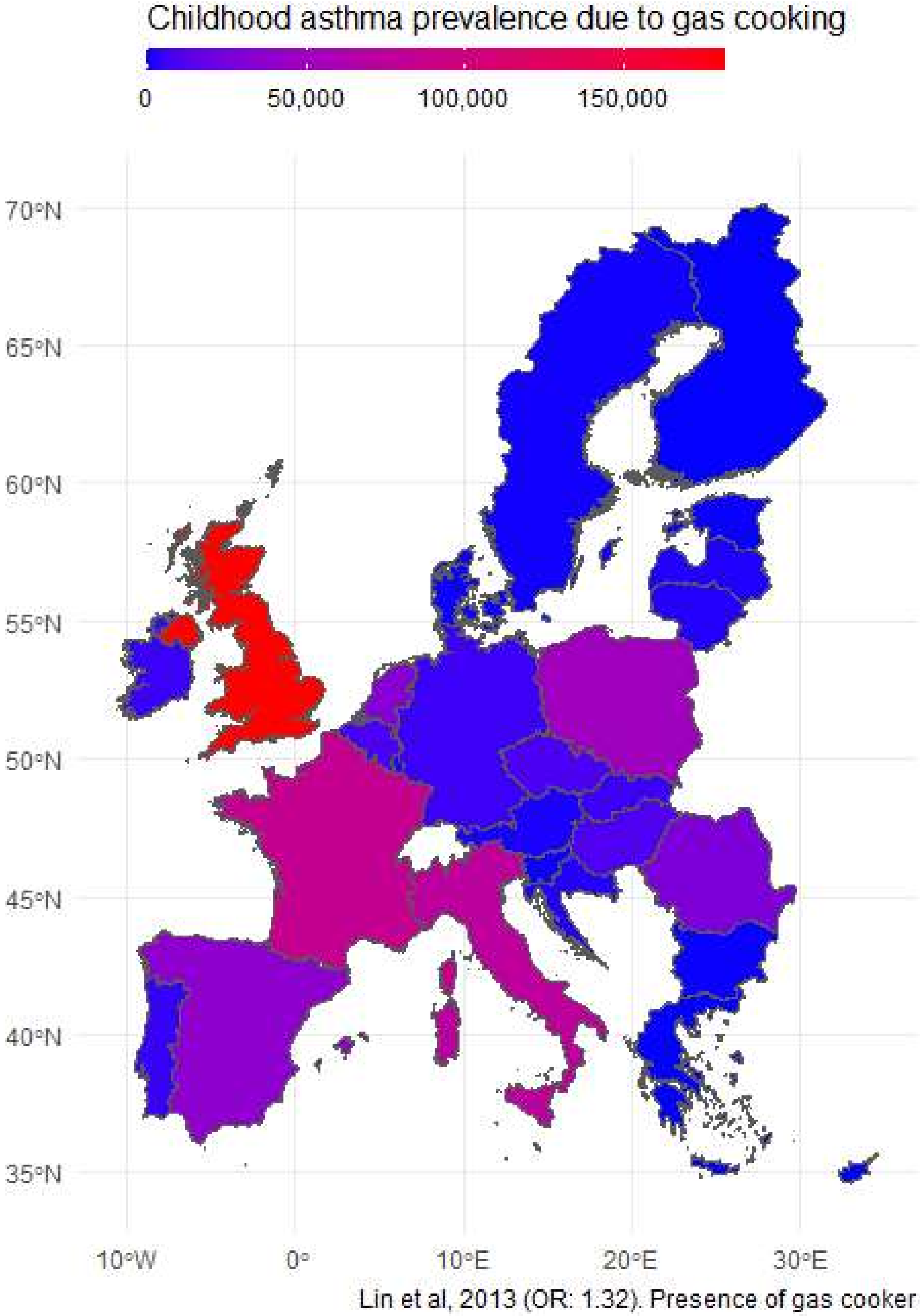

Figure 14. Estimated paediatric asthma prevalence associated with presence of gas cooking appliances by country, according to OR reported by Lin et al (2013) (presence of gas cookers, OR=1.32). Number of estimated paediatric asthma cases range from 0 in Cyprus and Malta to 182,203 in UK.

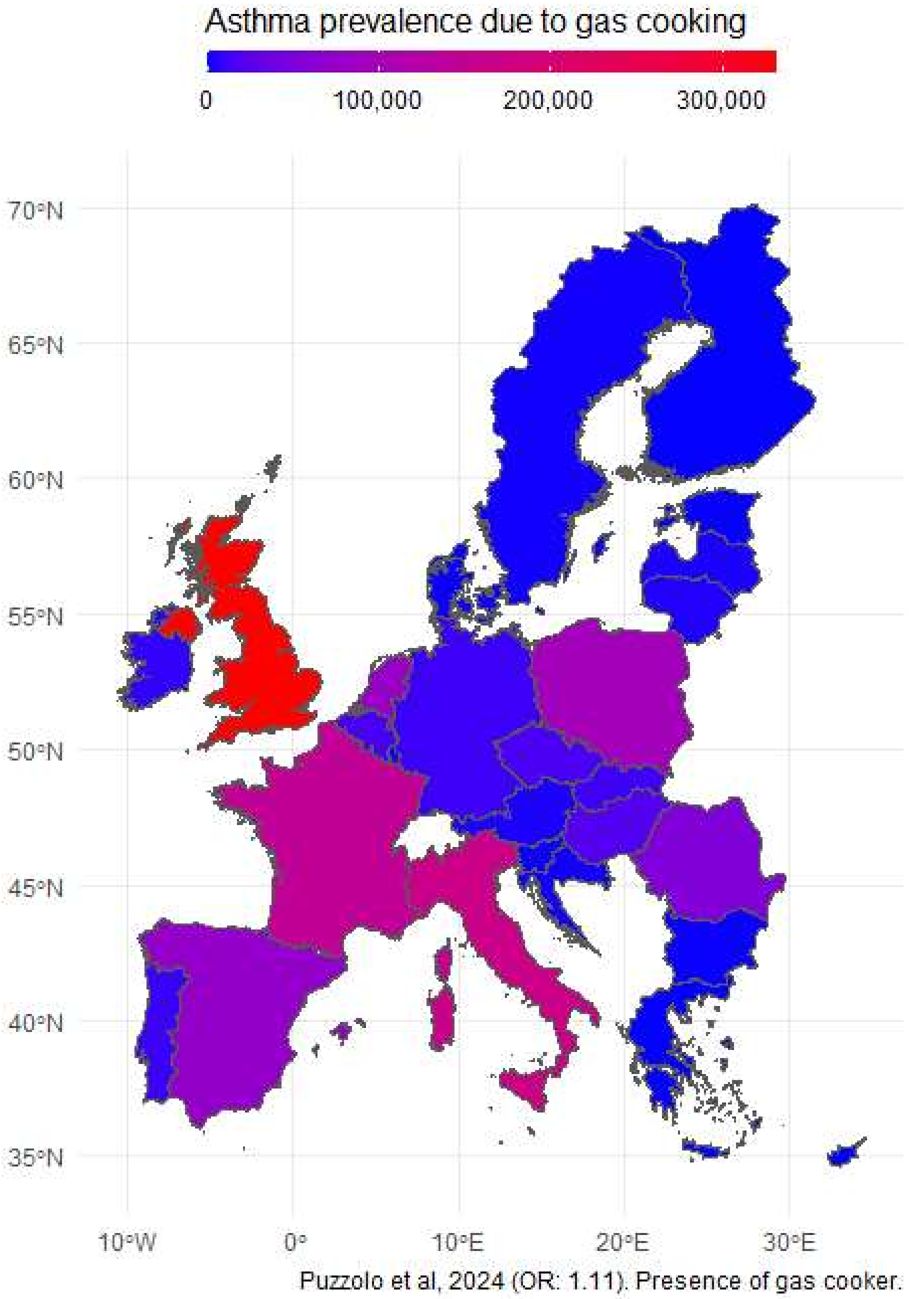

Figure 15. Estimated total asthma incidence associated with presence of gas cooking appliances by country, according to OR reported by Puzzolo et al (2024) (presence of gas cookers, OR=1.11). Number of estimated total asthma cases range from 0 in Cyprus and Malta to 331,023 in UK.

Table 7. Estimated number of asthma cases and population attributed fraction (%) associated with exposure to NO_2 indoors in households that cook with gas appliances (paediatric asthma), as well as with the presence of gas cookers by country (paediatric and total asthma).

Country	**Paediatric Asthma** ***Lin et al (2013)*** ***(RR=1.09)***		**Paediatric Asthma** ***Lin et al (2013)*** ***(OR=1.32)***		**Total Asthma** ***Puzzolo et al (2024)*** ***(OR=1.11)***	
	Cases	**PAF (%)**	**Cases**	**PAF (%)**	**Cases**	**PAF (%)**
Austria	66	0.080	1,397	1.70	2,719	0.59
Belgium	624	0.567	8,616	7.87	14,992	2.85
Bulgaria	26	0.057	370	0.79	698	0.27
Croatia	59	0.190	2,105	6.80	1,355	2.45
Cyprus	0	-	0	-	-	-
Czech Republic	614	0.885	9343	13.60	16,631	5.13
Denmark	11	0.018	499	0.83	789	0.29
Estonia	7	0.097	385	5.13	397	1.83
Finland	2	0.003	113	0.19	222	0.07
France	3,527	0.385	84,084	9.21	148,046	3.37
Germany	326	0.052	5713	0.92	10,934	0.32
Greece	8	0.008	117	0.13	250	0.04
Hungary	1,050	1.624	10,303	16.20	20,147	6.23
Ireland	149	0.172	5,446	6.32	7,517	2.27
Italy	6,510	1.544	74,802	18.02	166,506	7.03
Lithuania	93	0.499	2,202	11.87	3,380	4.43
Luxembourg	47	0.598	1,043	13.31	2,006	5.02
Latvia	83	0.544	1,710	11.30	2,584	4.19
Malta	0	-	0	-	0	-
Netherlands	2,468	1.271	33,177	17.31	80,045	6.71
Poland	4,372	1.078	49,226	12.27	94,279	4.59
Portugal	172	0.115	4,627	3.10	10,246	1.09
Romania	3,173	1.895	28,245	17.20	54,402	6.66
Spain	1,271	0.336	36,539	9.68	74,311	3.55
Sweden	7	0.005	743	0.48	1,265	0.16
Slovenia	33	0.191	534	3.07	1,022	1.08
Slovakia	418	1.233	6,021	17.98	11,118	7.01
United Kingdom	15,823	1.261	182,203	14.71	331,023	5.60
TOTAL EU	**25,116** (a)	**0.54** (b)	**367,362** (a)	**8.21** (b)	**725,863** (a)	**3.09** (b)
TOTAL EU+UK	**40,939** (a)	**0.57** (b)	**549,565** (a)	**8.46** (b)	**1,056,886** (a)	**3.19** (b)

(a) Sum of all cases; (b) Average of all PAF(%)

5.3.2 Healthcare and Social costs

The resulting estimated VSLY values, the estimated number of DALYS lost from childhood asthma due to gas cooking and their values by country are presented in Table 8 for costs associated with estimated number of paediatric asthma cases and Table 9 for costs related with estimated total asthma cases (paediatric and adult combined).

The estimated cost related with paediatric asthma cases associated with exposure to NO_2 from gas cooking emissions (according to risk estimates by Lin et al (2013) [10]) is presented in Table 8. The estimated cost of childhood asthma associated with NO_2 exposure from gas cooking emissions ranges from null cost in those countries that do not use gas appliances for cooking (e.g. Malta and Cyprus) to 123 million euro in the United Kingdom. As regards the EU, the estimated cost is 46 million euro in Italy, 28 million euro in Poland, 26 million euros in France, 22 million euro in the Netherlands and 17 million euro in Romania (Table 8). Overall, in the EU the estimated total cost related with paediatric asthma amounts 174 million euro, and this value raises to 298 million euros when the cost of the EU and the UK are combined.

Table 8 also presents the estimated cost related with paediatric asthma cases associated with the presence of a gas cooker at home, calculated using the risk estimates by Lin et al (2013) [10]. These estimated costs are considerably higher than those calculated using the risk estimates associated to NO_2 exposure from gas cooking emissions (also presented in Table 8). The cost of paediatric childhood cases associated with the presence of a gas cooker at home is estimated to be 1.44 billion euros in the UK, 626 million euros in France, 532 million euros in Italy and over 300 million euros in the Netherlands and Poland. Overall, in the EU the cost of the estimated number of paediatric asthma cases associated with the presence of gas cookers at home is estimated to be 2.6 billion euro. The estimated cost increases to 4.1 billion euro when the costs of the EU and the UK are combined. The current estimates are considerably higher than the costs of 1 (95% CI: 0, 2) billion US dollars estimated by Kashtan et al (2024) [36] for the USA. The estimates for the EU and UK are higher in spite of only including the value of a statistical life to asthma-induced deaths, whereas in the US study, Kashtan et al (2024) combines the medical cost related with asthma medication and the cost associated with the VSL to asthma induced mortality [36]. It should be highlighted that the current estimates for EU and UK are larger than those calculated for the USA, but the population in the EU and

UK combined is larger than the population in USA, therefore higher cost should be expected in Europe, as the exposed population to gas cooking emissions is larger.

Table 8. Estimated Disability-Adjusted Life Years (DALYs)[a] lost due to asthma (paediatric cases) from exposure to NO_2 concentrations indoors and presence of gas cooking appliances in households that cook with gas appliances by country.

Country	**VSLY (at 18)**	**DALYs lost due to asthma *(Lin et al (2013) (RR=1.09)***	**Value of DALYs lost due to asthma (*Lin et al (2013) (RR=1.09)***	**DALYs lost due to asthma (*Lin et al (2013) (OR=1.32)***	**Value of DALYs lost due to asthma *(Lin et al (2013) (OR=1.32)***
Austria	0.212	2.68	0.57	56.91	12.08
Belgium	0.207	25.52	5.29	354.38	73.39
Bulgaria	0.123	1.08	0.13	15.07	1.85
Czech Republic	0.168	25.15	4.23	386.42	65.05
Denmark	0.227	0.45	0.10	20.41	4.64
Estonia	0.153	0.30	0.05	15.76	2.42
Finland	0.192	0.07	0.01	4.58	0.88
France	0.183	143.34	26.19	3,430.76	626.82
Germany	0.206	13.34	2.75	234.06	48.19
Greece	0.138	0.31	0.04	4.76	0.66
Hungary	0.156	42.44	6.63	423.26	66.11
Ireland	0.363	6.11	2.22	224.26	81.50
Italy	0.175	260.08	45.62	3,035.42	532.46
Latvia	0.144	3.36	0.48	69.86	10.03
Lithuania	0.165	3.78	0.62	89.95	14.87
Luxembourg	0.383	1.93	0.74	42.96	16.46
Netherlands	0.225	99.36	22.38	1,353.17	304.77
Poland	0.161	176.10	28.32	2,004.52	322.32
Portugal	0.156	6.91	1.08	186.73	29.13
Romania	0.140	126.22	17.67	1,145.31	160.30
Slovenia	0.169	1.35	0.23	21.70	3.67
Spain	0.165	51.86	8.58	1,495.86	247.47
Sweden	0.215	0.30	0.06	30.32	6.53
United Kingdom	0.188	656.79	123.61	7,659.49	1,441.54
TOTAL EU	**0.192 (b)**	**992.03 (c)**	**173.99 (d)**	**14,646.42 (c)**	**2,631.60 (d)**
TOTAL EU+UK	**0.192 (b)**	**1,648.83 (c)**	**297.60 (d)**	**22,305.91 (c)**	**4,073.15 (d)**

(a) Disability-Adjusted Life Years (DALY) represents the loss of one year of full health. It could be either because of premature death or because of the loss of a year of healthy life due to disability (b) Average of VSLY at 18 years old across all countries in 2023-EUR million; (c) Sum of estimated Disability-adjusted life years lost due to asthma (0-19 year olds) across all countries; (d) Sum of estimated cost of DALYs lost due to asthma in 2023-EUR million

The estimated population attributable fraction for paediatric asthma associated with exposure to NO_2 from gas cooking emissions represents 1,648 estimated DALYs across the EU and UK (Table 8). This figure increases to 22,305 estimated DALYs when considering the population attributable fraction for paediatric asthma associated with the presence of gas stoves at home. The latter estimated number of DALYs are considerably larger than those estimated by Knibbs et al in Australia (2,756 DALYs; 95% CI: 1,271, 4,242) [35]. Nonetheless, when the population of Australia and the combined population of UK and EU are taken into consideration, the number of DALYs normalised by the population are similar in both studies.

As regards the estimated number of total asthma cases (paediatric and adult) related with the presence of a gas cooker at home (Table 9), the cost is estimated to be 1.1 billion euro in the EU, and 1.7 billion euros when the cost of the EU and the UK are combined. The countries with the highest estimated costs from total asthma cases associated with the presence of gas cookers at home are UK (597 million euro), France (248 million euro), Italy (224 million euro), Poland (133 million euro) and the Netherlands (129 million euro).

Table 9. Estimated Disability-Adjusted Life Years (DALYs)[a] lost due to asthma (total cases) associated with presence of gas cooking appliances in households by country.

Country	**VSLY (at 35)**	**DALYs lost due to asthma** ***Puzzolo et al (2024) (OR=1.11)***	**Value of DALYs lost due to asthma** ***Puzzolo et al (2024) (OR=1.11)***
Austria	0.231	19.78	4.57
Belgium	0.225	128.45	28.94
Bulgaria	0.137	5.21	0.72
Czech Republic	0.185	145.85	26.98
Denmark	0.248	7.05	1.75
Estonia	0.169	5.61	0.95
Finland	0.209	1.58	0.33
France	0.198	1255.19	248.24
Germany	0.225	80.95	18.19
Greece	0.150	1.64	0.25
Hungary	0.174	162.80	28.30
Ireland	0.395	80.43	31.74
Italy	0.190	1183.38	224.61
Latvia	0.160	25.94	4.15
Lithuania	0.184	33.53	6.16
Luxembourg	0.416	16.18	6.73
Netherlands	0.245	524.75	128.57
Poland	0.177	749.39	133.00
Portugal	0.170	65.52	11.13
Romania	0.156	443.78	69.31
Slovenia	0.184	7.61	1.40
Spain	0.179	549.09	98.29
Sweden	0.234	10.45	2.44
United Kingdom	0.205	2914.29	597.17
TOTAL EU	**0.210 (b)**	**5,504.16 (c)**	**1,076.76 (d)**
TOTAL EU+UK	**0.210 (b)**	**8,418.45 (c)**	**1,673.93 (d)**

(a) Disability-Adjusted Life Years (DALY) represents the loss of one year of full health. It could be either because of premature death or because of the loss of a year of healthy life due to disability. (b) Average of VSLY at 35 years old across all countries in 2023-EUR million. (c) Sum of Disability-adjusted life years lost due to asthma across all countries. (d) Sum of cost of DALYs lost due to asthma in 2023-EUR million.

6. STRENGTHS AND LIMITATIONS

Some limitations, but also several strengths, have been identified in the current health impact assessment study, as described below.

The estimated country-averaged indoor NO_2 concentrations in households using gas or electric cooking appliances are lower than those measured in households in various studies conducted in Europe in recent years [7, 8]. In addition, the difference between estimated country-averaged indoor NO_2 concentrations for households using gas and electric cooking appliances is less pronounced than differences observed in observational studies [7, 8]. Consequently, the disease burden attributed to NO_2 exposure from gas cooking indoors is likely to be underestimated by the calculations in this study. A more accurate estimate could be obtained if data on indoor NO_2 concentrations measured in a large number of households across the 27 European Union countries and the United Kingdom was available. Therefore, it is recommended to conduct exposure assessment of relevant indoor air pollutants in a wider range of European countries so future health impact assessments could use more accurate data that will reflect the true nature of the health burden, expected to be larger than current calculations.

Background information on population, background rates of the health outcomes could not be found for all countries for the same year. The most recent database describing the population for most of the countries was 2018. However, for Portugal and Luxembourg, the database corresponded to 2017. Likewise, the most recent data for years of life lost was 2018, except for Portugal and Luxembourg, which was 2017. On the other hand, the exposures were interpolated based on EEA maps available for 2023 [2]. The misalignment on the reference years for each database will introduce some level of error on the calculations as not all of the databases correspond with the same reference year. However, the discrepancies on using databases with nearby reference years for population, background health outcome rates and NO_2 concentrations are expected to be minimal. The EU population is increasing at a very small rate, approximately 0.8 million persons per year between 2005 and 2023 [104], with 513 million inhabitants in 2018 [105]. In 2023, the EU population was 448.8 million as of 1st of January 2023 [106]. In the UK, the most recent mid-year estimates of the population, corresponding to 2022, was 67.7 million [107]. Combining the EU and UK population renders 516 million inhabitants in 2023, representing a small increase of population of 0.6% with reference to the year 2018, the reference year used for most of the databases. Therefore, despite using different reference years according to the availability of databases, the overall error expected in the estimation of the health impacts is negligible.

Indoor NO_2 concentrations were estimated for households using gas and electric appliances at a finer geographical scale reflecting small regions (NUTS 3 level). Population was also available at the same geographical scale. However, background health outcome rates were available at coarser geographical units. Mortality background data was available at basic regions (NUTS-2) level, whereas asthma background rates were available at the country level. Each health impact assessment was conducted at the largest geographical unit where all databases were available. Thus, in the case of the impact on mortality associated with gas cooking, regional variations within countries can be assessed in addition to national variations across Europe. On the contrary, this is not possible for asthma burden, as only the burden of disease at the national level could be estimated. It would be advisable to provide access to health outcomes background rates at smaller geographical scales to allow analysing health impacts also at regional levels. This would be very useful to develop targeted public health policies within countries focusing on specific areas, and hence being more efficient with the resources required to implement those policies.

A fundamental assumption underlying any health impact assessment is the existence of a causal relationships between environmental exposures and health outcomes [108]. As regards NO_2 exposure, the External Review Draft of the 2015 ISA conducted by USEPA stated that long term respiratory health effects are deemed likely to be a causal relationship and that the evidence is suggestive of, but not sufficient to infer, a causal relationship with mortality [68]. On the other hand, a recent meta-analysis concluded that associations between exposure to NO_2 with mortality rated moderate for all-cause mortality [4].

The concentration response functions selected to estimate the effect of exposure to NO_2 on mortality and between the presence of gas stoves with total (paediatric and adult) asthma are statistically significant. In addition, concentration response functions for mortality were endorsed by EIONET to calculate the health costs of air pollution from European industrial emissions [98]. On the other hand, the concentration response functions available for paediatric asthma are indicative but do not reach statistical significance. A recent review by Li et al (2023) concluded that the current evidence did not support causality for the association between gas cooking and NO_2 exposure with asthma [65]. On the other hand, a systematic review and meta-analysis spanning studies from 1980 to 2019 identified a significant increase on the risk of paediatric asthma upon exposure to NO_2 [85].

Another assumption inherent to the reliability of the health impact assessment is that the concentration response functions used on the calculations are not affected by exposures to other pollutants occurring concurrently. Sensitivity analysis using multipollutant models suggested that the effect of NO_2 on mortality was robust to adjustments to other common air co-pollutants [12-14].

One of the main strengths of the current health impact assessment is that it is the largest study conducted so far, focussing on the burden of disease of the 27 countries in the European Union in addition to the burden of disease in the United Kingdom. It assesses the health impacts associated with gas cooking in a population of 516 million inhabitants, of which 180 million are exposed to gas cooking emissions at home. This is considerably larger than previous studies conducted in USA [36, 37] and Australia [35], with populations of 335 million (131 million exposed) and 26 million (10 million exposed), respectively.

Another strength of this study is that assesses the health impacts related with a wider range of health outcomes, including premature mortality and years of life lost, paediatric and total asthma. Previous studies have generally focussed on estimating the effects of gas cooking on paediatric asthma [35-37]. Only one study has recently assessed the effects of gas cooking on mortality in the USA [36]. The current study includes estimates of total asthma burden, in addition to paediatric asthma, therefore provides a more comprehensive assessment of the health impacts associated with gas cooking emissions.

The current health impact assessment has evaluated the effects of using gas appliances for cooking considering both the risk estimates associated with the presence of gas hobs in the kitchen, as well as the effects associated with exposure to NO_2 emitted from gas cooking appliances. This approach is quite novel, as most of the previous studies focused on evaluating the impacts related with the presence of gas stoves at home [35-37] and only one recent study also included the effects associated with NO_2 exposure from gas cookers in the health impact assessment [36]. This approach was possible thanks to the work conducted in this study to develop the first spatially detailed map of indoor NO_2 concentrations according to cooking fuel type used in households for every small regional unit area (i.e. NUTS- 3 level) across the EU and the UK. Being able to estimate indoor exposure to NO_2 emitted from gas cooking appliances opens up the possibility to assess a wider range of health outcomes reflecting a better estimate of the health effects associated with gas cooking emissions. In addition, these maps of indoor NO_2 concentrations could be a useful tool for future environmental health studies.

In spite of our efforts to include a wider range of health outcomes and to evaluate the burden of disease related not only to the presence of gas cookers, but with exposures to NO_2 emitted from gas cooking appliances, the health impact associated with the use of gas cookers is expected to be larger than the current calculations. Other health effects associated with other pollutants emitted during gas cooking (e.g. benzene, toluene, CO) could not be included in the current health impact assessment for several reasons. Firstly, exposure to other gases also emitted during gas cooking could not be estimated, as no information on indoor exposures to these gases is available at a European scale, which is required to conduct the current analysis. In addition, there are no comparable EEA maps for those gases as the one available for NO_2 that could be used to estimate exposures covering the European geography. Lastly, little information is available on indoor to outdoor ratios applicable to households that use gas cookers vs those that use electric appliances. Therefore, indoor exposures related to gas or electric appliances for these gases could not be estimated. Further research should focus on characterising exposures indoors to air pollutants emitted from gas and electric cooking appliances covering a large number of households across all the European countries. Maps to estimate exposures in ambient and indoor environments to a wider range of air pollutants could also be developed to allow estimating health effects associated with their exposure.

Finally, the current health impact assessment did not include other health effects that have been associated with gas cooking emissions, such as hospital admissions, COPD or wheeze. Background health outcome rates could not be found for wheeze. It is recommended that background rates for a wider variety of health effects becomes available to facilitate conducting health impact assessments for these health effects. In the case of hospital admissions, a recent large study indicates an increased risk in hospital admissions with stroke and atrial fibrillation associated with chronic NO_2 exposure [15].

However, the study reported risk differences rather than risk ratios, which precludes conducting the health impact assessment according to the proposed methodology. Finally, a lack of reliable concentration response function for additional respiratory or cardiovascular health effects prevented estimating the impact of gas cooking on a wider range of health effects. Further research should focus on providing these risk estimates that would allow including a larger set of health outcomes on the health impact assessments. Such information would be valuable to design policies commensurate with the burden of disease associated with the exposures.

Overall, the health impact associated with exposures to gas cooking emissions is expected to be larger than estimated in the current study, as the effects of more gases emitted by gas cookers and a wider range of health effects known to be related to gas cooking emissions should be included in the health impact assessments. Gaps in the availability of data or scientific evidence have been identified. Research efforts and resources should focus on generating new evidence, which will allow updating the calculations with a more comprehensive set of health outcomes whenever data and scientific evidence becomes available.

Finally, the current health impact assessment was followed by an economic valuation of the societal and monetary costs of the estimated burden of mortality and asthma associated with gas cooking exposures. The economic valuation provides valuable insights informing policy makers of the scale of the impacts, not only compared with other environmental risks, but also in relation with the different health effects evaluated. This information would be useful to focus the public health measures to alleviate the most relevant and impactful health impacts and economic costs related with exposure to gas cooking emissions.

7. CONCLUSIONS

This study has conducted a health impact assessment and an economic valuation of the impacts associated with two risk factors related with gas cooking across countries in the EU and the UK. These are the presence of gas cookers at home and the exposure to indoor NO_2 emitted from gas cooking appliances. It has calculated the first estimate of premature mortality and number of years lost associated with exposure to NO_2 emitted during cooking with gas appliances for Europe. It has also provided an estimate of the number of asthma cases for all ages within the population. These estimations were possible thanks to the development of the first detailed map of indoor NO_2 exposures related to gas cooking across the EU and UK. The indoor NO_2 concentrations were calculated by combining existing ambient NO_2 maps provided by the European Environmental Agency [2] and data from the most comprehensive measurement campaign conducted in Europe characterising indoor and outdoor levels of NO_2 in 7 European countries [7].

In terms of mortality, the estimated number of premature deaths is 40 thousand in the EU and UK (36 thousand in the EU), which represents an estimated 160 billion of euros lost across the EU and UK (142 billion euro in the EU). There are also an estimated 77 thousand years of life lost across EU and UK (61 thousand in the EU), representing 14 billion of euros lost (11 billion euro in the EU).

The estimates of children suffering asthma linked with long term exposure to NO_2 emitted by gas cooking appliances across EU and UK is 41 thousand children (25 thousand in the EU), which represents an estimated 1.6 thousand DALYs (992 DALYs in the EU) and 298 million of euros lost (174 million of euro in the EU). On the other hand, estimates of asthma associated with presence of gas cooking appliances at home increases to 550 thousand for the paediatric population (367 thousand in the EU), and 1 million for all (paediatric and adult) population across EU and UK (726 thousand in the EU). This represents an estimated 4 billion euros for paediatric population (2.6 billion euro for the EU) and 1.7 billion for the total population across the EU and UK (1.1 billion euro for the EU) associated with the presence of a gas stove for cooking at home.

The health impacts associated with gas cooking have been assessed and the estimated number of premature deaths, years of life lost, as well as the estimated number of children and total population suffering asthma have been calculated. The economic valuation of the health effects associated with gas cooking has been assessed, both considering the exposure to NO_2 emitted from gas cooking appliances, as well as from the presence of gas cookers at home. The cost of premature mortality, paediatric and total asthma cases has been estimated to be 157 billion euros for the EU, increasing to 180 billion euros when the cost in the EU and UK are combined.

The countries that would benefit most from switching to cleaner cooking appliances are United Kingdom, France, Italy, Poland, Romania, the Netherlands, Spain and Hungary. These countries account for 94% of premature mortality, 90% of years of life lost, 91% of total asthma and 93% of paediatric asthma of the combined estimated health burden related with gas cooking emissions in the EU and UK. Policies aiming to reduce or eliminate gas cooking emissions in these countries would contribute to a reduction of approximately 90% of the estimated burden of disease attributed to exposure to NO_2 from gas coking emissions and associated with the presence (and use) of gas appliances for cooking according to the current health impact assessment. Although the health impacts are less pronounced in the rest of the countries as gas cooking is less prevalent, it is also recommended to implement policies in these countries to reduce the burden of disease related with gas cooking emissions on the population using gas appliances for cooking.

A set of strengths and limitations of the current health impact assessment were identified and discussed in detail. This is the largest study conducted so far estimating the health impacts associated with gas cooking in terms of the size of the population under consideration. It also includes a wider range of health outcomes, including premature mortality, years of life lost, paediatric and total asthma burden. This study is the first to report the impact and costs related with premature mortality from exposure to NO_2 emitted during cooking with appliances in Europe. It is also the first in reporting the number of asthma cases for the overall population, including all ages, children and adults.

Overall, it is expected that the burden of disease attributed to exposure to gas cooking emissions would be larger than the current estimates, since not all the health outcomes associated with all the air pollutants emitted by gas appliances could be incorporated in the current health impact assessment. Recommendations have been included to generate data and scientific evidence that would enable to revise these calculations. Despite this, the current study is the most accurate and comprehensive, providing useful information at the European level as regards exposure to harmful pollutant emissions related with gas cooking use, especially for premature mortality, childhood and overall asthma linked with presence of gas cookers and indoor NO_2, emitted by gas cookers. The current estimates offer valuable insights for policy makers useful for developing and implementing policy measures aimed at reducing exposure to gas cooking emissions among the European population. Likewise, the current study would be useful to raise awareness about the health effects and economic costs associated with gas cooking emissions among policy makers in other regions of the world.

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