Health-related social costs of air pollution due to residential heating and cooking

In the EU27 and UK

CE Delft

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This report was prepared by:
Marisa Kortekand, Joukje de Vries, Pien van Berkel and Sander de Bruyn

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Further information on this study can be obtained from the contact person Marisa Korteland (CE Delft)

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Content

Introduction to Version 1.2

The first version of this final report was published on March 31, 2022.
Unfortunately, we discovered a flaw in the energy consumption data used to divide the total health-related social costs of heating and cooking over the various fuel-technique combinations. By mistake, Eurostat's energy carrier categories and subcategories were added, leading to some double counting.

The current 1.2 version of this report includes the correct final energy consumption figures. As a result, the recalculated relative shares of the various fuel-technique combinations in total health-related social costs are somewhat different. Figures 1, 3, 4, 16, 17 and 25 and Tables 16, 17 (new) and 18 changed compared to the former version.

Nevertheless, the conclusions of this research are not altered. Coal and wood remain the main contributors to health-related social costs. The total social cost figures per country/region also remain the same, as these have been calculated directly from the emission reports without double counting.

Summary

Introduction

Air pollution is a problem in many European areas as a result of transport, industrial and household activities using fossil fuels and biomass. Residential heating and cooking activities are an important source of greenhouse gas and air polluting emissions, making up 84% of total household energy use (Eurostat, 2021c). Air pollution is one of the greatest risks to health, by causing stroke, heart disease, lung cancer, and both chronic and acute respiratory diseases, including asthma. These health effects lead to economic and welfare losses due to lower life expectancies, illness, greater healthcare spending and lower productivity.

In this study, we quantified these health-related social costs of outdoor air pollution caused by residential heating and cooking. We looked at the impact of seven air pollutants ($PM_{2.5}$, NO_x, NH_3, SO_2, CO, CH_4 and NMVOCs) in the EU27+UK as a whole and four individual countries (UK, Spain, Italy and Poland). We estimated the amount of emissions and calculated their social costs by using “environmental prices”. Those prices vary among the EU27+UK countries, accounting for differences in income levels and population densities. Prices distinguish between emissions in rural and urban areas and consider various stack heights (only for $PM_{2.5}$). We also conducted a literature review on indoor pollution.

Main results

Health-related social costs of European residential heating and cooking are € 29 billion

The total health-related social costs of outdoor air pollution due to domestic heating and cooking activities by households in the EU27+UK amounted to € 29 billion (0.2% of total GDP) in 2018. This translates into a cost of 130 €/year for an average European household, as Table 1 shows. Most costs (94%) relate to direct emissions that arise at home from fossil-fuel and biomass based techniques. A small part of the costs (6%) is related to indirect emissions caused by electricity and heat production; some heating and cooking technologies have no direct emissions, but use electricity or collective heat (district heating).

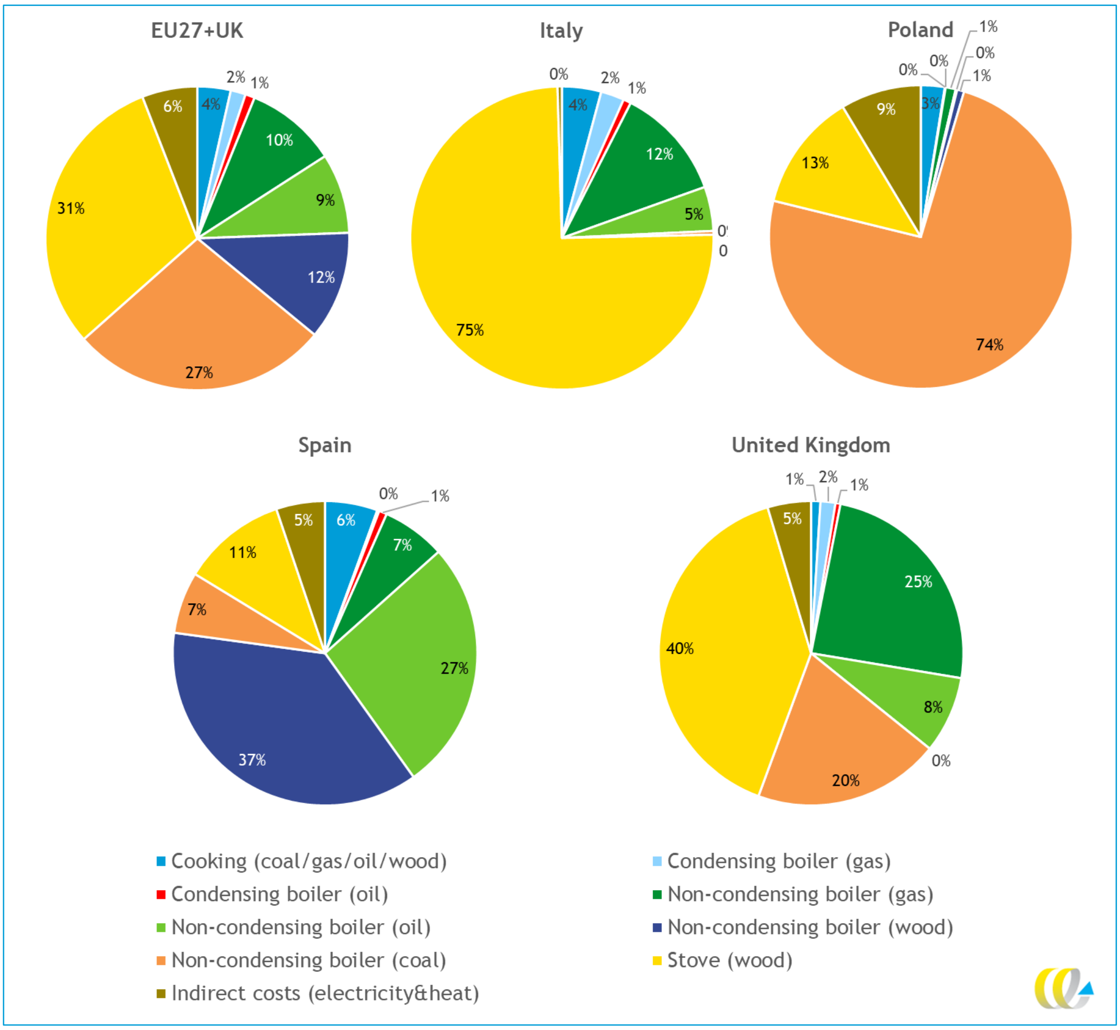
Table 1 - Total health-related socials costs of outdoor air pollution due to domestic heating and cooking (2018)

Country/region	Total costs (billion €)	Total costs per household (€/year)
Poland	3.3	228
Italy	4.7	180
EU27+UK	29	130
Spain	1.2	65
UK	2.7	92

Coal and wood are the main contributors to health-related social costs of outdoor air pollution in the EU

Table 1 also reveals that households in Poland and Italy face health-related social costs that are higher than the EU-average. This is mainly due to the fuels used for domestic heating. Poland is among the highest coal using countries. Coal boilers account for 36% of the final energy consumption by households and represent 74% of all health-related social costs in the country. In Italy, wood stoves are the main contributors to air pollution. Although they account for 22% of total final energy consumption by households, they cover 75% of total health-related costs in the country, as shown in Figure 1.The same holds for the UK and the EU27+UK as a whole where wood stoves make up 40%, respectively 31% of the total health-related costs. In Spain, wood boilers are the main contributors, with 37% share in total costs, followed by (non-condensing) oil boilers that make up 27% of the costs.

Figure 1 – Total health-related socials costs of outdoor air pollution due to domestic heating and cooking, differentiated by technique-fuel combination (%, 2018)



For each fuel-technique combination we calculated the health-related social costs in €/GJ output and in €/household/year. The results for EU27+UK are provided in Table 2, both showing that coal boilers and wood stoves are on top of both lists. The health-related social cost of using a coal boiler is € 1,200 per year, while that of using a wood stove is € 750 per year. For comparison, we roughly estimated that driving a diesel car for one year causes health-related social costs of € 210. Non-condensing gas boilers are frequently used within the EU27+UK area and show health costs figures of about € 30 per year. This is three times higher than the cost of using heat pumps, which are about € 10 per year. The cleanest technologies are heat pumps and 100% renewable options such as solar.

Table 2 – Average health-related social cost of technique-fuel combinations for heating in the EU27+UK (2018)

Technique-fuel combination	Cost per unit of output delivered (€/GJ)	Cost per household (average €/year)
Non-condensing boiler - Coal	29.2	1,233.3
Stove – Wood	17.9	756.1
Non-condensing boiler – Wood	3.8	159.3
Stove – Oil	3.3	139.8
Condensing boiler – Wood	3.2	136.8
Non-condensing boiler - Oil	2.9	122.8
Condensing boiler - Oil	2.5	105.4
Stove - Gas	1.8	77.0
Electric radiators	1.0	40.2
Non-condensing boiler - Gas	0.7	30.0
Condensing boiler - Gas	0.6	25.7
Combined heat and power (CHP)	0.5	20.0
District heating	0.3	13.5
Aerothermal heat pump	0.3	10.9
Geothermal heat pump	0.2	8.7
Solar	0.0	0.0

Alternative fuel-technique combinations can reduce health-related social costs

Switching to alternative fuels and/or techniques can reduce the health-related social costs considerably. Although not all alternative technique-fuel combinations are currently available on the market, we estimated the health-related social costs of some alternative heating options. This may help policy makers in designing climate and air quality policies for the built environment. Table 3 shows these results, including central values, upper and lower bounds to indicate uncertainties for the situation now and the potential situation in the future when all electricity will be produced by renewable resources. The performance of current 'green' hydrogen boilers would be € 2.6 per GJ output (central value), which is comparable to oil boilers and dirtier than gas boilers. Grey hydrogen boilers might be cleaner than gas boilers, but only based on the central value of € 0.31 per GJ output. Heat pumps are still the least emitting, followed by the hybrid heat pump. The latter performs better than gas boilers (€ 0.61/GJ) or electric radiators (€ 1/GJ output). However, if countries succeed in making their electricity production renewable, health-related social costs of green hydrogen, heat pumps and other electric appliances can drop significantly.

Table 3 - Health-related social cost of alternative technique-fuel options in the EU27+UK (€/GJ output and €/household/year, 2018)

Technique	Current health-related social costs		Potential health-related social costs in the future	
	per unit of output delivered (€/GJ)	per household (€/hh/year)	per unit of output delivered (€/GJ)	per household (€/hh/year)
'Green' hydrogen boiler	€ 2.6 [€ 2.4-€ 5.9]	€ 108.1 [€ 102.2-€ 249.6]	€ 0.2 [€ 0.1-€ 3.6]	€ 9.3 [€ 3.3-€ 150.8]
Grey hydrogen boiler	€ 0.3 [€ 0.2-€ 3.7]	€ 13.3 [€ 7.3-€ 154.8]	€ 0.3 [€ 0.2-€ 3.7]	€ 13.3 [€ 7.3-€ 154.8]
Heat pump (geothermal)	€ 0.2	€ 8.7	~€ 0	~€ 0
Hybrid heat pump	€ 0.3	€ 12.1	€ 0.1	€ 5.2

Notes:
- Central values are displayed with lower and upper bounds between brackets.
- 'Green' hydrogen refers to production by electrolysis. Depending on the type of electricity used for this process, it is truly green (only renewable electricity excl. biomass) or 'green' (current electricity mix).
- Current health cost estimates are based on the energy mix used for electricity production in 2018.
- Potential cost estimates assume electricity production with 100% renewable energy, excluding biomass, reducing the indirect costs of electricity used for heating to zero.

Indoor pollution also causes health-related social costs

Heating and cooking do not only result in health damages outdoor. For many pollutants, concentration levels are often higher indoors than outdoors. Besides, European citizens tend to spend most of their time indoors, which means that indoor air quality plays a significant part in their general state of health. Especially in households where fossil and/or biomass fuels are used in unvented stoves for cooking and heating, indoor air pollution levels of $PM_{2.5}$, NO_2 and CO can be substantial. On the contrary, heating and cooking techniques that use electricity do not cause direct emissions indoor since no combustion take place in the dwelling. Other factors that determine indoor air quality are the type of food and the way it is prepared, the insulation level, ventilation and exhaust hoods, other household activities, outdoor air pollution and room size and exposure to pollutants. This means that health impacts on households within and between European countries will vary widely.

In this study, the health impacts of indoor air pollution have not been taken into account quantitatively as our review of the literature shows that the methodology of estimating those costs still needs further research and verification. This means that the presented health-related social costs are only related to outdoor pollution and will therefore be a considerable *underestimation of* the total health-related costs people face from using heating and cooking appliances. More research is needed to come up with an estimate of health-related social costs of both indoor and outdoor pollution related to domestic heating and cooking.

Conclusion and recommendations

In this study we have shown that there are significant health-related social costs associated with current domestic heating and cooking activities in the EU27+UK. In order to lower the health damages due to air pollution, it is necessary to direct policies towards it. Urging the replacement of technique-fuel combinations based on wood, coal, oil and gas, by cleaner alternatives is an important step in the right direction. (Hybrid) heat pumps are promising techniques in this regard. In addition, it is crucial to make the production of electricity and (collective) heat production more sustainable.

1 Introduction

1.1 Background

Besides the occurrence of climate problems, many cities throughout Europe are struggling with poor air quality as a result of transport, industrial and household activities using fossil fuels and biomass. Residential heating and cooking activities are an important source of greenhouse gas and air polluting emissions. About half of total $PM_{2.5}$ emissions stem from residential, commercial and institutional sectors (EEA, 2021b). NO_x emissions due to domestic heating and cooking are also substantial. While much of the NO_x emissions come from the exhausts of petrol and diesel engines, it is for example estimated that up to 22% of NO_x emissions in London come from gas boilers used for heating (Seals & Krasner, 2020).

Air pollution is one of the greatest environmental risks to health. By reducing air pollution levels, countries can reduce the burden of disease from stroke, heart disease, lung cancer, and both chronic and acute respiratory diseases, including asthma (WHO, 2021a). In 2019, 307,000 premature deaths in the EU27 were attributed to chronic exposure to fine particulate matter and 40,400 premature deaths relate to chronic nitrogen dioxide exposure (EEA, 2021a). The health consequences of air pollution result in welfare losses due to lower life expectancies and illness, greater healthcare spending and lower productivity, resulting in economic losses (Can Europe & Friends of the Earth, 2021). More and more studies also recognise the health effects of indoor air pollution, next to outdoor pollution that is already receiving more attention. This study focusses on the total health-related social costs of air pollution due to domestic heating and cooking in the EU27+UK.

1.2 Aim and approach

This project aims to:
1. Estimate the total human health-related social costs of outdoor pollution due to technologies used for space heating, domestic hot water and cooking in the EU27, individual Member States and the UK.
2. Further assess the health-related social costs in four case study countries (Spain, Poland, Italy and UK): show the social costs of outdoor pollution per technology and fuel combination.
3. Consider indoor pollution and evaluate to what extend it is possible to estimate the total health-related social costs of both indoor and outdoor pollution.
4. Provide insight in the impact of alternative technique-fuel combinations on reducing the health-related social costs of residential heating and cooking.

In order to meet these objectives, we carried out the following research steps:
- Set up a solid and robust framework to value health-related social costs. In this framework, we include live years lost, medical care and productivity losses using WHO (2013) guidelines and combine these with a valuation framework that is used to value external costs in Europe (EC, 2020). This results in a set of so-called “environmental prices” for the air-polluting substances under consideration.
- Use all available and relevant statistical and research data to estimate total emissions for the EU27 and UK and per heating technology/energy carrier combination. Combining these emissions with the environmental prices yields total cost estimates.

- Consider some relevant alternative technique-fuel combinations and analyse how their implementation might impact emissions and subsequently the health-related social costs.
- Analyse (scientific) literature on indoor pollution and investigate if it would be possible to develop a methodology to estimate the social costs of indoor emissions that, combined with environmental prices, would lead to estimates of total health cost figures.

1.3 Scope

In this study we set the following research boundaries:

- *Air-polluting substances:* this study focuses on calculating the health-related costs caused by outdoor emissions of seven pollutants: fine particulate matter ($PM_{2.5}$), nitrogen oxides (NO_x), ammonia (NH_3), sulphur dioxides (SO_2), carbon monoxide (CO), methane (CH_4) and non-methane volatile organic compounds (NMVOCs). From earlier studies that considered a larger number of pollutants (see (CE Delft, 2019)), we conclude that these seven substances constitute over 95% of total damage costs of outdoor pollution from residential heating systems.[1] Whether black carbon should be distinguished from $PM_{2.5}$, is still under scientific debate. (WHO, 2013) did not provide a guideline on this issue. Therefore, we did not consider black carbon separately. PM_{10} is not taken into account due to potential overlap with $PM_{2.5}$.
For indoor pollution, we focus on the most relevant substances ($PM_{2.5}$, NO_2 and CO). Besides identifying relevant factors, we consider whether it is methodologically possible to come up with a quantitative cost estimate for indoor pollution.

- *Health impact:* we consider the (direct) health impact of air pollution and related social costs. By damaging the ecosystem and natural resources, air pollution can also have indirect negative repercussions on human health, e.g. through damage to agricultural crops, leading to poor nutrition and ultimately impact health. This indirect link is however not included.

- *Average health impact*: this study is based on average impacts on human health, even though in practice not every individual is exposed to the same level of air pollution. For instance, the impact varies with duration and concentration of the exposure. In addition, children, elderly, pregnant women and people who already suffer from diseases such as asthma and chronic obstructive pulmonary disease (COPD), will be more sensitive to air pollutants and experience more health effects than others.

- *Emissions*: we considered direct emissions (Scope 1) and emissions related to the generation of purchased electricity and heat (Scope 2). Scope 1 emissions derive from the burning of fuels (e.g. natural gas, oil, coal or biomass) by households for heating and cooking. Some heating and cooking technologies use electricity and/or houses are connected to district heating systems. Emissions related to the use of electricity and/or heat do not occur at the household level, but at the power plant. To ensure a fair comparison of heating technologies, we take into account these emissions related to the generation of purchased electricity and/or heat and these are included as ‘indirect’ (Scope 2) emissions.

1 $PM_{0.1}$ is not included in this study, but its impact on health might need further attention in future studies as these ultrafine particles can penetrate deeper into the body and might have more severe health effects.

- *Link with climate change:* heating and cooking using fossil fuels or electricity generated by fossil fuels also have an indirect negative impact on health via their role in climate change. This, in turn, threatens human health, in particular via heat waves and extreme weather events. This is however outside the scope of the present study.

- *Residential heating and cooking systems:* in this study we focussed on residential heating and cooking. Emissions from the industrial and service sectors are therefore outside the scope of this study. The main reason is data availability; while the data on households are already scarce, data specifically on air pollution from heating systems in the industrial and service sectors is often missing. Although these sectors can use similar technologies as for residential heating, the scale of these techniques is generally larger and the length of chimneys is higher (leading to more dispersion of pollutants). Therefore, we cannot combine the residential and non-residential sources of pollution from heating and cooking. All results in this study cover both residential heating and cooking activities, except Paragraph 3.1 and Chapter 4 (only heating). Space cooling is not included in the analysis; its energy demand is still relatively low, although it has more than tripled since 1990 and we expect it to increase further in the future as the world gets hotter (IEA, 2020).

- *Investment costs and practical issues*: this study solely focusses on the health-related social costs of heating and cooking activities. The consumer and infrastructural costs of investing in commonly applied or alternative heating fuel-techniques are not considered, although these are relevant for the (political) debate on a transition towards cleaner heating and cooking. The same holds for practical issues that determine whether a certain technique is suitable for particular types of dwellings. Homes must be well insulated to be heated with, for example, an electric heat pump. Using collective heating techniques is not obvious in areas where the density of the buildings is low.

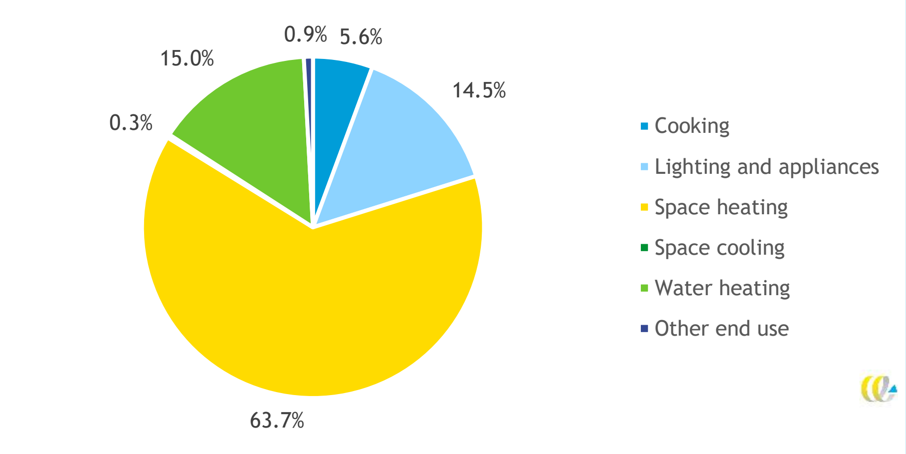
- *Geographical region*: this study covers the current EU27 area and the UK. Since data is provided for 2018 (and earlier years), when the UK was still part of the European Union, we will refer to EU27+UK in the remainder of this report.

- *Time period covered*: total health-related social costs are calculated for the year 2010-2018 to show their development over time. The other analyses cover 2018. Environmental prices are given for the year 2018 (in price level 2020).

1.4 European residential sector

The residential sector in the EU27+UK consisted of 223 million households in 2018 (Eurostat, 2021a). These households use energy for various purposes, such as space and water heating, space cooling, lighting and electrical appliances. As Figure 2 shows, the main use of energy by households is for space heating (63.7%), followed by water heating (15.0%).
Cooking makes up 5.6% of energy consumption in EU households (Eurostat, 2021c).

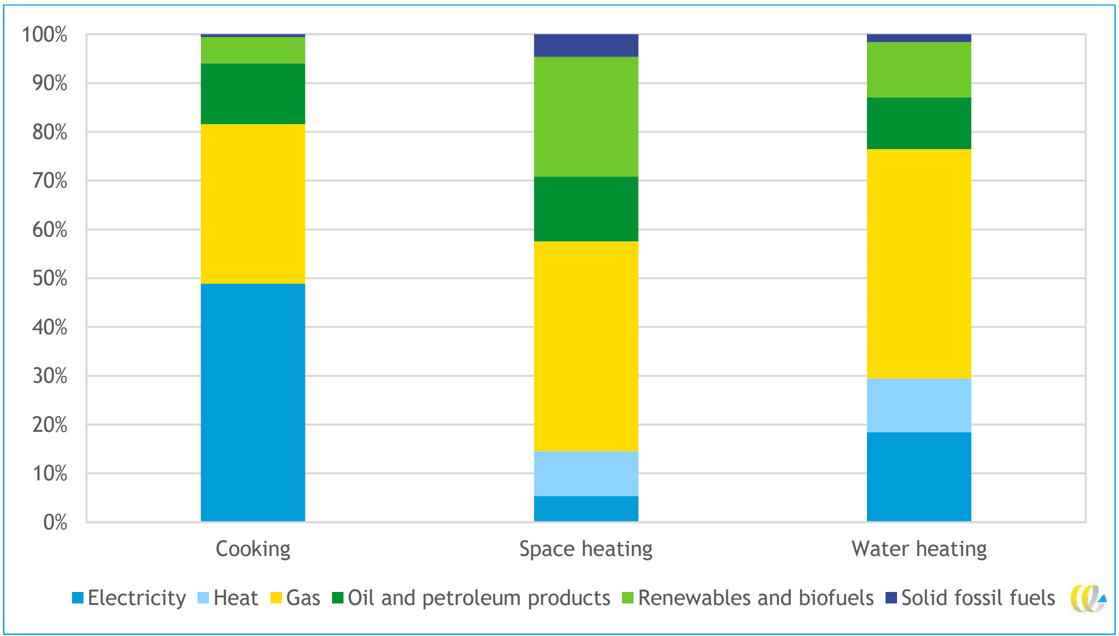
Figure 2 - Residential energy consumption by end-use in the EU27+UK (% of total, 2018)



Source: Eurostat, (2021c).

Figure 3 shows that the energy needs for space and water heating in the EU27+UK are mainly provided by (natural) gas and renewables and biofuels. Natural gas covers 43% of the energy needs for space heating and 47% of energy used for water heating. The shares of renewables and biofuels are 25% and 11% respectively. When it comes to cooking, electricity plays a larger role (49%) but is still closely followed by gas (33%).

Figure 3 - Energy used in the total final energy consumption for domestic heating and cooking in the EU27+UK (%, 2018)

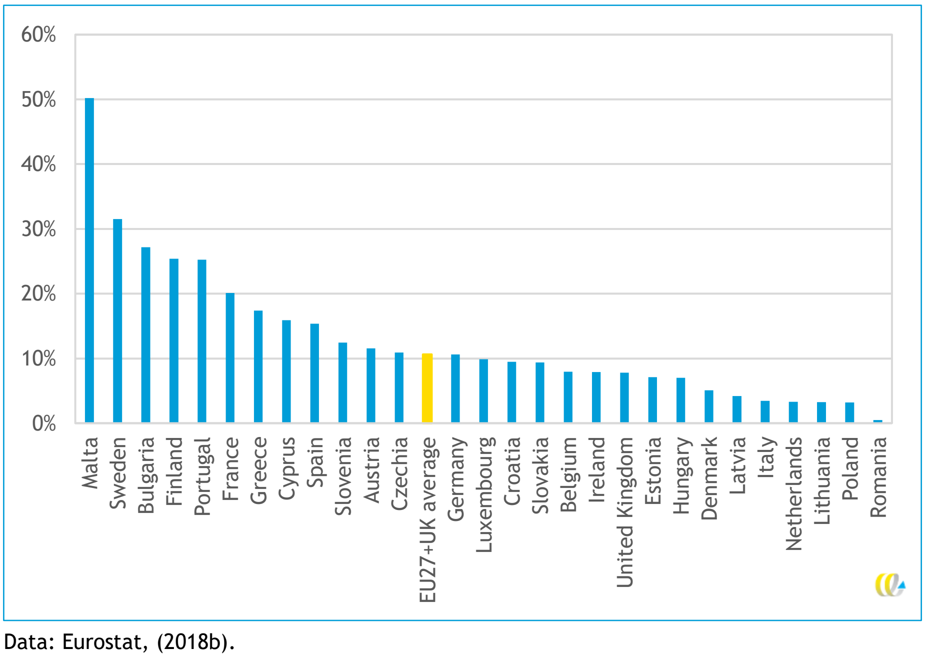


Data: Eurostat, (2021c).

Note: Heat covers CHP/district heating (derived heat). Renewables include heat pumps (ambient heat).

Between EU Member States, we observe differences in the use of energy products (also see Figure 25 in Annex C). For instance, most countries use a significant share (over 20%) of renewables and biofuels for cooking and heating their homes[2], but there are also countries that principally use gas for this purpose (Belgium, Germany, Netherlands, Italy, Luxembourg and UK). Cyprus, Ireland and Greece mainly use oil and petroleum products for space heating, whereas Sweden, Finland and Denmark mostly rely on derived heat. In Poland, solid fuels provide for the majority of energy needs for space heating (Eurostat, 2021c). Some countries, such as Malta and Sweden show a relatively large share of electricity use, as shown in Figure 4. Especially for those countries it is important that we include Scope 2 emissions of electricity (see Paragraph 1.3). Otherwise our analysis would have led to an underestimation of total health-related social costs there.

Figure 4 - Electricity use as share of total energy use for domestic heating and cooking in the EU27+UK (%, 2018)



Data: Eurostat, (2018b).

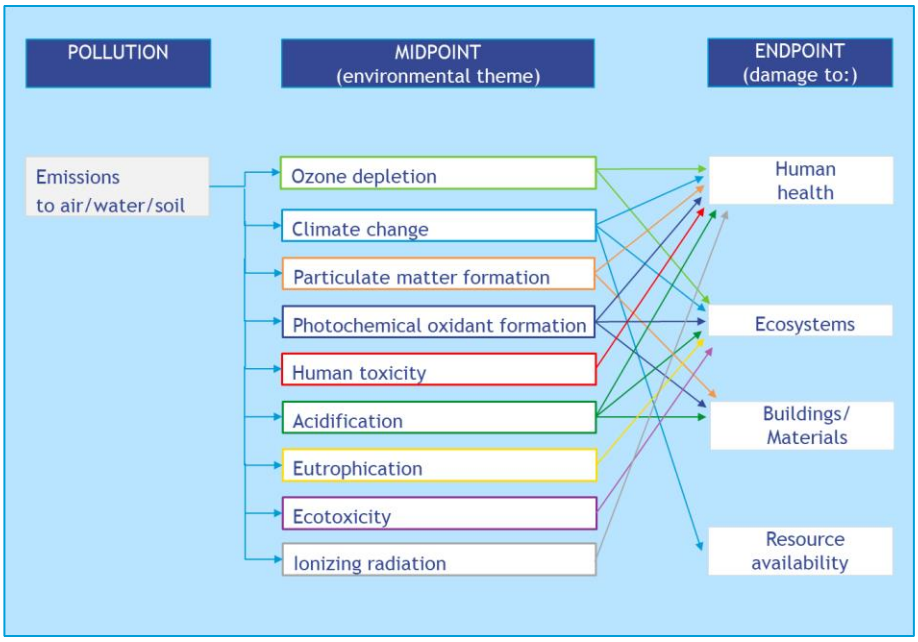
1.5 Air pollution and environmental prices

Numerous (economic) activities in every-day life cause pollutants as by-products that are emitted to the atmosphere, water and soil. Many of these substances have a negative (direct or indirect) impact on the environment. Environmental scientists distinguish a total of 10 to 20 relevant indicators that together characterise (changes in) the state of the environment. A well-known example is ‘climate change’, to which substances as carbon dioxide (CO_2) and methane (CH_4) contribute. Other indicators are for example ‘human toxicity’, ‘freshwater eutrophication’ and ‘photooxidant formation’. These are referred to as the midpoint impacts of emissions. These changes in the state of the environment are important because they go on to have an ultimate impact, on human health or biodiversity, for example. These latter impacts are known as endpoint impacts.

[2] These two categories are merged by Eurostat data but in fact have different impact on health and the climate.

In environmental science three related levels are thus distinguished: the pollutant level, the midpoint level and the endpoint level. Figure 5 illustrates the relationship between them.

Figure 5 - Relationship between emissions (at pollutant level) and impacts (at mid- and endpoint levels)



In this study we calculate the social costs of seven pollutants that are emitted directly or indirectly to air by residential heating and cooking techniques. We take into account their impact on human health (endpoint, also see Paragraph 1.3) through particulate matter formation and smog/photochemical oxidant formation (midpoints). These substances are taken up in the human body by breathing. After inhalation, they can spread throughout the entire respiratory system. The inhalation of the air polluting substances poses a risk of several health problems, as described in Textbox 1.

Textbox 1 – Health impacts of air pollutants

- **Particulate matter (PM)** is the term for a mixture of liquid and solid particles in the air (also known as aerosols) and are so small that they can be inhaled and cause serious health problems. PM emissions are characterized by size. In particular the smaller particles can get deep into the lungs and may even get into the bloodstream. This is why $PM_{2.5}$ poses a greater risk to human health than PM_{10} (EPA, 2021c). Next to primary PM directly emitted by fuel combustion, secondary PM is mainly formed through chemical reactions between SO_2, NH_3 and NO_X. These secondary inorganic aerosols are considered as harmful as PM aerosols. There is a close, quantitative relationship between exposure to high concentrations of small particulates (PM_{10} and $PM_{2.5}$) and increased mortality or morbidity, both daily and over time. Outdoor PM is ranked as the 4th risk factor for total deaths globally, through cancer, lower- and chronic respiratory diseases and cardiovascular diseases (HEI, 2020). People with heart or lung diseases, children and older adults are the most likely to be affected (EPA, 2020). Conversely, when concentrations of small and fine particulates are reduced, related mortality will also go down – presuming other factors remain the same (WHO, 2021a).
- **Non-methane volatile organic compounds (NMVOCs)** are formed upon incomplete combustion of fuels. They are a great contributor to the formation of ozone at ambient levels and as such indirectly responsible for adverse health effects. Ozone (SOMO35) causes respiratory problems, chronic obstructive pulmonary

disease (COPD), strokes and is probably related to cardiovascular diseases. Additionally, some NMVOCs have been classified as carcinogens, amongst some of which occur in diesel exhaust (Wierzbicka & others, 2014).

- **Nitrogen oxides (NO_x)** consist of nitrogen dioxide (NO_2) and other gaseous oxides containing nitrogen. Burning fuels is the main source of NO_x (EPA, 2021b). Therefore, indoor gas stoves and kerosene heaters are the main sources of NO_x pollution in urban areas – together with motor vehicle exhaust (EEA, ongoing). NO_x emissions cause direct effects through the formation of NO_2, and indirect effects through the formation of secundairy inorganic aerosols and ozone. Short exposures to elevated concentrations of NO_2 can irritate airways in the human respiratory system and can aggravate respiratory diseases (particularly asthma). Longer exposures contribute to the development of asthma and potentially increase susceptibility to respiratory infections. Reduced lung function growth is also linked to NO_2 at concentrations currently measured (or observed) in cities of Europe and North America (WHO, 2021a). Nitrogen oxides react with other chemicals in the air to form both particulate matter and ozone. Both of these are also harmful when inhaled due to effects on the respiratory system (EPA, 2021b).
- **Sulphur dioxides (SO_2)** is caused by burning fossil fuels. It is an important component for PM formation leading to similar diseases as emissions of $PM_{2.5}$ (EPA, 2021d) and, to a lesser extent, to ozone formation. Short-term exposures to SO_2 can furthermore harm the human respiratory system and make breathing difficult. People with asthma, particularly children, are sensitive to these effects of SO_2. Hospital admissions for cardiac disease and mortality increase on days with higher SO_2 levels (EPA, 2021b). The air pollutant can also react with other compounds in the atmosphere to form PM-pollution SO_2 is used as the indicator for the larger group of gaseous sulphur oxides (SO_X).
- **Carbon monoxide (CO)** is a colourless, non-irritant, odourless and tasteless toxic gas. Therefore, it is not detectible by humans either by sight, taste or smell. It is produced by the incomplete combustion of carbonaceous fuels such as wood, petrol, coal, natural gas and kerosene (WHO, 2021b). Breathing air with a high concentration of CO reduces the amount of oxygen that can be transported in the blood stream to critical organs like the heart and brain (EPA, 2021a). Low levels of indoor CO can cause fatigue in healthy people and chest pain in people with heart disease. Moderate to higher concentrations of indoor CO are associated with amongst other impaired vision, reduced brain function, headaches, dizziness and nausea (EPA, 2021e). At very high levels, which are possible indoors or in other enclosed environments, CO can cause CO intoxication. Outdoor emissions of CO contribute to ozone formation.
- **Ammonia (NH_3)** is mainly caused by agriculture (manure and fertiliser use), but the substance also has numerous indoor sources, including smoking, cooking and cleaning. NH_3 primarily contributes to (secondary) $PM_{2.5}$ formation.
- **Methane (CH_4)** is emitted to air due to incomplete combustion of fossil fuels, particularly natural gas which is a common fuel for residential appliances. Methane is an important ingredient in the formation of ozone

These negative health effects lead to medical treatment costs, production loss at work (due to illness) and, in some cases, even death. Ambient (outdoor) air pollution in both cities and rural areas was estimated to cause 4.2 million premature deaths worldwide in 2016 (WHO, 2021b). About 58% of outdoor air pollution-related premature deaths were due to ischaemic heart disease and stroke, while 18% of deaths were due to chronic obstructive pulmonary disease and acute lower respiratory infections respectively, and 6% of deaths were due to lung cancer.[3]

Social costs reflect the adverse welfare effects of these health impacts on society. They comprise both direct (health care) expenditures (e.g. for hospital admissions, loss of working days) and indirect health impacts and accompanied welfare loss (e.g. discomfort of diseases such as COPD, increased mortality risk/reduced life expectancy due to air pollution). By attaching environmental prices to the air pollution emissions, these social costs are estimated.

[3] Some deaths may be attributed to more than one risk factor at the same time. For example, both smoking and ambient air pollution affect lung cancer (WHO, 2021a).

Environmental prices are indices expressing the social cost of environmental emissions in Euros per kilogram of substance emitted. They are also known as ‘external costs’ since the social costs of environmental damage are often not fully paid by the polluter(s). For the substances considered in this study, environmental prices are calculated through the damage cost method, which is commonly used by economists for assigning a value to externalities.[4] This approach means that environmental quality is valued on the basis of the estimated damage occurring due to air polluting emissions. The damage cost method proceeds from people’s willingness to pay (WTP) for avoiding those emissions and related health damage in terms of life expectancy reduction, (minor and net) restricted activity and working days, respiratory hospital admissions and increased morbidity and mortality risk. For example, the value people attach to (healthy) life years is included in this approach. A value of € 70,000 is used as value of a life year (VOLY) and Quality Adjusted Life Years (QALY) (CE Delft, 2018a)). This implies that on average, people’s willingness to pay for one additional (healthy) life year, or avoiding losing a (healthy) life year, is around € 70,000, in the EU. Based on the VOLY, the value of premature death due to air pollution is estimated. QALY is used to value morbidity due to air pollution.

In this study, we take into account the social costs related to these health effects. Not all health effects mentioned in Textbox 1 have been quantified in our social cost figures. Only impacts that have been included in the WHO (2013) framework have been included in the present study.[5] Table 4 shows which health effects have (not) been included.

Table 4 - Included health effects of exposure to NO_2, $PM_{2.5}$ and ozone

Concentration of	Caused by emissions of…	Effects proven and included	Effects proven but not included	Effects probable but not included
PM_{10}/$PM_{2.5}$	$PM_{2.5}$ PM_{10} NO_x SO_2 NH_3	All cause mortality (chronic) Infant mortality Work days loss Restricted activity days (minor and net) Chronic bronchitis (COPD) Respiratory hospital admissions Cardiovascular hospital admissions	Non lethal cancers	Medication use Lower respiratory symptoms Diabetes
Ozone	NMVOC NO_x SO_2 CO CH4	Acute mortality Respiratory hospital admissions Cardiac hospital admissions Restricted activity days (minor)	COPD Restricted activity days asthmatic children	Chronic mortality Work days loss Non-lethal cancers
NO_2	NO_x	Increased mortality risk (long-term)* Bronchitis in asthmatic children^ Respiratory hospital admissions^		Cardiovascular effects Acute mortality

Source: CE Delft (2020).

Notes: * Impacts calculated using Relative Risks (WHO, 2013) and country-specific incidence rates.
^ Impacts calculated using Concentration Response Functions (CE Delft et al., 2019) using European incidence rates.

[4] Most environmental prices are currently based on damage costs, except for greenhouse gasses. For those economic valuation of these substances, the abatement cost method is prescribed. The environmental price is calculated as the cost of the most expensive technique required to meet governments climate targets.

[5] With the exception of respiratory problems for asthmatic children aged 6-12.

Environmental prices change over time due to inflation and changes in average income. They also differ per country or region due to differences in:
- Level of income, which influences the willingness-to-pay to avoid negative health effects of air pollution.
- Population density. The more people live in the vicinity of the emission source, the higher the damage in terms of premature death and diseases. Therefore, prices differ due to the location of the emission. Urban areas have higher population density, therefore more people are likely to inhale an emission than in rural areas.
- Other conditions, such as atmospheric and geomorphological conditions. For example, in Northern Italy, in the Po valley, air pollution tends to be more harmful as the nearby mountains limit dispersion of pollutants.

Another important aspect is the stack height of the emissions. Emission close to the ground such as from a car or a gas stove are inhaled to a higher extent than the same volume of emissions from a higher chimney, e.g. a power plant). Subsequently, more health damage is caused per ton emission at lower stack heights and environmental prices are higher compared to high stacks.

We set up a social damage cost framework to value health-related social costs to reflect the need to differentiate in the various aspects described above. The main methodology stems from the Environmental Prices Handbook (CE Delft, 2018a), with further differentiation added based on (Humbert et al., 2011). The methodology is described in detail in Annex A.1. Using this methodology, we constructed a set of environmental prices for the EU27+UK as a whole and individual Member States. These prices reflect the social health-related social costs per substance in terms of €/kg emitted. For $PM_{2.5}$, SO_2, NO_x and NH_3 a distinction between urban and rural areas is made. In addition, the stack height of $PM_{2.5}$ emissions is taken into account. Prices for CO, CH_4 and NMVOC are taken from (CE Delft et al., 2019). Table 5 shows the 2018 average environmental prices for the EU27+UK. Environmental prices for each individual EU Member State and the UK are presented in Annex A.2.

Table 5 - Differentiated environmental prices for the EU27+UK (€/kg, 2018)

Substance	Urban	Rural	Population-weighted average
$PM_{2.5}$			
High stack	24.9	22.0	20.9
Low stack	32.4	26.5	27.2
Ground level	94.0	50.3	78.8
Emission-weighted average	48.8	32.2	40.9
SO_2	12.85	10.4	11.4
NO_X	20.91	11.6	14.0
NH_3	18.71	18.7	18.5
CO	-	-	0.025
CH_4	-	-	0.111
NMVOC	-	-	1.3

Note: Population-weighted average prices are based on environmental prices for urban, rural and remote areas.

1.6 Reading guide

At the start of the project, we constructed a set of environmental prices for air pollution substances, see Paragraph 1.5 and Annex A. These prices are used in Chapter 2 to estimate the total health-related social costs of outdoor air pollution due to domestic heating and cooking for the EU27+UK and the individual countries. Chapter 3 presents health-related social cost estimates per heating technique-fuel combination for the EU27+UK average and four country cases (UK, Spain, Italy and Poland). The total health-related social cost figures of those four countries are also differentiated by technique-fuel combination. Chapter 4 analyses some alternative technique and fuel combinations, whose future implementation might reduce current health-related social costs. Finally, Chapter 5 is about indoor pollution. Chapter 6 covers the conclusions.

2 Total health-related social costs

In this chapter, we estimate the total health-related social costs of outdoor pollution caused by residential heating and cooking in the EU27+UK. Paragraph 2.1. describes the methodology. In Paragraph 2.2 we present the results, after which they will be discussed in Paragraph 2.3. Finally, in Paragraph 2.4, the direct health-related social costs of heating and cooking is compared with those related to transport activities.

2.1 Methodology

In order to determine the total health-related social costs of outdoor air pollution, we multiply the environmental prices (euro/ton emitted substance, see Paragraph 1.5 and Annex A) with the corresponding amount of total air pollution emissions for the EU27+UK as a whole and the individual countries. Since we use national air emissions accounts, we consider this as a top-down approach. We distinguish between direct and indirect emissions.

Direct emissions

With respect to direct emissions, we use Eurostat statistical data (national air emissions accounts) on total direct emissions from residential heating and cooking[6] in the EU27+UK and each Member State. The time period 2010 to 2018 is available for all EU countries.
In this study, direct emissions are the air emissions that emerge from private households. They derive from the burning of fuels by households for heating (space heating and domestic hot water) and cooking. Annex B.1 shows the direct emissions from residential heating and cooking in the EU27+UK. Since environmental prices differ in value for urban and rural areas, we need to distinguish urban and rural emissions as well. We assume that the share of emissions originating from rural areas in a country is equal to the percentage of the population living in rural areas. We combined the percentages of the population living in urban areas, towns and suburbs to represent the share of emissions originating from urban areas.

It should be noted that some direct emissions start indoor and, dependent on the specific situation (ventilation, etc.), a certain amount of indoor emissions end up outdoor. This is particularly relevant for cooking. The emission figures of Eurostat cover outdoor pollution[7] and our environmental prices reflect health costs due to outdoor pollution. In Chapter 5 we pay some qualitative attention to indoor pollution and provide starting points for estimating indoor pollution impacts.

[6] The reported category is “heating/cooling”, but since space cooling is fully based on electricity, no direct emissions are reported. This category includes emissions from cooking (2015).

[7] Given their scope and methodology. The distinction between indoor and outdoor is not explicitly made.

Indirect emissions

Eurostat only publishes data on direct emissions from residential heating and cooking, and does not report on emissions related to the generation of purchased electricity (Scope 2 emissions). Several heating and cooking technologies require electricity, e.g. electric radiators, heat pumps and electric stoves. The emissions that are related to the use of electricity are not allocated by Eurostat to individual households, but to the electricity producers/suppliers. To make a fair comparison between the heating and cooking technologies, we must also take these emission into account (see also Paragraph 1.3).
In order to estimate the total amount of emissions related to the use of electric heating and cooking technologies in the various countries, we considered several approaches (see Annex B.1.2).We concluded that the option that best suits this study is calculate average emissions intensities for NO_x, SO_2, NH_3, $PM_{2.5}$ and NMVOC of electricity and heat production based on the methodology of European Environmental Agency (EEA). We combined these emission factors (per GJ input) with electricity and heat demand for domestic heating and cooking (in GJ input)[8] in order to determine the total amount of indirect emissions in the EU27+UK and the individual countries.

Subsequently, we combined the indirect emissions with environmental prices for NO_x, SO_2, $PM_{2.5}$, NH_3 and NMVOC emissions. In principle prices for emissions on high altitude from electricity generators would apply. However, distinction in stack height can only be made for the substance $PM_{2,5}$ (see Chapter 2). For the other substances, prices applied here are the same as those used for direct emissions with respect to height, which might lead to some overestimation of the health-related costs. With respect to location, one could argue that electricity generation is further away from households compared to fuel combustion at home, so that damage can be assumed to be relatively lower. However, valuing the emissions with 'rural' environmental prices would not be correct as we do not know exactly where power plants are situated in each country, some might be located in or near cities. Therefore, the most justifiable option is to value indirect emissions with environmental prices based on average population density, since it is unknown to what extent power plants are situated in urban or rural areas.

2.2 Results

Total health-related social costs of outdoor pollution

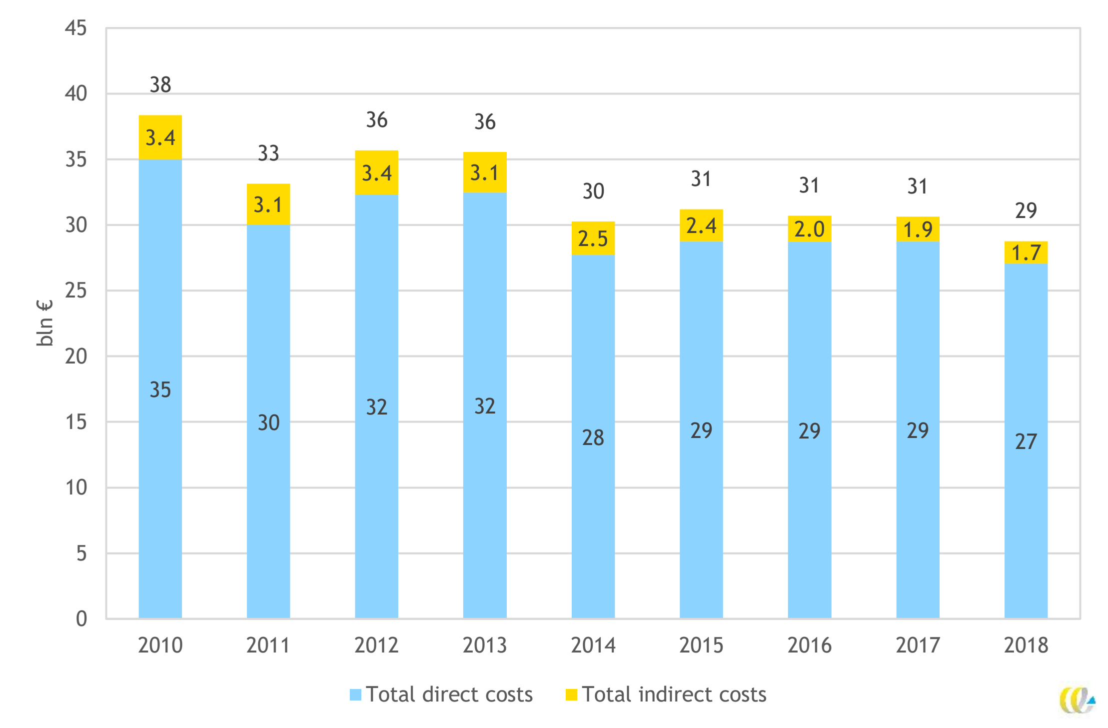
In 2018, the total health-related social costs of outdoor air pollution due to domestic heating and cooking activities by households in the EU27+UK amount to € 29 billion. This is about 0.2% of total GDP in that area[9]. Figure 6 shows the development over time. It depicts that total costs have decreased by approximately € 9 billion since 2010.[10]

[8] For some countries, no energy demand data is available for the years 2010-2014. This data is interpolated based on their share in total EU demand for the period 2015-2018.

[9] Total GDP was € 15,9 trillion in 2018 in the EU27+UK (2018).

[10] Due to data limitations, we could determine the direct costs for the period 2010-2018, not for earlier years.

Figure 6 - Total health-related social costs due to domestic heating and cooking in the EU27+UK (bln €)



Note: For the countries Bulgaria, Cyprus, Greece, Ireland, Latvia, Malta, Poland, Romania, Slovakia and Slovenia, NH_3 emissions are not included due to lack of data.

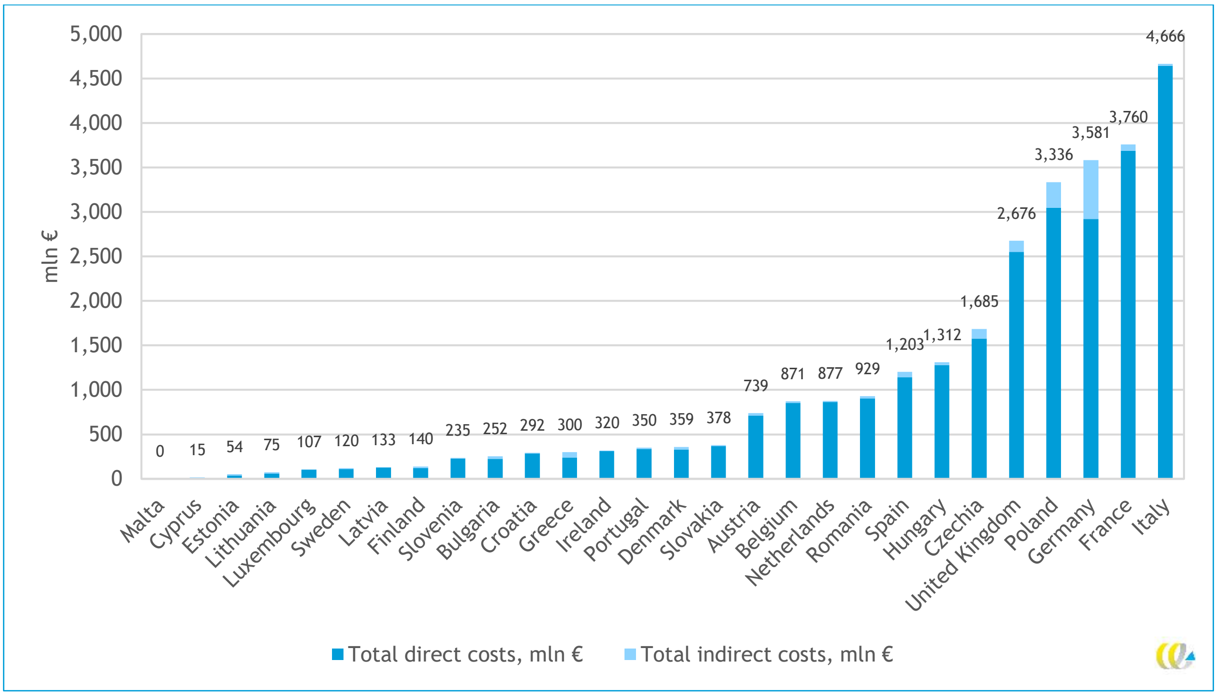
Direct emissions, those that that occur at the same location as where they are caused, have been the most important source of health-related costs, accounting for over 90% of total costs. These costs are highest in urban areas. About € 20.5 billion (76%) of the total direct costs in 2018 arises in urban areas and € 6.5 billion (24%) in rural areas. This is due to the fact more emissions arise in urban areas and the environmental price per kg emissions is also higher. The latter point is explained by the fact that emissions in urban areas have a greater impact because more people are affected given higher population densities.[11]

Figure 7 shows the total health-related cost estimates for individual countries in 2018. Italy has the highest costs, nearly € 4.7 billion (or 0.26% of Italian GDP), almost entirely caused by direct emissions. The second largest cost estimate is for France, amounting to € 3.8 billion (0.16% of French GDP), followed by Germany with € 3.6 billion (0.11% of German GDP). Malta has the lowest total costs from heating and cooking, with less than € 0.3 million damage costs.

In most countries direct emissions are responsible for over 80% of the total health costs. In Germany, a relatively large share (18%) of total costs originates from indirect emissions due to electricity and derived heat production. This also holds for Greece (20%), Lithuania (21%), Estonia (29%), Cyprus (80%) and Malta (28%).

11 Subsequently, the direct health costs per household are much higher in urban areas of a country compared to those in rural areas (see Figure 27 in Annex C).

Figure 7 – Total health-related social costs due to domestic heating and cooking per country (mln €, 2018)



In all countries, direct health costs are higher in urban areas than in rural areas, even though almost half of the population in some East European countries live in rural areas (see Figure 26 in Annex C)[12].This is due to higher damage costs in those areas.

It should be noted that the total cost figures presented above *cannot* be used to indicate how 'clean' or 'dirty' domestic heating and cooking are in particular countries. This is due to the fact that population size is an important factor underlying total cost figures. This is the case for Italy, France and Germany that have many inhabitants. Their total energy use for domestic heating and cooking is very high whereas the energy consumption per household low (Italy) or moderate (Germany, France, although above EU-average)(see Figure 28 and Figure 29 in Annex C). This illustrates the need to report total health-related costs per person and per household in the next paragraph.

Health-related social costs per person and per household

Over the years, the total health-related costs of domestic heating and cooking per household have been decreasing in the EU27+UK area. As shown in Figure 8 the costs per household decreased from approximately 180 €/year in 2010 to nearly 130 €/year in 2018. Because the average household size in the EU has been decreasing, the environmental costs per person decreased at a slower pace, from around 75 €/year to 55 €/year. This means that in 2018 the average EU citizen suffers a welfare loss of € 55 per year, due to health-related impacts from outdoor air pollution resulting from residential heating and cooking activities. These estimates include health effects due to direct and indirect emissions. The vast majority of costs (91-94%) stems from direct pollution.

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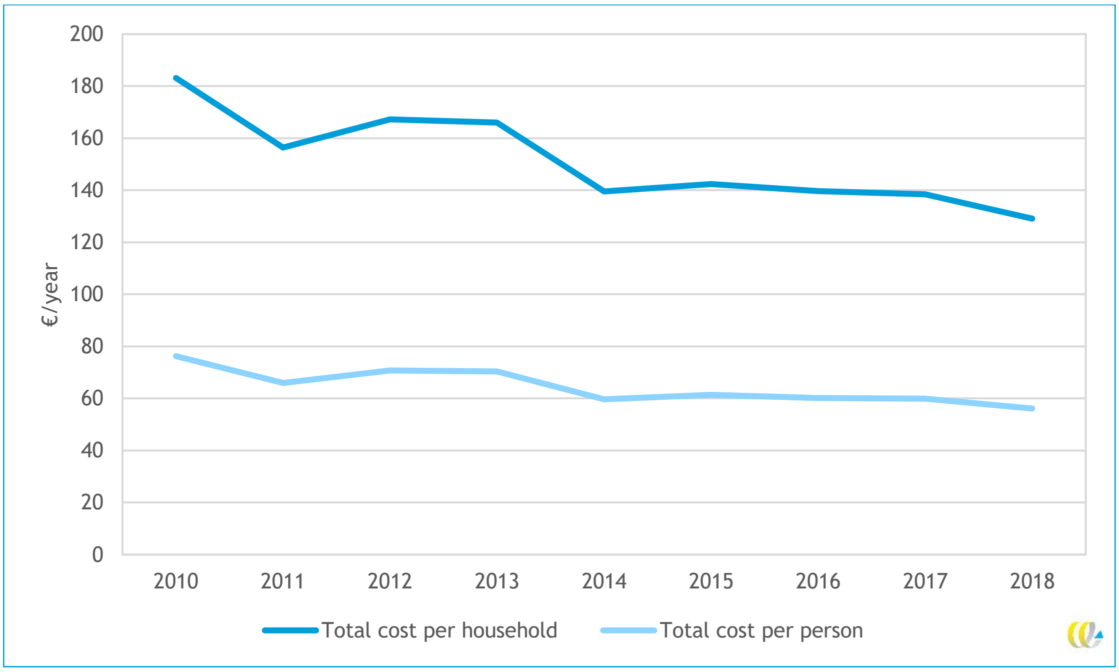
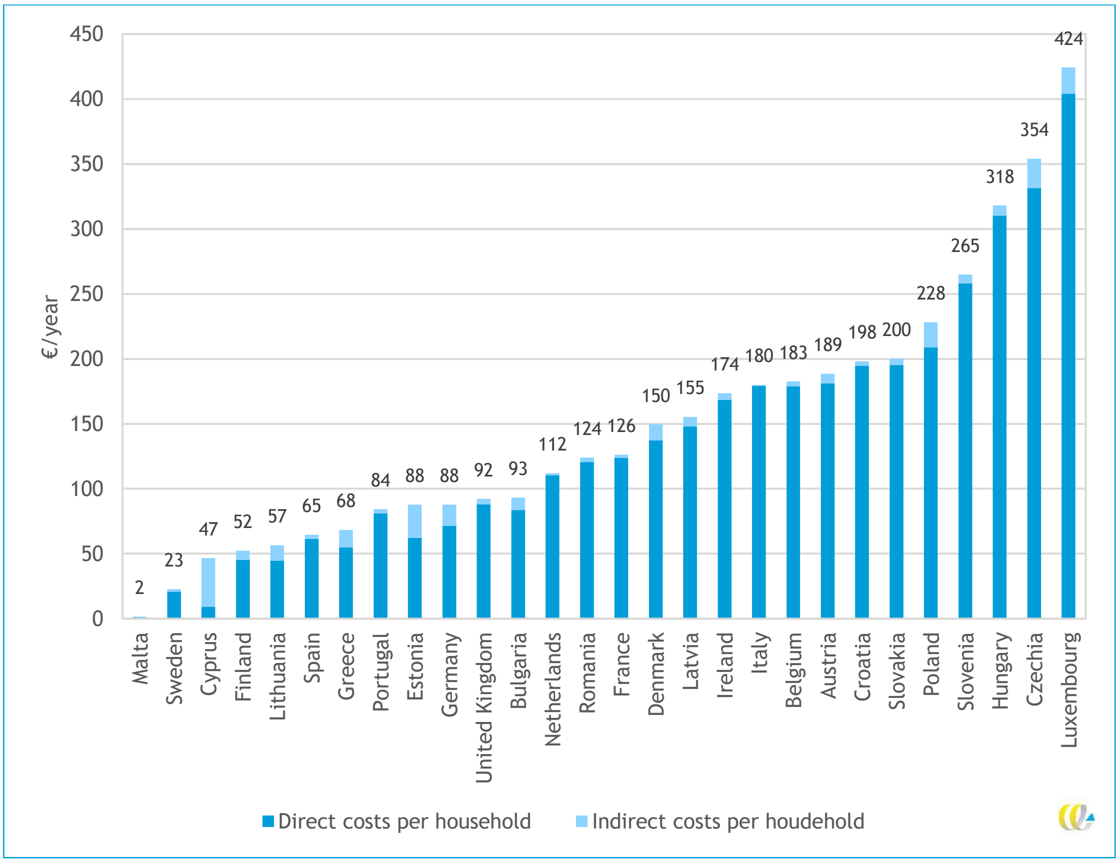
[12] Meaning that also almost half of total emissions are assumed to take place in rural areas.

Figure 8 - Total health-related social costs per household/person due to domestic heating and cooking in the EU27+UK (€/year, 2018)



When we consider the total health-related costs per country, Luxembourg turns out to be the country with the highest cost per household in 2018, see Figure 9. On average, each household in Luxembourg faces nearly 425 €/year of health-related damage costs due to the pollution caused by heating and cooking activities, to be explained by a high GDP (leading to relatively high environmental prices) and a high level of energy consumption per household (see Paragraph 2.3), Luxembourg is followed by a number of Eastern European countries (Czechia, Hungary, Slovenia, Poland, Slovakia and Croatia). In these countries, total health-related costs are 200-355 €/year per households. Sweden is among the countries with the lowest health-related costs: 23 €/year, due to a relatively high use of low emitting cooking and heating techniques (see Textbox 2 in Paragraph 2.3).

Figure 9 – Total health-related social costs per household due to domestic heating and cooking per country (€/year, 2018)



In all countries except Cyprus, the direct costs make up the largest share of the total costs. Indirect costs are much smaller. They are particularly related to NO_x emissions of electricity and derived heat production (see Figure 30 in Annex C)[13]. In the next paragraph, we will present a more in-depth analysis of the difference in health cost figures between countries.

2.3 Explanation of the results

There are multiple factors that might explain why the health-related costs of residential heating and cooking per household differ between countries. Most relevant are:

- the volume of emissions, determined by:
  - the amount of energy consumed;
  - the heating technologies and energy carriers that are used.
- the environmental price per emissions.

[13] Only in Poland, most indirect costs stem from SO_2 emissions. The emissions of other substances are small.

Energy consumption

It can be expected that the health costs are higher in countries where the average energy consumption of households is relatively high. The vast majority of energy in the residential sector is used for space heating. One factor that stands out as having an important influence on heating demand is climate. This is illustrated by the heating degree days index, which is calculated by adding the temperature difference between outside and inside for all days with a temperature below 15°C. A higher heating degree days index corresponds to a higher heating demand. Countries with high heating degree days indices are Finland, Sweden, Estonia, Latvia and Lithuania (CE Delft, 2020). These indeed translate into a high energy use per household in Finland and Sweden (see Figure 29 in Annex C). These countries have the highest energy consumption per household (three to four times the European average), followed by France and Luxembourg. In latter countries, households' energy demand for space heating might be due to the insulation level of the buildings (well-insulated homes require less energy to reach similar comfort levels), or the size of the dwelling and/or the household. France and Luxembourg are indeed among the countries with the highest health-related costs per capita. However, energy demand only tells part of the story. The two countries with the highest heating demand (Finland and Sweden) are not the countries with the highest health costs since they use relatively 'clean' techniques and energy carriers (see below).

Heating technologies and energy carriers

As mentioned, European countries differ substantially in fuel types used for residential heating and cooking (also see Paragraph 1.4). In countries with a higher share of 'dirtier' fossil fuels, the health costs due to outdoor pollution will be relatively higher. Textbox 2 describes Poland as an example. Alternatively, the fact that Finland and Sweden have the highest energy use per household, but relatively low health-related costs is due to their way of heating and cooking, using clean heating fuels. Sweden is also described in Textbox 2. We will take a closer look at the health costs associated with different technologies and energy carriers in Chapter 3.

Textbox 2 - Sweden and Poland: examples of a low and high health cost country

Sweden is a high-income country with a high amount of heating degree days yet has one of the lowest total health-related costs per household in the EU (23 €/year) thanks to a high use of electricity (27%) and district heating (42%) for domestic heating and cooking, whereas these have low emission rate. This is due to the fact that about 75% of electricity production in Sweden comes from hydroelectric (45%) and nuclear (30%) power. More than 17% of the electricity comes from wind power (Swedish Institute, 2021).

Poland is one of the Eastern European countries with a high health-related costs per household, nearly 230 €/year per household. Although classified as a high-income country, its environmental prices are lower than the European average and it has quite a moderate energy consumption per household. This illustrates the importance of fuels used. Poland is among the highest coal using countries for heating and cooking. The share of coal used in individual heating systems is nearly 48% and for district heating this share is about 73% (Forum Energii, 2019). There is also a substantial use of biomass for home heating in Poland. Air pollution emissions of coal are substantial and the health-related social costs of a boiler based on coal (in €/GJ output) are the highest of all techniques considered. They are about 8.5 times higher than those of a boiler fuelled with wood, ten times higher than an oil boiler, 45 times higher that a gas boiler and 75 times higher than a heat pump (see Paragraph 3.1.2).

Environmental prices

Besides the volume emissions, the environmental price that is attached to each emission determines the total cost estimate. Environmental prices are country specific and reflect average income (measured as GDP per capita), population density and age distribution (Paragraph 1.5). Countries with relatively high environmental prices include Luxembourg, Germany, Belgium, Netherlands and the UK, i.e. mostly Western European countries. This is in large part due to a high average income. Luxembourg indeed has the highest GDP in Europe and, together with a high energy consumption per household, this explains the high health-related cost estimate per household. The other countries that have relatively high environmental prices, show relatively low total cost estimates per household, indicating that emissions are relatively low due to low and/or clean energy consumption.

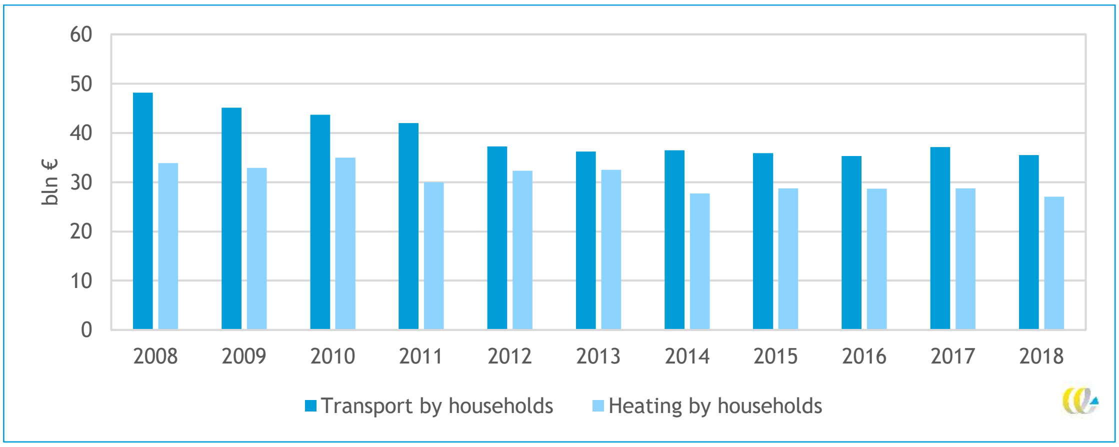
2.4 Comparison with transport activities

A study by IIASA shows that the contribution of residential heating and cooking to total $PM_{2.5}$ emissions are comparable to traffic-related emissions. Household appliances are designated as important sources of pollution, sometimes just as much as traffic (in e.g. Poland, Slovakia) (Kiesewetter & Amann, 2014). In this context, it is also relevant in this study to compare the health-related costs of direct emissions due to heating and cooking in the residential sector with the health-related costs of all non-commercial transport activities by households.

All emissions data stems from (Eurostat, 2018a) and the same set of environmental prices is used. For transport, the ground level prices for fine particulate matter are applied, whereas heating and cooking outdoor emissions are valued at the low stack height. Prices at ground level are higher than at low stack height, due to the closer proximity of the exhaust location to the population.

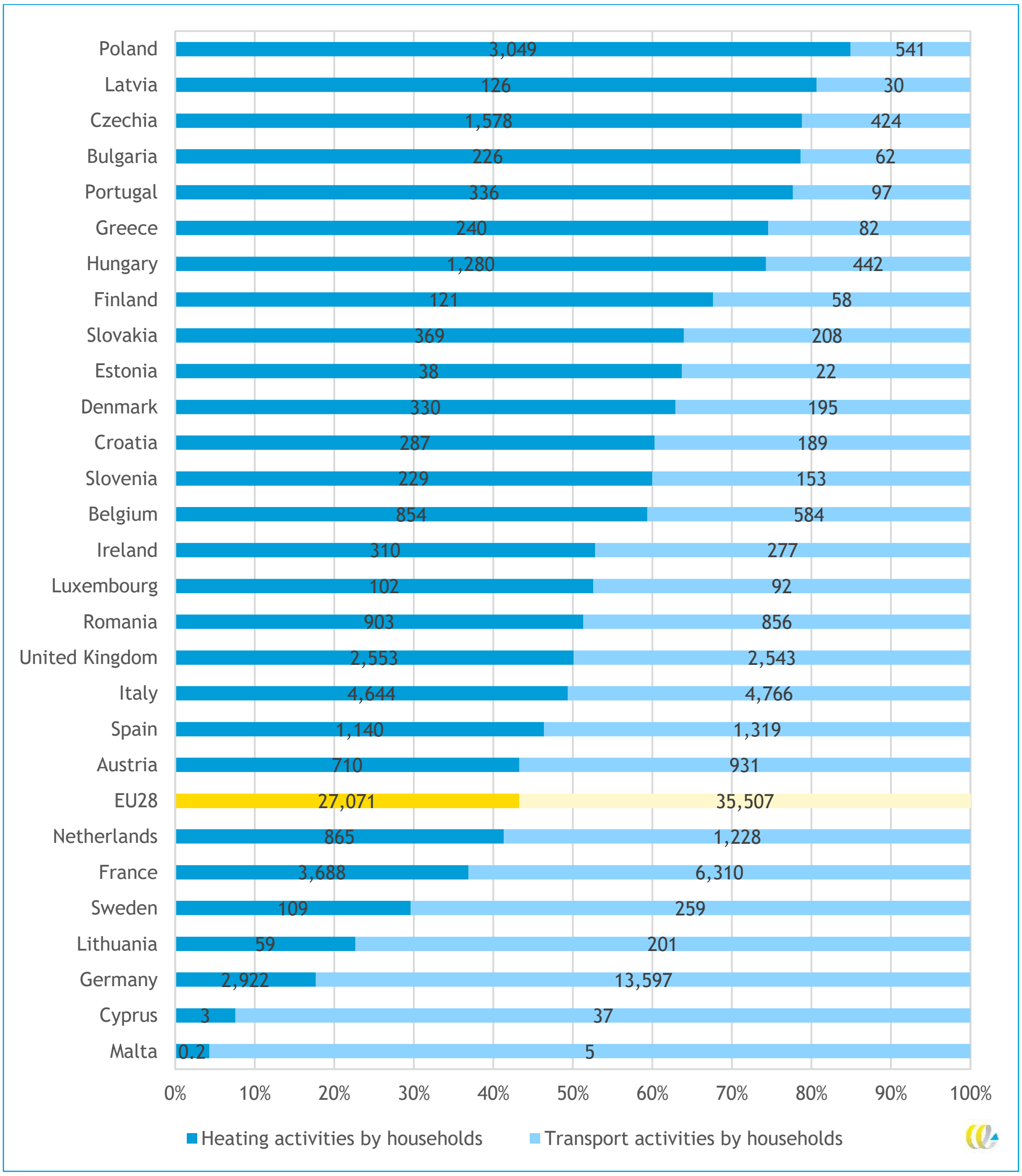
Figure 10 reveals that the total health-related social costs for both residential transport and heating and cooking are substantial: € 27 billion for heating and cooking, € 36 billion for transport in 2018. With respect to the evolution over time, health costs due to transport have decreased more (~ 26% in 10 years) compared to heating and cooking (~15%).

Figure 10 - Direct health-related social costs due to household transport and heating emissions in the EU27+UK (bln €)



When considering EU countries individually, the importance of residential heating and cooking in pollution and associated health impacts is even more evident. Figure 11 shows that for the majority of EU27+UK countries (18 out of 28), health-related social costs due to heating in the residential sector are higher than the costs due to transport in the residential sector.

Figure 11 - Relative health-related social costs from heating and transport activities in the residential sector (2018)



Notes: Numbers are shown in million euros. The horizontal axis represents the relative share (in % of total) of costs due to heating and transport activities by households.

3 Health costs differentiated by technique-fuel combination

Although the total health-related social costs presented in Chapter 2 provided useful insight in the magnitude of the outdoor air pollution problems and differences between countries, it is crucial for policy makers to gain insight in the underlying factors. The type of technology and fuels that are used are relevant here. In this chapter, we therefore consider the health-related social costs per heating technique-fuel combination due to outdoor pollution. Paragraph 3.1 first reveals the health costs per technique-fuel combination in €/GJ output for the EU27+UK and the four individual country cases (Spain, Italy, Poland, UK). Then these results are put in perspective by translating them into average cost figures for households. Paragraph 3.2. shows which technique-fuel combination is responsible for which part of the total health-related social costs in the four country cases. In Paragraph 3.3 a rough, illustrative comparison is made with the health-related costs of a diesel car.

3.1 Health-related social costs per heating technique-fuel combination

3.1.1 Methodology

The differentiated approach is largely based on an open source dataset by (Pezzutto et al., 2019), in which energy consumption characteristics per heating technique and energy carrier are provided for each EU Member State and the UK. It is the only dataset to our knowledge that includes data on both the type of techniques and energy carriers per country. We checked the data and improved it whenever possible (see 'data verification' in Annex B.2). Table 6 gives an overview of the heating techniques that are distinguished in the 'Pezzutto'-database. Cooking is not included. A full description of the various techniques is provided Table 15 in Annex B.2.

Table 6 - Included heating technologies

Fossil based heating technology	Technologies using electricity
Boilers - non-condensing and condensing	Electric radiators
Stoves	Heat pumps - aerothermal and geothermal
Combined Heat and Power (CHP)	Solar collectors
District heating	

Notes: CHP and district heating are collective heating techniques, the other options are private heating systems. No differentiation is made between stoves and open fireplaces, due to lack of more detailed data.[14]

The analysis is based on (EMEP-EAA, 2019) that provides general emissions factors for all types of sectors, including residential installations. We selected the appropriate emission factors from the EMEP database and linked them to the heating techniques. The most relevant substances (SO_2, NO_x, $PM_{2.5}$, NMVOC and CO) are covered by EMEP. CH_4 and NH_3 are excluded, since emission factors are unavailable for the fossil fuel based technique-fuel combination. The same holds for CO and NH_3 for electricity and derived heat techniques, for which the calculated emissions factors based on EEA-methodology are used. Further details and emissions factors are displayed in Table 19 in Annex B.2.

[14] As a result, open fires were assumed to be stoves, so their impact is factored in but is likely to be underestimated (see Annex B.2).

In order to make these figures comparable, we need to express these costs in term of energy *output* instead of energy input. Therefore the average efficiency factors of installations are used to calculate health costs per GJ of energy output per heating technique per country. Combined with the environmental prices (see Paragraph 1.5 and Annex A), this leads to health cost estimates for several (fossil-based and electric-based) heating techniques in the EU27+UK and four case study countries.

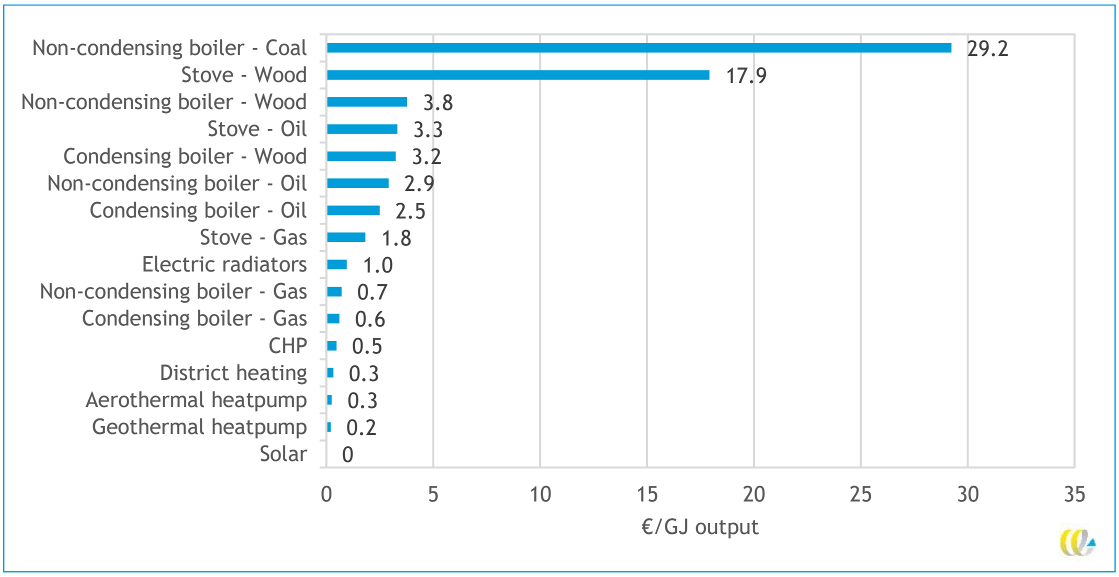
It should be noted that the analysis is based on average emissions values for a particular type of appliance. There is still a lot of variation in devices, for instance due to their technical state, age and efficiency. We were not able to find information on the age groups of appliances in the countries under consideration and correct for that.[15] This means that we base ourselves on the average emission values as reported in the EMEP literature or calculated based on EEA methodology (for electricity and derived heat) and average efficiency values for technique-fuel combinations in (Pezzutto et al., 2019).

3.1.2 Results and explanation

Health-related social costs per heating technique-fuel combination

Average health-related social costs per heating technique-fuel combination for the EU27+UK area as a whole are shown in Figure 12. It shows the costs per GJ of output, so that the costs of technique-fuel combinations are comparable.

Figure 12 – Health-related social costs of technique-fuel combinations for EU27+UK (€/GJ output, 2018)



Note: CHP stands for ‘Combined Heat and Power’.

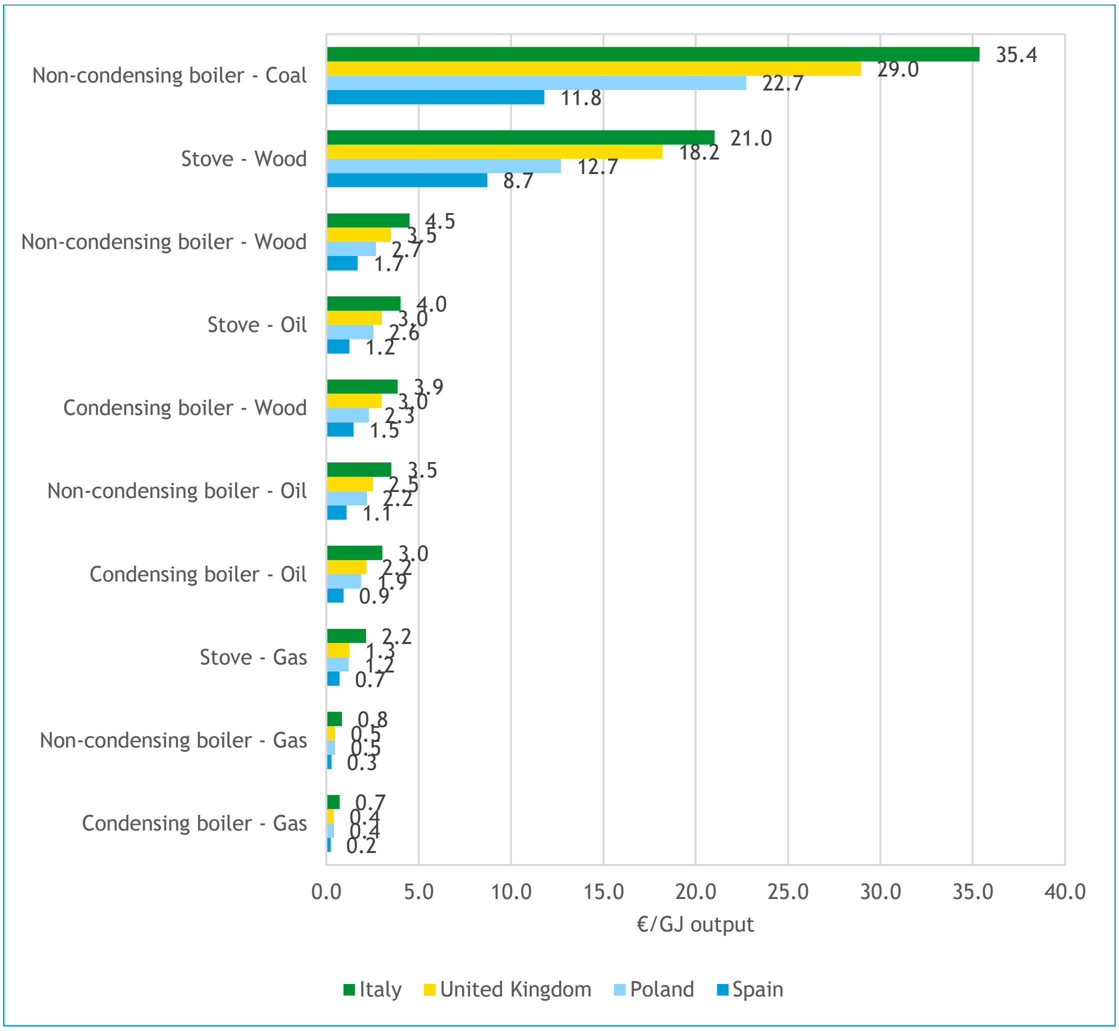
Non-condensing boilers that use coal as energy carrier, impose the highest health-related social costs on households, namely 29.2 €/GJ output. They are followed by wood stoves that have a cost of 17.90 €/GJ output. Gas boilers are the best performing fossil fuel techniques, with a costs of 0.6-0.7 €/GJ output.

15 And even within generations the performance of devices differs. Correcting for that would require fieldwork.

The cleanest options are solar thermal techniques, with no health-related social costs as they have no direct emissions and are assumed to be self-sufficient.[16] They are directly followed by some electrical and derived heat based options, whose costs range from 0.2 to 0.5 €/GJ output. These techniques do not lead to emissions at home, but cause indirect emissions at the electricity/heat production plant. The associated emissions and health costs therefore depend on the energy mix used at generator plants.[17]

Figure 13 and Figure 14 show the health-related social cost of each technique-fuel combination in the four case study countries, in terms of €/GJ output. Please note that these results indicate the health-related social costs *when* a particular technique-fuel combination is used for heating in a particular country. These figures do ***not*** take into account whether or not a particular technology is actually applied in the country and, if so, to what extent (this is done in Paragraph 3.2).

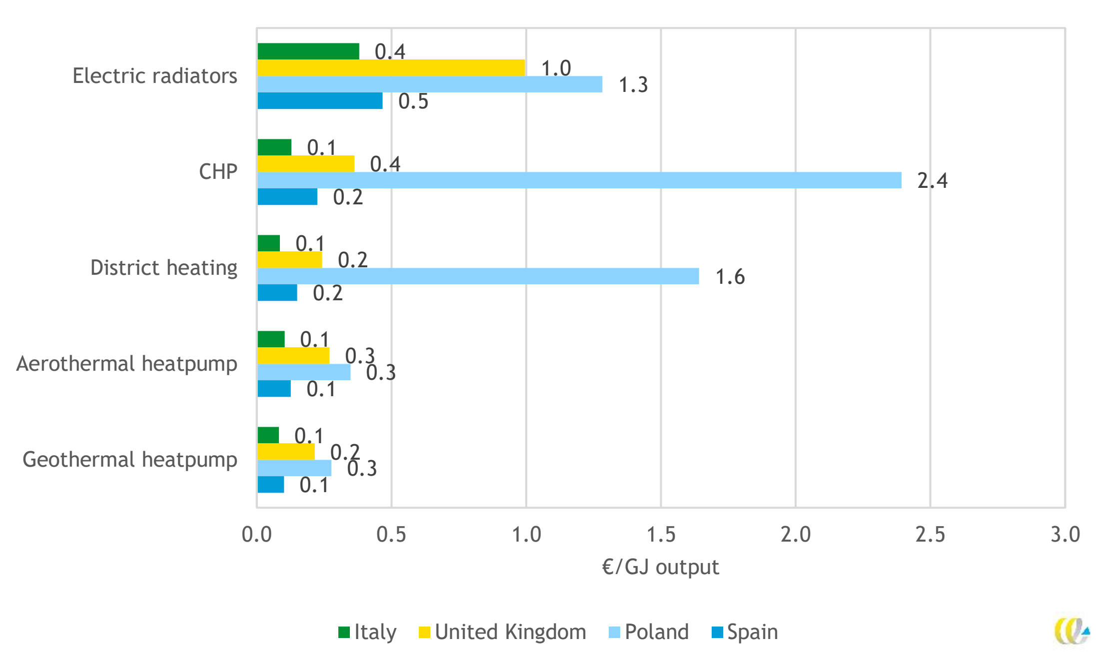
Figure 13 – Health-related social cost of fossil fuel based technique in the four countries (€/GJ output, 2018)



16 They might use a small amount of electricity from the grid for functioning, but this is assumed to be negligible.

17 Given the methodology of estimating emissions factors for electricity and derived heat, in which total emissions of the sector are assigned to electricity and heat based on production output, the emissions factor of electricity is highest.

Figure 14 - Health cost by electricity and derived heat based techniques in the four case study countries (€/GJ output, 2018)



Since energy efficiencies of installations and EMEP factors used in this study are not country specific[18], the health costs for fossil fuel base techniques only differ between individual countries because environmental prices vary among them due to differences in income levels, population density and atmospheric/geomorphological conditions (see Paragraph 1.5). Of the four countries, Italy has the highest prices for NO_x, $PM_{2.5}$ and SO_2 and the second highest prices for NMVOC and CO. In the UK, it is vice versa. Spain has the lowest environmental prices, Poland the second lowest. Table 10 in Annex B.2 gives an overview. Due to these environmental price differences, the health costs of coal boilers range, for example, from 35.4 €/GJ for Italy to 11.8 €/GJ for Spain (see Figure 13).

For electricity and derived heat options, health cost differences also arise due to differences in the fuel mix used in the various countries (see Figure 31 and Figure 32 in Annex C). Poland uses a lot of coal, both for electricity (81%) and heat production (88%), which means that it causes more air pollution to use the produced electricity and derived heat. The UK and Italy mainly use natural gas; it accounts for around 40% of electricity production and over 60% for heat. In Spain the production is more of less equally divided by coal, natural gas, nuclear and wind (14-20%).[19]

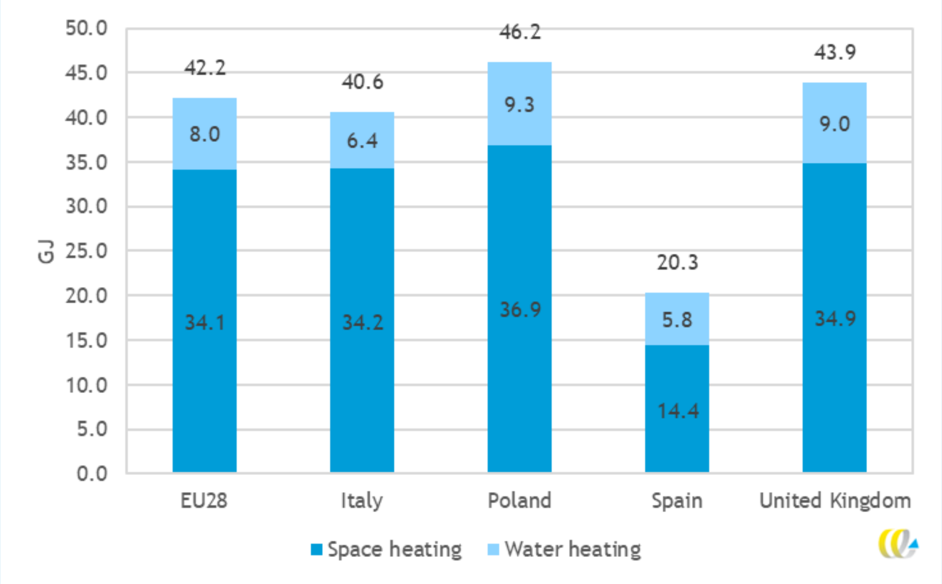
[18] Due to a lack of data. In practice, they are likely to vary between countries and techniques of different ages, etc. (also see Paragraph 1.3 on scope).

[19] For Spain no heat production is reported.

Average yearly health-related social costs for households

The results on the average health-related social cost per heating technique-fuel combination in terms of € per GJ, presented in the former paragraph, are difficult to interpret; what do they imply for an average household? Therefore, we translate these results into average yearly health-related social costs for households, using Eurostat figures on final energy consumption in households for heating (GJ) and the number of households. Figure 15 shows the *average* final energy consumption for space and water heating per household in 2018.[20]

Figure 15 - Average final energy consumption for heating per household (GJ input, 2018)



Source: Eurostat, (2018b).

Since the average energy consumption per household in each country is published in terms of GJ input, we combined it with the health-related social costs per technique-fuel combination in terms of GJ input. Subsequently, we translated these total costs figures into €/GJ output, using average efficiency data per technique-fuel combination. Comparison at the technique-fuel level requires results in GJ output because the efficiency of the used heating appliance determines how much energy is produced from the (the same) energy that is delivered to the appliance. This efficiency differs between techniques. Stoves are, for instance, very inefficient (50%) meaning that 1 GJ input only leads to 0.5 GJ of energy in the home. On the other hand, heat pumps are very efficient due to the use of existing heat (over 400%). Table 7 shows the average yearly health-related social costs per household due to home heating for the various technique-fuel combinations.

[20] In practice, energy consumption levels will vary among households/dwellings, depending on behaviour, home isolation, etc.

Table 7 – Average health-related social cost of each heating technique per household (€/year, 2018)

Technique-fuel combination	EU27+UK	Italy	Poland	Spain	UK
Solar	0.0	0.0	0.0	0.0	0.0
Geothermal heat pump	8.7	3.3	12.8	2.0	9.4
Aerothermal heat pump	10.9	4.2	16.1	2.6	11.9
District heating	13.5	3.5	75.9	3.0	10.7
CHP	20.0	5.2	110.6	4.6	15.9
Condensing boiler - Gas	25.7	29.2	18.7	4.7	17.8
Non-condensing boiler - Gas	30.0	34.0	21.8	5.4	20.7
Electric radiators	40.2	15.4	59.3	9.5	43.7
Stove - Gas	77.0	87.4	56.1	14.3	55.0
Condensing boiler - Oil	105.4	122.8	87.4	18.8	95.2
Non-condensing boiler - Oil	122.8	143.0	101.8	21.9	110.9
Condensing boiler – Wood	136.8	156.7	106.5	29.6	131.7
Stove – Oil	139.8	163.2	117.9	25.2	131.8
Non-condensing boiler – Wood	159.3	182.5	124.1	34.5	153.4
Stove – Wood	756.1	853.3	586.9	176.8	799.6
Non-condensing boiler - Coal	1,233.3	1,436.3	1,051.1	239.2	1,272.4

Table 7 reveals that coal boilers cause the highest yearly health cost for all four countries and the EU27+UK as a whole. Wood stoves (renewables) follow with the second highest yearly cost. The differences between countries is mainly caused by the difference in average consumption. For instance, the cost in Spain is significantly lower for all techniques and fuels, because yearly energy consumption is less than half of that of the other case study countries. Most likely this is due to the warmer climate, there is less need for space heating in Spain than countries with a colder or more mixed climate. Secondly, yearly costs differ to the differentiated environmental prices between countries (also see Paragraph 2.3). Lastly, the energy mix for techniques on electricity and heat causes a difference in yearly cost between countries. This is most clear for Italy, where costs for district heating and electric radiators are relatively low (when put in order of lowest to highest, the order for Italy is not the same as for the other countries). This is mainly due to a relatively 'clean' energy mix for electricity as compared to the other countries (see Figure 31 and Figure 32 in Annex C).

3.2 Total health-related social costs per country differentiated by technique-fuel combination

3.2.1 Methodology

In order to differentiate the total health-related costs presented in Chapter 2 by technique-fuel combinations for the four case study countries, our analysis consists of three steps.

1. Determine the final energy consumption per fuel and technique in each country. Eurostat, (2018b) provides data on the final energy consumption of each type of fuel for water heating, space heating and cooking in the residential sector. However, no Eurostat information is available on the energy consumption per heating and cooking technique. For this part of the data, we use the dataset of Pezzutto et al., (2019).

Cooking is not divided further into techniques, only by fuel (electricity, gas, wood or coal).[21] The resulting dataset is our best approximation of the situation in each of the four countries and it is verified, based on country specific data provided by national statistical/energy organisations and consultation of the national partners in this project. Based on this dataset, we estimated the final energy consumption per technique-fuel combinations in each country (see Table 16 in Annex B.2).

2. Combine the final energy consumption per technique-fuel combination in each country with the health-related social costs per technique-fuel combination (see Paragraph 3.1). This yields a total social costs estimates for the four countries. Since data on individual techniques is used to derive these figures, we consider this as a bottom-up approach.
3. Differentiate total health-related social costs by technique-fuel combinations. For total cost estimates we recommend using the top-down methodology and results presented in Chapter 3 as this is a more direct estimate[22]. Therefore, we use the results of Step 2 to determine the relative share (%) of technique-fuel combinations in total health-related costs. Subsequently, we apply these shares on the total costs estimates of Chapter 2.

3.2.2 Results and explanation

Figure 16 shows the total health-related social costs due to outdoor pollution subdivided by the technique-fuel combinations used. The aim is to show how much the various heating techniques contribute to the total costs in de four countries and the EU27+UK. Underlying (absolute) data is given in Table 18 in Annex B.2.

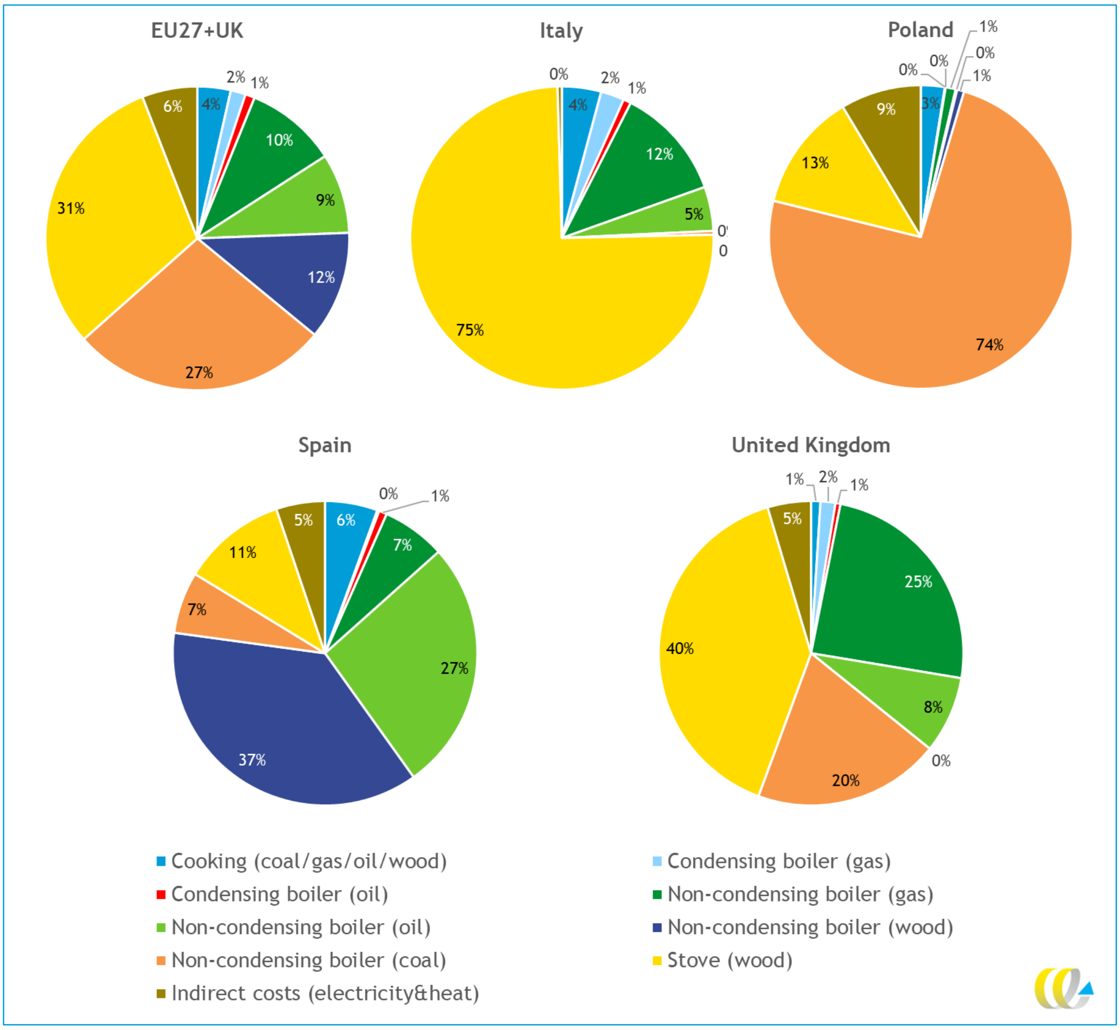
In the EU27+UK as a whole, wood stoves represent the largest share of the costs (31%), even though the shares of this technique-fuel combination in terms of final energy consumption is much lower, only 14%. This is due to the fact that a wood stove is relatively high polluting. Its health-related social costs are 18 €/GJ or 756 €/household/year (see Paragraph 3.1.2). The most common heating technique in Europe is a non-condensing boiler (58%), of which gas boilers are most prominent (35% of total energy consumption). All non-condensing boilers account for 58% of the total social costs. This is mostly due to coal boilers: only 4% of energy consumption is from coal boilers, but they are responsible for 27% of the total health-related social costs (29 €/GJ and 1,233 €/hh/year). Conversely, heating techniques based on electricity and heat are relatively clean: only 6% of total costs are indirect costs even though 22% of total energy consumption is provided by them.

In Spain, mainly non-condensing boilers are used, they account for 72% of total final energy consumption for heating and cooking. Many of these boilers work on oil (25%) and wood (23%), whose health-related social costs are 1.1 €/GJ respectively 1.7 €/GJ (22-35 €/hh/year). As a result, these technique-fuel combinations are major contributors (78%) to the total health-related social costs in Spain. A decent share of the boilers uses gas (23%), but the health-related social costs are lower: 0.3 €/GJ or 5.5 €/hh/year. Therefore, these gas boilers only account for 7% of the total health-related costs. Wood stoves, on the contrary, are used to a limited extend (3% of total final energy consumption), but cover 11% of the total health-related costs. This is due to their level of pollution and associated health-related social costs: 8.8 €/GJ or 177 €/hh/year.

[21] For cooking, no data on different techniques is available. Therefore, we consider cooking to be a technique in itself. When calculating its health costs, we adopted a similar approach as for heating, based on the final energy consumption for cooking in the residential sector from Eurostat, differentiated by fuel and the EMEP emission factors for cooking on fossil fuels. Emission factors for cooking on electricity are shown in Table 20 (Annex B.2). Consequently, the same environmental prices are applied as for heating.

[22] In theory, top-down and bottum-up aproaches would yield the same results. In practice, there are always differences due to other data sources and underlying methodologies.

Figure 16 – Total health-related social costs due to outdoor pollution differentiated by technique-fuel combination (%, 2018)



In Italy, wood stoves are the main contributors to the total health-related social costs. Although they account for 22% of total final energy consumption, they cover 75% of total health-related costs in the country. They are followed by non-condensing gas boilers delivering a large part of the final energy used for heating and cooking (45%) and responsible for 12% of the total health-related social costs.

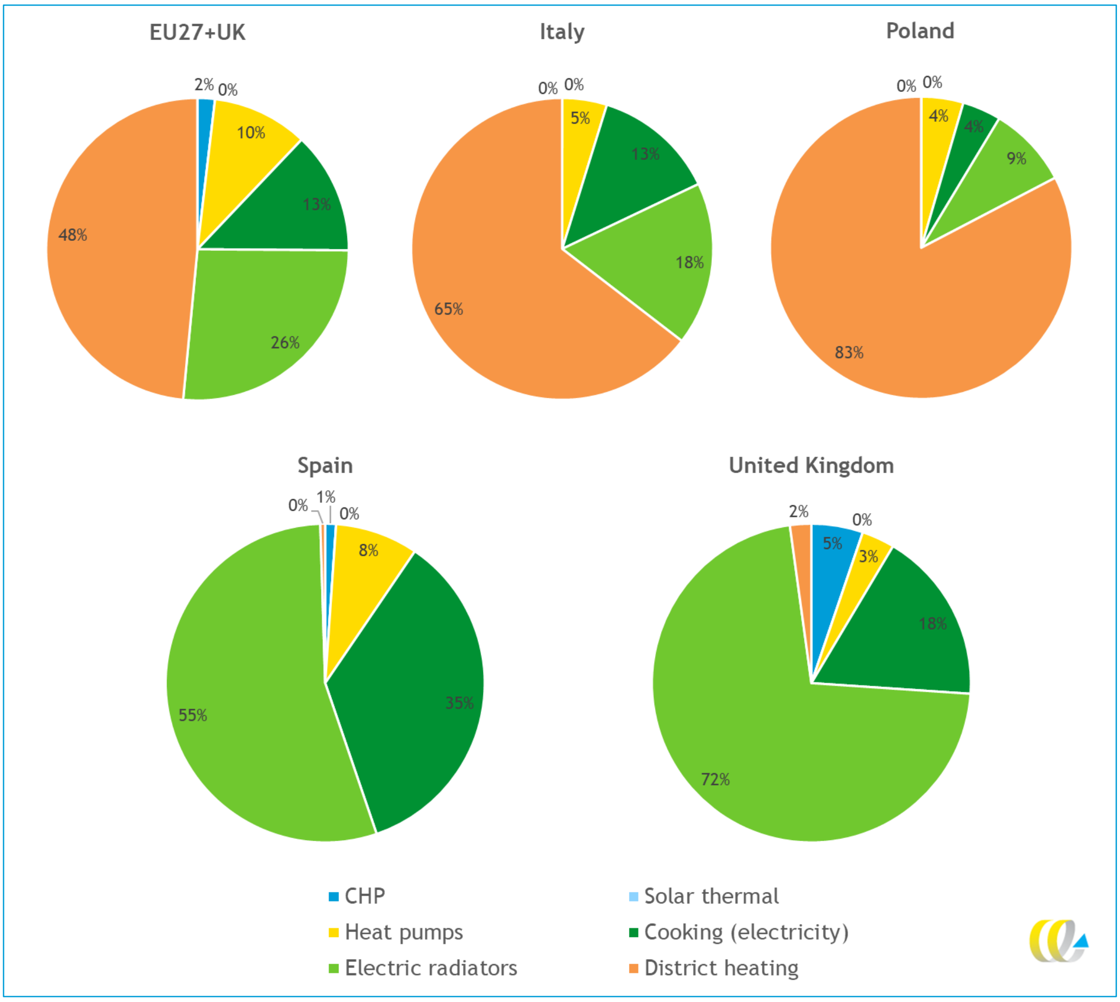
The same holds for the UK, where wood stoves cover only 6% of finale energy consumption, but make up 40% of UK's health-related costs. The second largest contributors to total health-related social costs are gas boilers with a share of 25% in total costs. Non-condensing boilers on coal are important to consider as they are responsible for 20% of the costs, although this heating option covers only 1% of the final energy consumption.[23] Its health-related costs are highest of the technique-fuel combination included in this study: 29 €/GJ or 1,272 €/hh/year.

[23] This underlines the need to phase out the sale of coal in domestic settings. Since 2021 the UK started to phase out the sale of coal in domestic settings (to be complete by February 2023).

In Poland, relatively polluting options are used. Coal boilers account for 36% of the final energy consumption and represent 74% of all health-related social costs in the country. Their health-related social costs are 22.7 €/GJ or 1,051 €/hh/year. Wood stoves cover a share of 12% in energy consumption and 13% of total health-related social costs. Together these two heating options represent 48% of energy consumption and 87% of the health-related social costs.

Figure 16 also shows that the technique-fuel combinations which produce indirect health costs through electricity and heat production make up relatively low shares in the total costs figures (<10%). Figure 17 breaks down these indirect costs. It shows that, in the EU as a whole, almost half (48%) of the indirect costs are caused by district heating. In Italy and Poland, the majority of indirect costs also originated from district heating. In Spain and the UK, majority of indirect costs is caused by electric radiators. These results reflect the degree of application of the various techniques in the countries, since all indirect emissions are valued according to the average electricity and/or heat mix in the given country.

Figure 17 - Total indirect health-related social costs differentiated by technique-fuel combination for the four case study countries and the EU27+UK (%, 2018)



3.3 Rough comparison with diesel cars

Air pollution debates have often been related to transport, for example on bans on polluting vehicles and transport fuels, and less on domestic heating and cooking installations.
Here we present a *indicative* and *illustrative* comparison between the EU27+UK average yearly health-related outdoor air pollution costs of one diesel car and a gas boiler, wood stove or heat pump.[24]

Diesel car

The analysis of diesel emissions is based on data in CE Delft, (2018b), which estimated that total health-related costs of (direct) air pollution due to diesel passenger cars amount to € 21,736 billion in the EU27+UK (2016). This includes the substances $PM_{2.5}$ and NO_x. SO_2 is excluded, since fuels for road traffic in Europe are desulfurized; they do not significantly account anymore for the health effects of road traffic emissions.

In Europe there were about 109,7 million diesel cars in 2016 (Eurostat, 2021b). If we distribute the total health-related costs of diesel equally among these diesel cars, making the simplifying assumption that all car owners drive the same amount of miles in a year, the annual health-related social costs are € 180 per diesel car. In 2020 prices, this is nearly € 210 per year.

Gas boiler, wood stove or heat pump

In 2018, the average energy consumption for home heating was 42.2 GJ per year per EU27+UK household; 34.1 GJ for space heating and 8 GJ for water heating. These estimates are based total final energy consumption and population figures by Eurostat, (2018b) and Eurostat, (2018c).

If households choose to use (non-condensing) gas boilers for space and water heating, they face average health-related social costs of € 30 per year.[25] If they would use a wood stove instead their annual costs rise to over € 750 per household. If households use a (aerothermal) heat pump their health-related costs would only be slightly over € 10 per household per year.[26] A heat pump has no emissions at home, but indirect emissions to deal with at the heat production plant (based on the average energy mix in a country).

Conclusion

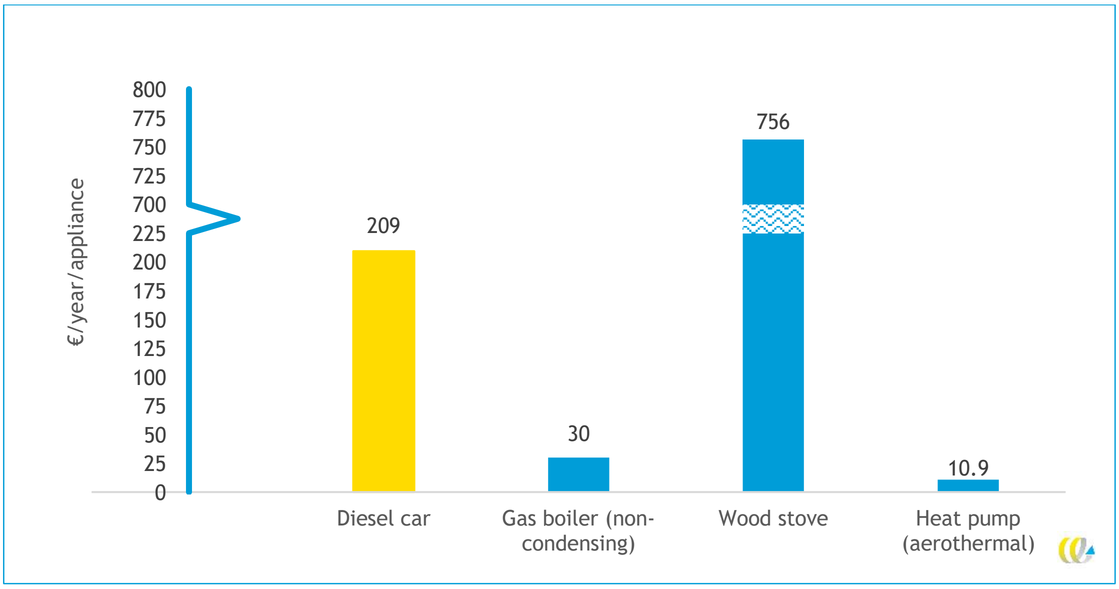
A rough and indicative estimate of health-related social costs per diesel car and heating appliances reveals that driving a diesel car for one year causes health-related social costs of € 210. Whether this is more of less than the health-related costs of home heating depends on the technique used. The costs of using a wood stove for one year is much higher, over € 750, whereas the costs of using a gas boiler are lower, € 30 per year. Latter is, however, still three times higher than the annual costs of using a heat pump, which is € 10 per year. Figure 18 summarizes these findings.

[24] Since the underlying methodologies of both estimates are different and simplified assumptions are made. We assume that one household owns one diesel car and one heating technique.

[25] In the EU27+UK, most boilers are currenlty of the non-condensing type (Pezzutto, et al., 2019).

[26] The majority of heat pumps are aerothermal (Pezzutto, et al., 2019).

Figure 18 - Indicative average health-related social costs of a diesel car and heating appliances (€2020 per year)



4 Alternative technique-fuel combinations

In this chapter we consider the health-related social costs of alternative technique-fuel combinations. Paragraph 4.1 covers some methodological choices. The characteristics of hydrogen boilers are considered in Paragraph 4.2 as there is much attention for this alternative fuel. Paragraph 4.3 covers heat pumps and hybrid heat pumps, which are often compared to hydrogen boilers in policy debates regarding the transition towards clean heating. Paragraph 4.4 provides an overview of the estimated health-related social costs Results are given in terms of €/GJ output and €/household/year for the EU27+UK and the four case study countries.

4.1 Methodological choices

There are several options to reduce the health-related social costs, among which improving home insulation and the development cleaner and more energy-efficient heating and cooking technologies.[27] In order to give some idea on what can be done to reduce the health-related social costs by switching to alternative heating techniques/fuels, we estimate the social costs of some alternative options. This might help policy makers to decide where to focus on in terms of policies. Ideally, we would have therefore considered the use of alternative technique-fuel combinations and their impact on total health-related social costs in the EU27+UK and four case study countries in the future (say 2030). After all, policy implementation takes some time and in the meantime techniques develop due to innovations and energy mixes can be expected to change, both affecting direct and indirect costs of current and alternative techniques.

Such analysis would, however, imply making many quantitative assumptions on top of those already made in former calculations in this study. For example, we would need to assume degrees of technical innovation (for new and existing techniques), developments in energy production (electricity, heat), changes in energy consumption levels, infrastructural and practical issues that determine to what extent an alternative technique is available and suitable for particular groups of houses/households and what current techniques will be replaced. All these factors affect the outcomes of the analysis. As a result, they would be quite difficult to interpret and we consider the added value of such analysis as limited. Therefore, we compare alternative technique-fuel combinations *as if* they are currently available and applied. We will qualitatively describe what can be expected in future years.

This chapter includes a selection of alternative technique-fuel combination, based on current (policy) debates. In addition, alternative district heating options might play an important role in decarbonising heat provision in the built environment. It is a collective form of heating, supplying hot water to buildings through heat grids. The heat is supplied to the building's central heating system and can originate from a variety of sources.

[27] When home insulation improves, better ventilation is also crucial. Otherwise the risk of high indoor pollution levels increases (see Chapter 5).

Many existing district heating systems currently utilise heat from natural gas-fired combined heat and power (CHP) plant. The main other sources are ‘waste’ heat from industry, geothermal heat, low-temperature ‘waste’ heat from data centres, solar thermal energy and collective heat pumps (CE Delft, 2020). Using biofuels can increase local air pollution (IRENA, 2017) unless district heating facilities are equipped with adequate flue gas cleaning devices (Fachinger et al., (2018). Within the scope of this study, it is not possible to quantitively evaluate the various options for district heating and their consequences on the health-related social costs. It is worthwhile mentioning that they exist though.

4.2 Hydrogen boiler

Introduction

At the moment a lot of attention is paid to hydrogen to be used in the built environment as a potential solution for the decarbonisation of natural gas grids. The main advantage of hydrogen is that it can replace natural gas in existing pipework. Compared to gas-free heating technologies such as district heating and heat pumps, switching to hydrogen requires relatively little adjustments to the energy infrastructure and to buildings (ECW, 2020b). However, there are also reasons to assume that hydrogens role in providing heat for the built environment will be limited in the future. This is due to the fact that the use of hydrogen is not energy efficient and (therefore) relatively expensive. Besides, hydrogen is expected to be used in sectors that are harder to decarbonise than the built environment (see Textbox 3). Nevertheless, in the light of this discussion, it is interesting to consider what the implementation of hydrogen boilers would do to the health-related social costs.

Textbox 3 – Hydrogen in the built environment

Hydrogen in sectors that are hard to decarbonise
Currently, hydrogen accounts for less than 2% of energy consumption in the EU. The vast majority (96%) of hydrogen is produced from natural gas, emitting significant amounts of CO_2 in the process (EC, 2021).
Green hydrogen (hydrogen that is produced from renewable electricity) is only expected to play a role in decarbonising sectors where other alternatives might not be feasible or might be more expensive, such as transport and energy-intensive industrial processes (EC, 2021). The EU hydrogen strategy (EC, 2020) also mentions that between 2030 and 2050, renewable hydrogen technologies should reach maturity and be deployed to reach all hard-to-decarbonise sectors where other alternatives might not be feasible or have higher costs.

On the national level, similar conclusions are drawn. The Dutch ‘hydrogen ladder’ also shows that hydrogen will not play a major part in decarbonising the built environment. As green hydrogen is scarce, it should first be used in sectors where there are no sustainable alternatives to fossil fuels. To decarbonise the heavy industry, green hydrogen is the only possibility (Natuur & Milieu, lopend). The German hydrogen strategy (Öko-Institut, 2021) mentions that the use of hydrogen for heating buildings is controversial. Decentralised hydrogen heating systems are non-competitive compared to heat pumps and can at best play a niche role and only under the condition of very favourable framework conditions (high electricity costs, very low hydrogen prices).

Hydrogen is unlikely to become cheap and abundant enough to widely substitute fossil fuels and should therefore be prioritised for specific sectors (Ueckerdt et al., 2021). Examples of such sectors are chemical feedstocks, primary steel making, long-distance aviation and shipping. On top of that, betting on large-scale availability of hydrogen risks a lock-in of fossil fuel dependency if the upscaling of hydrogen falls short of expectations. Hydrogen may therefore be a distraction from the need to transition towards direct electrification (Ueckerdt et al., 2021).

Many heating technologies are cheaper than hydrogen
The reason why hydrogen will probably not play an important role in decarbonising the built environment, is that using hydrogen as an energy carrier for heating is relatively expensive. For space heating, direct electrification is significantly cheaper than using hydrogen (Ueckerdt et al., 2021). For example, ICCT, (2021) shows that air-source heat pumps are at least 50% cheaper than hydrogen-fuelled technologies in 2050. A study by Element Energy, (2021) on decarbonising heat in Poland, Czech Republic, Spain and Italy shows that heat pumps are the cheapest way to decarbonise heat for consumers. Heat pumps are typically 60% (Spain) - 142% (Italy) cheaper than hydrogen boilers. This entails that on the long run hydrogen may only be a cost-efficient option for those buildings that are very difficult or costly to decarbonise.

Using hydrogen for domestic heating is not energy efficient
Many sustainable heating technologies are more energy efficient than hydrogen boilers. Hydrogen is not a primary energy source but a secondary energy carrier: to produce green hydrogen, renewable electricity is turned into hydrogen. This means that hydrogen is subject to conversion losses during both supply-side production and demand-side utilisation (Ueckerdt et al., 2021). In the process of turning renewable electricity into hydrogen, 20-40% of energy is lost. If a boiler then turns hydrogen into heat, energy is lost again. In total, more than 50% of energy will be lost (Natuur & Milieu, lopend).

Health-related social costs of hydrogen boilers

Hydrogen holds promise as a clean fuel (Lewis, A., 2021), but air pollutants are generated in the hydrogen production process and when hydrogen is burned in boilers for residential heating. In order to estimate what the health-related social costs of hydrogen boilers would look like, we conducted a literature study on the indirect and direct emissions of hydrogen and multiplied them by the corresponding environmental prices per substance in the EU27+UK and the four individual countries (as used in Chapter 3).

Indirect emissions

With respect to indirect emissions, the amount and type of air pollutants depends on the way in which hydrogen is produced. Three types of hydrogen can be distinguished. In the EU, the majority of hydrogen is currently produced with natural gas by a steam-methane reforming (SMR) process. The hydrogen that is produced is referred to as ‘grey hydrogen’ when the CO_2 emissions that arise during the production process are released into the air. When the SMR process is combined with carbon capture and storage (CCS), the hydrogen produces is called ‘blue hydrogen’. ‘Green hydrogen’ is produced by electrolysis of water with renewable electricity (EPRS, 2021). In our analysis we focus on grey and green hydrogen.[28]

Grey hydrogen
Conventional hydrogen production via steam methane reforming (SMR) is energy intensive, co-produces CO_2 and releases air polluting emissions. Sun et al. (2019) estimate emissions of CO, NO_x, $PM_{2.5}$, PM_{10}, SO_2 and VOC in terms of mg/MJ of hydrogen produced. In line with the previous chapters, we exclude PM_{10} emissions (due to potential overlap with $PM_{2.5}$) and VOC emissions (we consider NMVOC). Consequently, the indirect emissions of 1 MJ of grey hydrogen in our analysis consist of: 2.18 mg CO, 6.26 mg NO_x, 1.97 mg $PM_{2.5}$ and 0.11 mg SO_2.

[28] Blue hydrogen is not taken into account as we do not know to what extent air pollutants are also captured. Besides, blue hydrogen is often only considered as an interim solution until there are sufficient amounts of (affordable) green hydrogen (ECW, 2020b).

Green hydrogen
Hydrogen produced by electrolysis is considered to be green as this process aims to use renewable electricity to produce hydrogen. In this case, the indirect emissions depend on the type of renewable energy used. If indeed wind, solar or hydropower energy are used, air polluting emissions are (practically) zero, implying that the indirect health costs of producing hydrogen are zero. However, when biomass is considered to be 'renewable' this is not the case as its input does lead to emissions. The burning of wood and other bio products leads to PM production, etc. Biomass covers a substantial part of the current energy mix to produce electricity in countries. Moreover, other polluting inputs such as gas, oil and sometimes coal are used as well (see Figure 31 in Annex B.2). This means that the electricity currently used for 'green' hydrogen causes air polluting emissions.

In order to estimate the current indirect emissions of electrolysis, we multiplied the average emissions of electricity production (see Table 20 in Annex B.2.) by the amount of electricity needed to produce 1 MJ of hydrogen, taking into account the efficiency of the electrolysis process. Estimates range from 57-65% in 2017 to 64-68% in 2025 (IRENA, 2018).[29] We used the (simple) average of 64% to calculate the electricity consumption per GJ of 'green' hydrogen production. As a result, we arrive at two estimates of indirect emissions:
- high estimate, based on the current EU energy mix to produce electricity for the electrolysis process;
- low estimate, assuming 100% renewable energy as intended by the definition of 'green' hydrogen, excluding biomass.

Direct emissions

There are also direct emissions from the use of a hydrogen boiler. When burning 100% hydrogen with 100% oxygen (O_2), the only combustion products are water and heat. However, hydrogen boilers use air to burn hydrogen, which contains a lot of nitrogen (N_2). The burning of hydrogen therefore leads to the thermal formation of NO_x, just as the combustion of fossil fuels.[30]

The precise amount of NO_x emissions is relatively uncertain. There are different opinions on whether the emissions of hydrogen boilers are much higher than gas boilers, similar or much lower. This is partly due to the fact that hydrogen boilers are not on the market yet and different set-ups can be used for testing and measurement. Subsequently, we use a range of values for the NO_x emission factor of a hydrogen boiler:
- The **central** value in our analysis is the European limitation on NO_x emissions from fuel boilers using gaseous fuels: 56 mg/kWh of fuel input (EC, 2013). This translates to a maximum of 15.6 g/GJ hydrogen input.
- As **upper** bound, we consider the emissions of hydrogen boilers to be higher than gas boilers.[31] A research paper by UK Department for Business, Energy and Industry Strategy (BEIS, 2019). They found that the NO_x emissions of a hydrogen boiler can be up to six times the NO_x emissions of a gas boiler. In the previous chapters, the NO_x emissions of a gas boiler were assumed to be 42 g/GJ (according to EMEP emission factors). As such, NO_x emissions of a hydrogen boiler could go up to 252 g/GJ.

[29] This efficiency is based on the lower heating value (LHV).

[30] The widely claimed benefit that only water is released as a by-product is only accurate when hydrogen is used in fuel cells. Burning hydrogen in boilers rather than in fuel cells generates toxic nitrogen oxides (NO_x) as well as steam (Lewis, 2021b).

[31] Given that the temperature of a hydrogen flame is much higher than a natural gas flame, the NO_X formation increases when switching from natural gas to hydrogen as a fuel (DNV GL & Bekaert Heating, 2020; Gersen, et al., 2020).

- The **lower** bound is based on a study on the development of high performance and low NO_x domestic hydrogen boilers (DNV GL & Bekaert Heating, 2020), which estimates that NO_x emissions could potentially reduce to 10-30 g/GJ. In the analysis we use 20 g/GJ as the lower bound of NO_x emissions. According to (Lewis, Alastair C., 2021) reducing NO_x emissions from hydrogen boilers is possible through control of combustion conditions. Examples of mitigation strategies are lowering flame temperature (which might affect performance) or flue gas recirculation (DNV GL & Bekaert Heating, 2020, Gersen et al., 2020). The expectation is that (very) low NO_x hydrogen boilers can be made, but in the absence of additional regulation it is the question whether they will be, since NO_x emissions are traded off against cost and energy efficiency (ENDS Report, 2021).

In order to translate the emissions per GJ input to GJ output, needed to make the results of various techniques comparable (see Paragraph 3.1.1), the efficiency of the hydrogen boilers is relevant. We assume that the efficiency of a hydrogen boiler is similar to the efficiency of a (condensing) gas boiler. In our analysis this is 99% (Pezzutto et al., 2019).

Results

Table 8 shows the total health-related social costs of green, 'green' and grey hydrogen boilers in the EU27+UK and the four countries, given as a range of values due to the uncertainty of NO_x emissions. It reveals that the costs of the current production of 'green' hydrogen are much higher than those of grey hydrogen, since electricity production is still fairly fossil-based and part of the electricity is lost during the electrolysis process (64% efficiency). The 'dirtier' the current energy mix used for electricity production in countries, the larger the difference between 'green' hydrogen and the other hydrogen options. Obviously, hydrogen produced by 100% renewable energy has the lowest cost as there are no indirect emissions involved.

Table 8 - Health cost of hydrogen boilers (€/GJ output, 2018)

	Grey hydrogen	'Green' hydrogen (current electricity mix)	Green hydrogen (100% renewable energy)
EU27+UK	€ 0.3 [€ 0.2-€ 3.7]	€ 2.6 [€ 2.4-€ 5.9]	€ 0.2 [€ 0.1-€ 3.6]
Italy	€ 0.4 [€ 0.2-€ 4.3]	€ 1.0 [€ 0.8-€ 5.0]	€ 0.3 [€ 0.1-€ 4.2]
Poland	€ 0.2 [€ 0.1-€ 2.4]	€ 4.7 [€ 4.6-€ 7.0]	€ 0.2 [€ 0.1-€ 2.4]
Spain	€ 0.1 [€ 0.1-€ 1.4]	€ 1.6 [€ 1.6-€ 2.9]	€ 0.1 [€ 0.0-€ 1.3]
UK	€ 0.2 [€ 0.1-€ 2.4]	€ 2.0 [€ 2.0-€ 4.3]	€ 0.1 [€ 0.0-€ 234]

Note: Central value is displayed, with lower and upper bounds between brackets.

We translated the health-related social cost figures in €/GJ into €/household/year, using the average energy consumption of households (see Figure 15 in Paragraph 3.1.2). Table 9 shows the average costs per household per year. The annual costs of a grey hydrogen boiler are a factor 1.4 higher than boilers on green hydrogen. Latter would be the cleanest hydrogen option, but only when 100% renewable energy (excl. biomass) is used to produce the electricity for electrolysis. Given the current energy mix of electricity production, 'green' hydrogen boilers would cause significant health-related social costs; 4 times (Italy) to 32 times (Poland) higher than those working on 'real' green hydrogen.

Table 9 - Average yearly health cost of hydrogen boilers (€/hh/year, 2018)

Country	Grey hydrogen	'Green' hydrogen (current electricity mix)	Green hydrogen (100% renewable energy)
EU27+UK	€ 13.3 [€ 7.3-€ 154.8]	€ 108.1 [€ 102.2-€ 249.6]	€ 9.3 [€ 3.3-€ 150.8]
Italy	€ 15.1 [€ 8.3-€ 175.8]	€ 40.5 [€ 33.7-€ 201.2]	€ 10.6 [€ 3.8-€ 171.3]
Poland	€ 9.7 [€ 5.3-€ 112.2]	€ 216.6 [€ 212.3-€ 319.2]	€ 6.8 [€ 2.4-€ 109.3]
Spain	€ 2.4 [€ 1.3-€ 28.0]	€ 32.6 [€ 31.5-€ 58.2]	€ 1.7 [€ 0.6-€ 27.3]
UK	€ 9.2 [€ 5.1-€ 105.5]	€ 90.4 [€ 86.3-€ 186.7]	€ 6.3 [€ 2.3-€ 102.7]

Note: Central value is displayed with lower and upper bounds between brackets.

4.3 Heat pumps and hybrid heat pumps

Introduction

Heat pumps extract heat from the outdoor air (air-source heat pumps) or from the ground (ground-source heat pumps) and upgrade it to a usable temperature by using electricity. Because heat pumps do not only use electricity, but also energy from the outdoor air or ground, they are very efficient heating technologies. The seasonal coefficient of performance (SCOP) shows how effective the heat pump is on an annual basis. It varies between 2 and 5-6. This means that a heat pump transfers 1 kWh of electricity into 2 to 5-6 kWh of heat (ECW, 2021).

The SCOP is calculated by dividing the total amount of heat that is produced by the amount of electricity used by the heat pump. The lower the temperature of the outdoor air or ground, the lower the efficiency of the heat pump (because more electricity is needed to upgrade the heat from the air or ground to a usable temperature). In winter, the ground usually has a higher temperature than the outdoor air, which is why the SCOP of a ground-source heat pump is typically higher. Another factor that determines the efficiency of the heat pump is the insulation level of dwelling: the SCOP of heat pumps in well-insulated homes is higher because these dwelling can be heated with lower temperatures. Finally, the share of heat that is used for domestic hot water compared to space heating has an impact on the SCOP. Domestic hot water requires higher temperatures than space heating, therefore the SCOP is lower in dwellings that use a relatively high share of heat for domestic hot water (ECW, 2021).

A hybrid heat pump consists of an electric heat pump in combination with a gas-fired boiler. The electric heat pump produced the majority of the heat that is required. About 20% of the time, the gas boiler produces heat. Hybrid heat pumps are not gas-free, but they might play a role in the transition towards clean residential heating in places that currently have a gas grid in place.

Health costs of heat pumps and hybrid heat pumps

Heat pumps have no direct emissions of air pollutants, their health effects relate to their use of electricity. The health-related social costs of (geothermal) heat pumps are 0.21 €/GJ output for EU27+UK, 0.08 €/GJ for Italy, 0.28 €/GJ for Poland, 0.10 €/GJ for Spain and 0.21 €/GJ for the UK, all based on the current electricity mix (see Paragraph 3.1.2).[32] The larger the proportion of renewable resources (wind and solar) in the national electricity mix, the lower the emissions of air pollutants (and greenhouse gases). If electricity would be produced with 100% renewable sources (no biomass), the health-related social cost of heat pumps will drop to zero.

When switching from a natural gas-fuelled boiler to a hybrid heat pump, natural gas use will reduce. However, electricity consumption will increase due to the electric heat pump. Therefore, the hybrid heat pumps have direct health-related social costs due to the gas boiler and indirect costs originating from the electricity used by the heat pump. It is reasonable to assume that the gas boiler is used to produce heat in 20% of the time, whereas the heat pump covers 80%. Therefore, we take a weighted average of the health cost of a condensing gas boiler (20%) and a geothermal heat pump (80%)(see Paragraph 3.1.2). Table 10 presents the health-related social costs of a hybrid heat pump, both in €/GJ output as in terms of average costs per household per year. Differences between countries arise due to differences in energy mix to produce electricity, environmental prices and (for the €/hh/year figures) average household energy consumption for domestic heating.

Table 10 – Health cost of hybrid heat pumps (€/GJ output, €/hh/year, 2018)

Country	Cost per unit of output delivered (€/GJ)	Cost per household (average €/year)
EU27+UK	0.3	12.1
Italy	0.2	8.5
Poland	0.3	13.9
Spain	0.1	2.6
UK	0.3	11.1

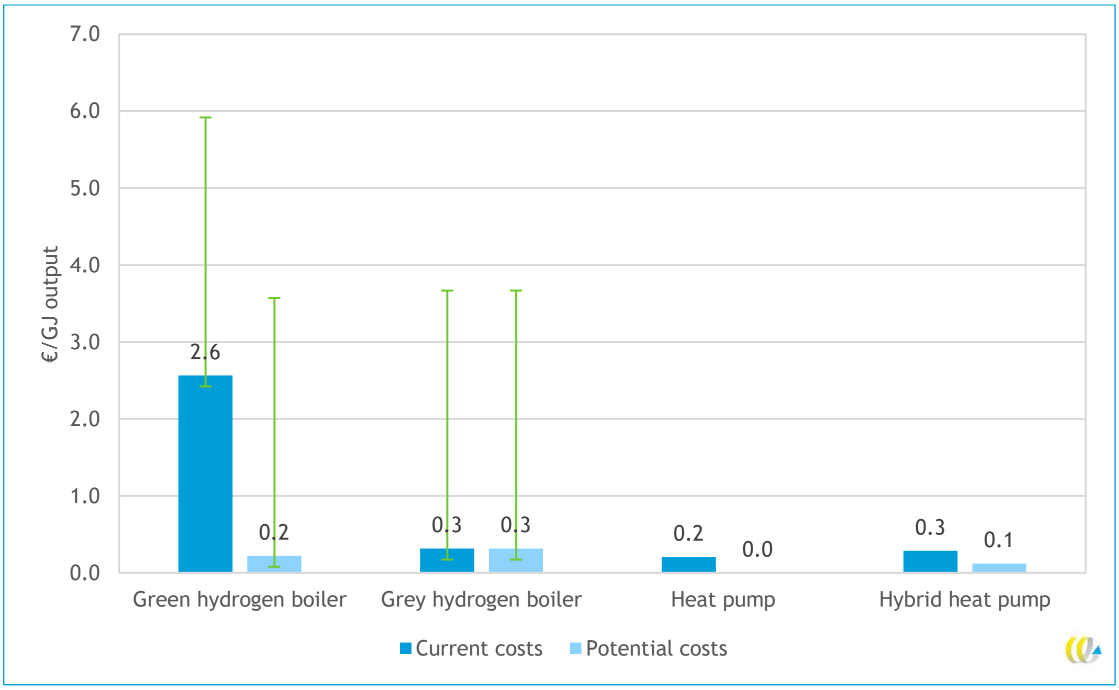
Again, these costs will decline when the electricity mix gets cleaner. Heat pumps will have zero social costs associated once the electricity mix is decarbonized. In that case, the indirect costs of a hybrid heat pump are reduced to zero, and the health-related social costs will only include emissions related to the 20% gas part. Cost figures would drop to about 0.1 €/GJ output for the EU27+UK, Italy, Poland, UK and 0.05 €/GJ for Spain. Average costs per household per year would decrease and amount to: € 5.2 in the EU27+UK, € 5.8 in Italy, € 3.7 in Poland, € 0.9 in Spain, and € 3.6 in the UK.

[32] In terms of costs per household per year: € 8.7 in the EU27+UK, € 3.3 in Italy, € 12.8 in Poland, € 2.1 in Spain, and € 9.4 in the UK.

4.4 Overview of results

Figure 19 summarises the health-related social cost estimates for the alternative technique-fuel combinations discussed in this chapter, for the EU27+UK. The current cost figures are based on the current situation: how electricity is produced (average energy mix) in the EU27+UK at the moment. However, all countries face the task of making their energy production more sustainable. Therefore, we calculated what health-related social costs levels would be feasible if the electricity that is used for home heating is 100% renewable and does not contain biomass. These estimations are represented by the potential cost figures in Figure 19.

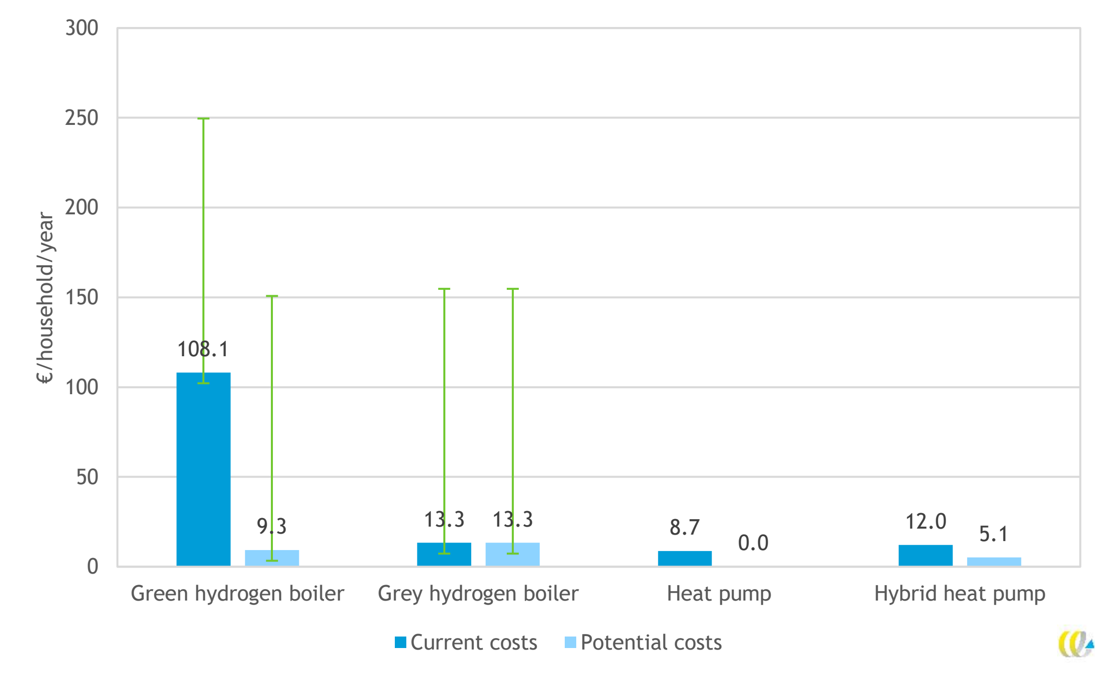
Figure 19 - Current and potential health-related social costs for alternative techniques in the EU27+UK (€/GJ output, 2018)



Note: Central values are mentioned, upper and lower bounds are green (reflecting the uncertain level of NO_x emissions for hydrogen techniques).

Figure 20 shows the average health-related cost per household per year for each alternative technique-fuel combination. It is calculated by multiplying the results in €/GJ output by the average annual energy consumption of households for heating (see Figure 15 in Paragraph 3.1.2).

Figure 20 - Current and potential health-related social costs for alternative techniques in the EU27+UK (€/hh/year, 2018)



Note: Central values are mentioned, upper and lower bounds are green (reflecting the uncertain level of NO_x emissions for hydrogen techniques).

If we compare the performance of the alternative options to those of the currently used technique-fuel combinations (see Figure 12 in Paragraph 3.1.2), we find that the main task of countries is to replace coal boilers and wood stoves in order to reduce air pollution. The health-related social costs of current 'green' hydrogen boilers would be 2.6 €/GJ output or 108 €/hh/year (central values), which is comparable to oil boilers. The costs of grey hydrogen boilers amount to 0.3 €/GJ output or 13.3 €/hh/year (central values), which means that they would be less polluting than gas boilers. Given the uncertain levels of NO_x emissions for hydrogen-based techniques though (indicated by the upper and lower bounds), these results should be interpreted with care. Solar thermal power and heat pumps are the least emitting heating techniques, directly followed by the hybrid heat pump. Latter pumps are associated with 0.3 €/GJ or 12 €/hh/year and thus perform better than gas boilers (0.6 €/GJ or 25.8 €/hh/year), electric radiators (1 €/GJ or 40.2 €/hh/year), etc. If countries succeed in making their electricity production renewable, health-related social costs of green hydrogen, heat pumps and other electric appliances can drop significantly.

Similar conclusions can be drawn from the cost estimates for the four individual countries, as reported in Table 11.

Table 11 - Health-related social cost of alternative technique-fuel options in the four countries (€/GJ output, 2018)

Technique	Current health-related social costs		Potential health-related social costs in the future	
	€/GJ output	€/hh/year	€/GJ output	€/hh/year
Italy				
'Green' hydrogen	€ 1.0 [€ 0.8-€ 5.0]	€ 40.5 [€ 33.7-€ 201.2]	€ 0.3 [€ 0.1-€ 4.2]	€ 10.6 [€ 3.8-€ 171.3]
Grey hydrogen	€ 0.4 [€ 0.2-€ 4.3]	€ 15.1 [€ 8.3-€ 175.8]	€ 0.4 [€ 0.2-€ 4.3]	€ 15.1 [€ 8.3-€ 175.8]
Heat pump (geothermal)	€ 0.1	€ 3.3	~€ 0	~€ 0
Hybrid heat pump	€ 0.2	€ 8.5	€ 0.14	€ 5.8
Poland				
'Green' hydrogen	€ 4.7 [€ 4.6-€ 6.9]	€ 216.6 [€ 212.3-€ 319.2]	€ 0.2 [€ 0.05-€ 2.7]	€ 6.8 [€ 2.4-€ 109.3]
Grey hydrogen	€ 0.2 [€ 0.1-€ 2.4]	€ 9.7 [€ 5.3-€ 11.2]	€ 0.2 [€ 0.1-€ 2.4]	€ 9.7 [€ 5.3-€ 112.2]
Heat pump (geothermal)	€ 0.3	€ 12.8	~€ 0	~€ 0
Hybrid heat pump	€ 0.3	€ 13.9	€ 0.08	€ 3.7
Spain				
'Green' hydrogen	€ 1.6 [€ 1.6-€ 2.9]	€ 32.6 [€ 31.5-€ 58.2]	€ 0.1 [€ 0.03-€ 1.3]	€ 1.7 [€ 0.6-€ 27.3]
Grey hydrogen	€ 0.1 [€ 0.07-€ 1.4]	€ 2.4 [€ 1.3-€ 28.0]	€ 0.1 [€ 0.07-€ 1.4]	€ 2.4 [€ 1.3-€ 28.0]
Heat pump (geothermal)	€ 0.1	€ 2.1	~€ 0	~€ 0
Hybrid heat pump	€ 0.1	€ 2.6	€ 0.1	€ 0.9
United Kingdom				
'Green' hydrogen	€ 2.1 [€ 2.0-€ 4.3]	€ 90.4 [€ 86.3-€ 186.7]	€ 0.1 [€ 0.1-€ 2.3]	€ 6.3 [€ 2.3-€ 102.7]
Grey hydrogen	€ 0.2 [€ 0.1-€ 2.4]	€ 9.2 [€ 5.1-€ 105.5]	€ 0.21 [€ 0.12-€ 2.4]	€ 9.2 [€ 5.1-€ 105.5]
Heat pump (geothermal)	€ 0.2	€ 9.4	~€ 0	~€ 0
Hybrid heat pump	€ 0.3	€ 11.1	€ 0.1	€ 3.6

Notes:
- Current health cost estimates are based on the energy mix used for electricity production in 2018.
- 'Green' hydrogen refers to production by electrolysis. Depending on the type of electricity used for this process, it is truly green (only renewable electricity excl. biomass) or 'green' (current electricity mix).
- Potential cost estimates assume electricity production with 100% renewable energy, excluding biomass, reducing the indirect costs of electricity used for heating to zero.
- Cost figures of hydrogen boilers do not include NH_3 and NMVOC emissions. These substances are included in the cost estimates of the other technique-fuel combinations in this study, but contribute a maximum of 1% to total cost per GJ output.

5 Indoor pollution

Heating and cooking activities do not only result in pollution of the ambient air, what previous chapter are about, but also cause indoor air pollution. For many pollutants, concentration levels are often higher indoors than outdoors (Seals & Krasner, 2020). Especially in households where fossil and/or biomass fuels are used in unvented stoves for cooking and heating, indoor air pollution levels can be substantial (WHO, 2021b). On top of that, European citizens on average spend 90% of their time indoors (EEB & Green Transition Denmark, 2021), which means that indoor air quality plays a significant part in their general state of health. Vulnerable population groups are predominantly exposed to pollution indoors (WHO, 2021b). This might be due to age or social-economic situation. Lower-income households may lack the financial means to invest in cleaner and energy-efficient heating techniques.

In this chapter, we pay attention to indoor pollution. Paragraph 5.1 describes the impacts on human health of indoor pollution, particularly focussing on $PM_{2.5}$, NO_2 and CO, after which Paragraph 5.2 provides an overview of factors that determine indoor air quality and subsequently the impact on human health. Given the numerous factors and the fact that research on indoor emissions factors (that can be used in addition to outdoor factors without double counting) are still in its infancy, we provide leads for future quantitative research in Paragraph 5.3 instead of presenting health costs estimates of indoor pollution that can be added to those in former chapters.

5.1 Health impacts from indoor pollution caused by cooking and heating

Indoor pollution due to cooking

In the EU, the main energy products that are used for cooking are gas and electricity (Eurostat, 2021c). Seals and Krasner (2020) describe that gas stoves (used for cooking) can be a large source of toxic pollutants indoors. Indoor pollution from gas stoves can even reach levels that exceed ambient air standards. The main pollutants from gas combustion are nitrogen dioxide (NO_2) and carbon monoxide (CO). Gas stoves are primary indoor sources of NO_2 and indoor NO_2 pollution levels can be much higher than outdoors (Belanger et al., 2013).

Cooking for half an hour on a gas stove may raise indoor NO_2 levels to twice higher than the WHO annual average guideline for outdoor NO_2 levels (NPR, 2021). A meta-analysis of 41 studies shows that children living in a home with gas cooking have a 42% increased risk of having current asthma, a 24% increased risk of lifetime asthma and an overall 32% increased risk of having current and lifetime asthma (Lin et al., 2013). Another study concludes that in the United States asthmatic children exposed to NO_2 indoors are at risk for increased asthma morbidity (Belanger et al., 2013).

NO_2 emissions are consistently higher in homes that cook with gas rather than electric stoves, and cook for longer periods of time (Seals & Krasner, 2020). Switching to an electric (including induction) cooking stove is therefore a cleaner household cooking option, since electric stoves do not produce indoor NO_2 emissions. In fact, switching an electric cooking stove has the greatest effect on decreasing indoor NO_2 concentrations because pollutants can be decreased at the source. Seals and Krasner (2020) even mention that replacing a gas stove with an electric stove can decrease the median NO_2 concentration by 51% in the kitchen.

$PM_{2.5}$ emissions from cooking are related to the type of meal that is being cooked and do not depend on whether a gas stove or an electric stove is used (Jacobs, 2021b)(see Paragraph 5.2). The use of solid fuels for cooking, is associated with exposure to indoor $PM_{2.5}$ (OECD & EU, 2020). The burning of wood (or other biomass) for cooking is common in several EU countries. The study by Fleisch et al., (2020) on residential wood stove use in northern New England (US) shows that the use of coal and biomass for cooking results in high concentrations of pollutants. We describe the adverse health effects of household air pollution from solid fuel use in the next paragraph.

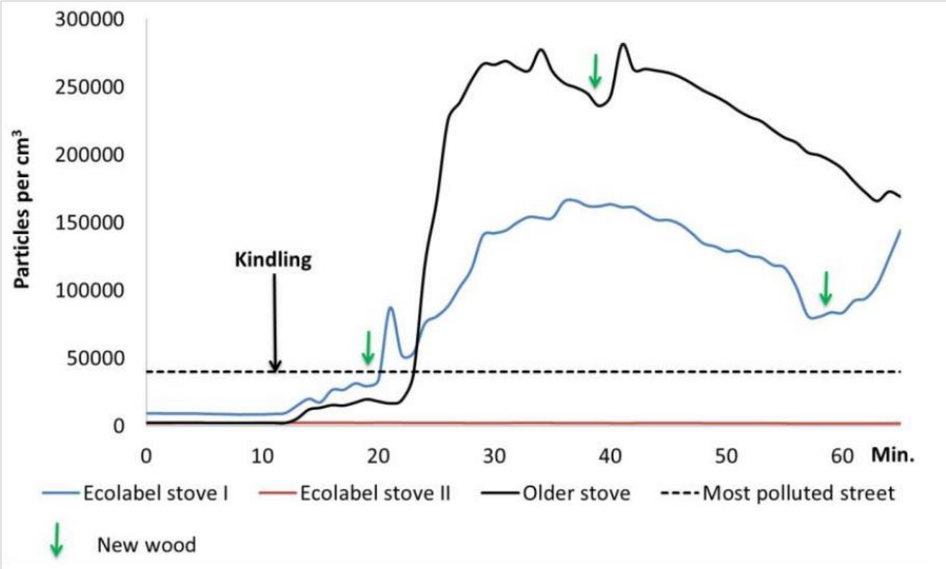
Indoor pollution due to heating

The main energy product used in the EU for space and water heating is gas (Eurostat, 2021c). When gas is used in a condensing boiler, this does not impact indoor air quality, as these are usually closed systems (Jacobs, 2021b).[33] Besides gas, electricity is often used for water heating in the EU (Eurostat, 2021c). Heating appliances that run on electricity – including heat pumps – do not negatively impact indoor air quality since no combustion take place in the dwelling (Jacobs, 2021b).

Besides gas, renewables and wastes (including wood) are often-used energy products for space heating in EU dwellings (Eurostat, 2021c) .Fireplaces are the main source of $PM_{2.5}$ contamination in dwellings, but wood stove home heaters are also important sources of $PM_{2.5}$ and CO. Wood stoves show peak concentrations of $PM_{2.5}$ in both the light-up phase and the refill phase, as illustrated in a study by (Cao et al., 2016) on residential wood stove use in Norway. This is due to the opening of the stove door. Figure 21 clearly illustrates this. Research from Finland shows that relatively short-lasting (a few hours) wood burning in wood stove home heaters increased residents' daily exposure to potentially hazardous $PM_{2.5}$ levels (Siponen et al., 2019). In their meta-analysis Amegah et al., (2014) found that the combustion of solid fuels (coal and biomass) at home adversely affects pregnancy.

[33] Not taking CO-accidents into account that occur due to a lack of maintenance or defects.

Figure 21 – Indoor air pollution from different wood stoves (particles per cm^3)



Source: EEB & Green Transition Denmark, (2021).

Note: 'Kindling' refers to the most polluted Danish street.

CO intoxication

In dwellings, a variety of items release CO and can affect indoor air quality: e.g. unvented kerosene and gas space heaters, leaking chimneys and furnaces and gas stoves (EPA, 2021a). High concentrations of CO pollution can lead to CO intoxication. Such high concentrations arise when gas cooking and heating appliances are either faulty or poorly installed, ventilated, or maintained (Seals & Krasner, 2020, WHO, 2018). Especially when unvented, these technologies may expose people to dangerous levels of CO.

CO-intoxication causes a substantial amount of deaths in many European countries. During the period 1980-2008, 140,490 CO-related deaths were reported. This corresponds to an annual death rate of 2.2/100,000 (Braubach et al., 2013).

5.2 Factors that determine indoor air quality

Indoor air quality is determined by many other factors besides heating and cooking appliances. This means that the indoor air quality of households within a country will vary widely, depending on the type of heating and cooking appliance used, but also on the factors we describe in this paragraph.

Type of food and the way it is prepared

Cooking food, regardless of the type of stove used, produces certain pollutants, such as fine particulate matter (Seals & Krasner, 2020). When cooking on gas or electric stoves, the majority of $PM_{2.5}$ is produced by the vaporising of grease particles from the pan. The type of pan makes a difference: $PM_{2.5}$ emissions from stainless steel pans are significantly higher than the $PM_{2.5}$ emissions from non-stick pans (O'Leary et al., 2019) .

Besides the type of pan that is used for cooking, the type of meal and the way it is prepared has an important effect on $PM_{2.5}$ emissions. Stir frying (e.g. of vegetables) and roasting meat produce more $PM_{2.5}$ than boiling food (Jacobs, 2021b) .

Insulation level (thermal efficiency of the dwelling)

As homes become more energy efficient, they also risk trapping air pollution indoors (Seals & Krasner, 2020). Especially in colder seasons, ventilation is typically limited (EEB & Green Transition Denmark, 2021). Furthermore, various studies show a deterioration in indoor air quality after renovation and energy saving measures (Jacobs et al., 2019). Therefore, ventilation is becoming increasingly important. New homes, in particular, are well-insulated. To supply the necessary change of air, new dwellings are provided with ventilation systems. However, according to Piet Jacobs (2021b) people often do not use these ventilation systems at the maximum capacity, which means that pollutants are trapped indoors. This is why especially in new homes, the Netherlands Organisation for applied scientific research (TNO) advises households to use an electric cooking stove rather than a gas stove. This is also because many exhaust hoods do not properly reduce all cooking-related pollutants. However, there are many arguments in favour of insulation measures. In fact, a lack of insulation might cause other health issues that are part of this study (see Textbox 4). Good working ventilation and exhaust hoods are therefore crucial.

Textbox 4 – Health effect due to lack of insulation

In this research we investigate the impact of several air pollutants on health-related social costs. However, the degree of air pollution is not the only determinant of indoor air quality. Low indoor temperatures, caused by a lack of insulation, are also associated with negative consequences for human health. In this box we elaborate on the consequences on human health from lack of insulation, however in this study we do not quantify or monetise the health effects from cold indoor temperatures.

The World Health Organization's *Housing and health Guidelines* show that cold indoor temperatures have adverse effects for human health. Cold indoor temperatures are associated with increased blood pressure, asthma symptoms and poor mental health. On top of that, cold homes contribute to excess winter mortality and morbidity. Most of the health burden can be attributed to respiratory and cardiovascular disease (WHO, 2018).

Lack of insulation is one of the main causes of cold indoor temperatures. The transition towards low-carbon heating technologies is often accompanied by improvements in the building's energy efficiency. In fact, improving a buildings' energy efficiency by applying insulation is often the first step towards low-carbon heat provision. Insulation is a no-regrets measure:
- insulation contributes to achieving climate goals because well-insulated buildings require less energy to achieve similar comfortable indoor temperatures;
- insulation is necessary to allow for most low-carbon heating techniques: heating techniques such as electric heat pumps require buildings to be well-insulated in order to function efficiently.

Research by the Health Council of the Netherlands (2020) shows that the energy transition in the built environment can contribute to realising healthy and comfortable homes, for instance by applying insulation and ventilation systems. However, to prevent unintentional negative health effects, attention should be paid that the new technologies are properly designed, installed, maintained and used.

Not only low, but also high indoor temperatures harm human health (WHO, 2018). With climate change, the increased frequency and duration of heat waves and improved insulation levels of homes (in which heat is more likely to get trapped), this topic is becoming increasingly important. Certain low-carbon heating technologies, such as heat pumps or heat and cold storage, can be applied for cooling as well as for heating.

Ventilation and exhaust hoods

According to Seals and Krasner (2020), when properly installed, maintained and operated, exhaust hoods can reduce NO_2 and other pollutant levels and are associated with better respiratory health. Piet Jacobs (2021b) also argued that well-functioning exhaust hoods are capable of capturing up to 90% of fine particles ($PM_{2.5}$) when using the back burners (when using the front burners, such exhaust hoods can capture 30% of $PM_{2.5}$). However, exhaust hoods do not always vent to the outdoors but rather recirculate emissions through filters that do not effectively clean the air.

According to TNO (2019), 50% of the exhaust hoods that are sold in the Netherlands are recirculation hoods. These recirculation hoods do not capture ultrafine particles and the majority (70%) of $PM_{2.5}$. On top of that, after a few weeks of using the recirculation hood, the NO_2 filter is often saturated and captures less than 20% of NO_2 (TNO, 2019).
By using a well-functioning exhaust hood, households can decrease exposure to particulate matter by 10–20% (TNO, 2019). In short, it is important to use ventilation systems and exhaust hoods that are properly installed, maintained and used. Ventilation is critical, however, it is not the sole strategy to prevent exposure to air pollutants (Licina et al., 2017). The first step to prevent emissions at the source.

Other household activities

Not only cooking, but also other household activities contribute to indoor air pollution. Indoor emissions of $PM_{2.5}$ are mainly the result of combustion processes (Fantke et al., 2017). Apart from cooking and the burning of wood, such combustion processes include smoking and burning candles (Fantke et al., 2017, TNO, 2019). Cleaning is another important source of indoor emissions of particulate matter (Licina et al., 2017).

Outdoor air pollution

Indoor air pollution is generated not only from indoor sources but also from outdoor air pollutants that are brought indoors in the processes of ventilation and penetration through the building envelope (WHO, 2021b). In indoor environments, concentrations of pollutants originating from outdoor air are influenced by their outdoor spatiotemporal patterns of concentration and, in particular, by the proximity of the building to outdoor sources (e.g. a busy road) (WHO, 2021b).

In the Netherlands, on average half of the $PM_{2.5}$ concentration indoors is caused by the ambient $PM_{2.5}$ concentration (TNO, 2019). In summer, the concentration of air pollution indoors is typically similar to the concentration of pollutants outdoors (Jacobs, 2021a). Filters can be used to prevent outdoor air pollution from entering inside the dwelling; filters can capture the majority (about three quarters) of $PM_{2.5}$ (Jacobs, 2021a).

Room size and exposure to pollutants

Potential health effects are a result of *(1)* concentration of pollutants and *(2)* the amount of time a person spends in the room in which pollution takes place (exposure).
The concentration of air pollution is not only determined by amount of emissions of air pollutants, but also by the size of the room in which the pollution takes place.
The concentration of air pollutants from cooking is higher in a small kitchen, compared to cooking the same meal in a large kitchen (or a kitchen that is attached to the living room).

Assuming that ventilation levels are similar, households with kitchens that are attached to the living room probably spend more time in the polluted air because the pollution is not limited to the kitchen. This means that exposure to air pollution is higher in these households, even though the concentration of pollutants is lower.

When studying the health effects of indoor pollution, it should be noted that many studies (the present study included) are based on the assumption of well-mixed indoor air. However, this is not a well representation of the inhalation intake fractions. Licina *et al.* (2017) found that the total inhalation intake increased by 1.4-1.9 times for nearby releases occurring at 0.5-1.5 heights. These results suggest that the well-mixed representation of an indoor environment probably underestimate the inhalation intake for certain types of indoor pollutant releases.

5.3 Leads for quantitative research

Given the numerous factors that will determine the ultimate impact of heating and cooking on indoor pollution, it is complicated to estimate the actual levels of indoor pollution and the associated health-related costs. Results would be highly uncertain. In addition, the methodology we thought out to estimate health-related social-costs related to indoor pollution need further investigation and verification. It is important that such figures could be added to the results of outdoor pollution (presented in former chapters) to form an integrated cost figure without the risk of double counting. Therefore we do not come up with a quantitative estimation here, but present leads for future quantitative research. The following insights are based on existing literature and gathered information.

Estimating the amount of indoor air pollution

With respect to fossil fuel-based domestic heating and cooking techniques, most pollution can be expected to start indoors. Part of the pollution ends up outdoor due to ventilation and exhaust hoods. Part will be inhaled and is therefore not included in the amount of emissions measured outdoors. It is a challenge to estimate this. Several studies focus on the indoor pollution of specific techniques and situations. WHO (2014a) gives an overview of some research and influencing factors. Global air quality guidelines are determined based on substantial research and consultation (WHO, 2021b), but they are defined in terms of concentration levels. Indoor Air Quality (IAQ) models can be used to estimate the impact of emissions on indoor pollution concentrations.

If this research path is chosen, environmental prices reflecting the health-related social costs of indoor pollution need to be defined in terms of concentrations instead of emissions. For stoves, some (underlying) indoor emissions factors are published, based on laboratory or simulated kitchen measurements for water heating and cooking (WHO, 2014b). For some gas appliances, emission factors are estimated in UCLA (2020).[34]

It is important to avoid double counting of direct emissions. This might be the case if indoor emissions are estimated and simply added to outdoor emissions, which are often already estimated/reported and valued (as we did in this study). We can think of three methods to minimise the risk of double counting:

- The difference between indoor emission factors and outdoor emission factors can be assumed to be the fraction of pollution that stays indoors.[35] These factors can be multiplied by the final energy consumption per fossil fuel technique. An estimate of total indoor emissions per year would then result.
- Consider emission factors between vented and unvented appliances, the difference might be the part that longer stays indoor.
- Consider total outdoor emissions and estimate what would have been the corresponding indoor emissions, based on research on the interaction between indoor and outdoor.

We consider the first method as most promising, but further research is needed to make sure this is the right way to go.

For techniques based on electricity and derived heat, air pollutants are emitted at the production sites instead of in homes. These indirect emissions are outdoor, but might (partly) come indoor from the outside. This depends on the exact location of the generators, stack heights, and, to a great extent, weather conditions and ventilation in houses.

Many studies consider the influence of outdoor environments on indoor air quality and estimate an indoor-outdoor ratio, see Leung (2015). Although there are large variations in I/O ratios for different measurements, it is still the most commonly used parameter for various studies (Leung, 2015). Many focus on the I/O ratio from transport emissions and concentrations on street level, which is generally estimated to lie around 50% (Jacobs, 2021b). Since this is a rough estimate and high stack emissions of electricity and heat generators might be less likely to end up indoors, further research is needed to determine the indoor pollution effect of indirect emissions of electricity and derived heat based technologies. It is advised to work with sensitivity analyses/a range of factors.

Valuation of indoor emissions

To estimate the total health damage due to household heating and cooking emissions, we differentiated the environmental prices to location and emission height. This differentiation is based on so-called intake fractions of emissions. These intake fraction indicate the portion of the emissions that is, at one point, inhaled by humans. For indoor pollution, intake fractions depend on numerous factors, such as air exchange rate, mixing factor, building volume, number of people inside, and exposure time (Humbert et al., 2011). Intake fractions of indoor emissions are typically substantially higher than those of outdoor emissions (Humbert et al., 2011).

[34] There are a limited number of recent studies that simulate and measure indoor air pollutant concentrations resulting from the use of gas appliances, and many are focused entirely on gas stovetop ranges.

[35] As also mentioned in UCLA (2020): “values correspond to total emissions factors when the appliance is turned on, regardless of whether an appliance is vented outdoors (meaning not all emissions aravel indoors)”.

The reason is that indoor pollution has fewer opportunities to spread over a large area. Houses and buildings are fairly closed environments, meaning that pollution may longer remain in the same area than it would outdoor. As a result, humans in a building are exposed to the emissions longer, potentially breathing in a larger portion before the emissions may have been filtered away. As a result, the health effects of indoor air pollution tend to be higher than those of outdoor air pollution, due to the higher intake fraction of the emissions indoors.

In scientific literature, there are few studies that provide precise estimations of indoor intake fractions for fine particulate matter. Table 12 gives an overview. All intake fractions are significantly higher (factor 500-2,000) than the intake fractions for outdoor air pollution. For comparison, intake fractions used by Humbert et al. (2011) for *outdoor* $PM_{2.5}$ emissions range from 0.1 ppm in rural areas to 23 ppm at ground level in urban areas. Further research is needed to validate those huge differences and determine to what extent this would inflating the environmental price of PM.

Table 12 – Values for indoor fine particulate matter intake fractions from literature

Assumption or situation	Intake fraction (parts per million)	Data source
Perfectly mixed environment, 100 minutes exposure (depositing particles)	4,200	Licina et al., (2017)
Perfectly mixed environment, 100 minutes exposure (non-depositing particles)	3,200	Licina et al., (2017)
US household, fulltime exposure	6,770	Humbert et al., (2011)
US household, non-fulltime exposure	4,740	Humbert et al., (2011)
Office with mechanical ventilation, fulltime exposure	3,610	Humbert et al., (2011)
Office with mechanical ventilation, non-fulltime exposure	1,080	Humbert et al., (2011)

6 Closing remarks

This study considers the average health impacts of outdoor air pollution related to domestic heating and cooking activities and uses environmental prices to value them. It reveals that substantial health-related social costs are caused by domestic heating and cooking in the EU27+UK area. We have presented various cost figures: total costs estimates and average costs per household for all individual EU27+UK countries and the region as a whole.
Costs are also distinguished by technique-fuel combinations for the EU27+UK and four case study countries. Countries that heavily rely on coal and wood for heating and cooking, show higher costs estimates as these fuels cause significant air pollution when used at home (direct emissions). The cleanest technologies are heat pumps and fully renewable options (excluding biomass) such as solar thermal.

Switching to alternative techniques/fuels might reduce the health-related social costs, provided that they are available on the market (or will be in the near future) and that they are suitable for large groups of dwellings (not considered here). Particularly (hybrid) heat pumps are promising. The potential role of hydrogen in the built environmental is highly uncertain. Greening the energy mix for electricity and collective heat production is also beneficial as this reduces the release of air pollutants at the generator plants (indirect emissions) that can be attributed to domestic heating and cooking activities.

The health-related social costs provided in this study only include outdoor pollution and are therefore an *underestimation* of the total health costs. The costs due to indoor air pollution have not been taken into account quantitatively. Yet, indoor air is often more polluted than outdoor air due to higher concentrations of certain pollutants and European citizens tend to spend the vast majority of their time indoors. More research is needed on the interaction of the numerous factors that determine the health impact of indoor pollution and the corresponding emissions factors (that can be used in addition to outdoor factors without double counting). We already provided some starting points for future research.

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A Social damage cost framework

In this chapter we set up a framework for estimating environmental prices for air polluting substances that can be used to estimate the total health-related costs of residential heating and cooking in the EU27+UK. Paragraph A.1 describes the methodology and Paragraph A.2 shows the prices for individual Member States.

A.1 Methodology

Introduction

The methodology for the social damage costs is mainly based on the Environmental Prices Handbook (CE Delft, 2018a) and the Handbook of External Cost of Transport (CE Delft et al., 2019), the latter of which was issued by DG Move and is widely used in quantification of air pollution effects. These handbooks provide extensive calculations of the estimated damage costs for various pollutants in various contexts, such as pollution due to transport.

In this study, we extend this methodology to provide more specific damage costs for some pollutants, to account for:
1. The location of the emission. Urban areas have higher population density, therefore more people are likely to inhale an emission than in rural areas.
2. The stack height of the emissions. Emission close to the ground such as from a car or a gas stove are inhaled to a higher extent than emissions from a higher chimney, e.g. a power plant).

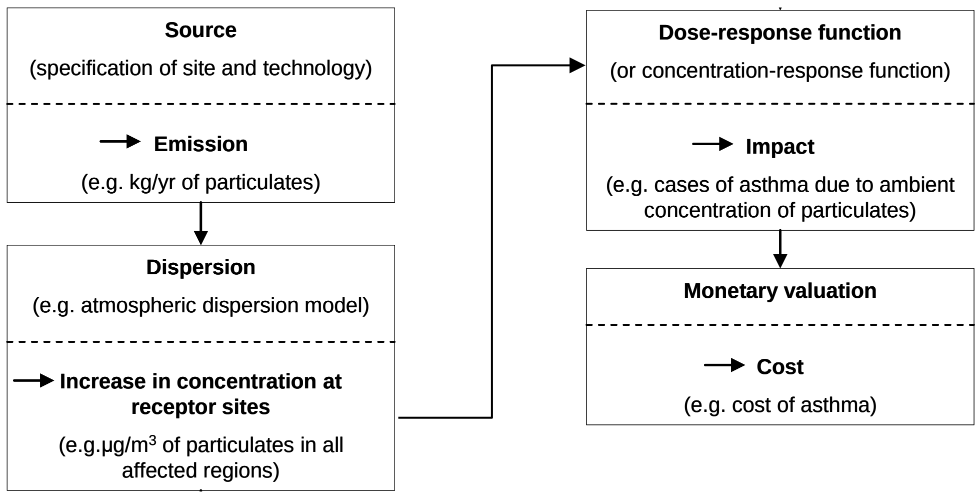
This is done for fine particulate matter on both stack height and location. For SO_2, NO_x and NH_3 the damage costs can be specified to location (urban vs. rural emissions).
The methodology to adjust damage costs estimates for PM, NO_2, SO_2 and NH_3 is explained below. For CO, CH_4 and NMVOC we cannot specify the damage cost to location or stack height, because too little research has been done on the relationship between the source location of the emission and the intake location of this emission. Emissions could in theory travel great distances, such that the location of emission does not equal the location of human intake of that emission.

Starting point

In both Handbooks the well-known Impact Pathway Method (see Textbox 5) is adopted, in which the relationship between air emissions and eventual impacts is estimated. After that, monetary values were attached to the identified and quantified damages caused at the endpoints.

Textbox 5 - Impact Pathway Approach

A given activity leads to emissions. In the case of residential heating and cooking, these emissions are primarily emissions to the air. These emissions are subsequently transported through the atmosphere to other regions where they are added to existing emission concentrations. This concentration then leads to changes in 'endpoints' relevant to human welfare (also see Paragraph 1.5). An example of such an endpoint — and the most important endpoint in this study — is human health. After that, monetary values are attached to the identified and quantified damages caused at the endpoints.



Source: CE Delft et al., (2019).

The Handbook of External Cost of Transport gives a country specific estimates of the social costs of air pollution for EU27+UK Member States plus some additional countries.
Both average and transport specific values are provided. It includes:
— Valuation for emissions of PM_{10}, $PM_{2.5}$, NO_x, SO_2, NMVOC with differentiation for $PM_{2.5}$ to height of exhaust and NO_x to population density of the point of release (rural or cities).
— Valuation includes ecosystem impacts and impacts on building and materials.
— Health and ecosystem impacts are differentiated to Member States based on the underlying NEEDS (2008) model.[36]
— With Concentration Response Functions (CRFs) for health-related impacts that are made consistent with the WHO, (2013) framework.
— Using a relative income elasticity of 0.8 to reflect differences in the willingness to pay to income (see Textbox 6).

[36] We used NEEDS values for the scenario 2010/2020 interpolated to actual emissions 2015, based on aggregation scheme "SIA_E_PPMc" for Human Health Impacts, based on average meteorology - corresponding to emissions from All SNAP-Sectors - unknown height of release.

Textbox 6 - Income elasticities of demand for a clean environment

There is some debate in economics as to whether the value of the willingness to pay (WTP) would be contingent on the income being earned. Although understanding the income elasticity of demand for an environmental good (or reduction in environmental harm) would be useful, some authors have emphasized that no clear connection between income elasticity of WTP (which is usually observed in contingent valuation studies) and income elasticity of demand (Barbier et al., 2017) can be observed. On the other hand, differences in income are likely to cause differences in valuation: for example hospital admissions may have lower costs in countries with lower incomes and working days loss are also less valuable.
In an extensive meta-analysis, the (OECD, 2012) concludes that the income elasticity for the WTP of environmental and health-related public goods would fall between 0.7 and 0.9. On the basis of this, CE Delft et al., (2019) has recommended to use and income elasticity value of 0.8. This implies that if a country's average income (expressed in purchasing power parities) is half the EU average, the valuation of a certain impact is around 58% lower ((0.5)0.8 = 0.58).

Adjustments made

Within the framework of the Handbook

The methodology of the Handbook of External Cost of Transport has been based on a two-stage routine:
- estimate general damage costs estimates, for human health, ecosystems and buildings;
- differentiate these general estimates to transport specifically.

We adjusted these values in three ways:
1. From the source calculations of the Handbook we can derive a damage cost estimate for human health only, including NH_3.[37]
2. Adjustments made to adjust the values of the Handbook to specific values to be used for emissions in the built environment. The calculations cover more types differentiation for $PM_{2.5}$ and NO_x - not only to transport, but also to electricity generation.
3. Update to the price level of the year 2020.[38]

An overview of the resulting prices is given in Annex A.2.

Outside the framework of the Handbook

We now arrive at the differentiation to these environmental prices outside of the DG Move Handbook framework. Based on the prices given above, and the paper by Humbert et al. (2011) we further differentiate the environmental prices to stack height and location. This differentiation enables the valuation of emissions more specific to the location of their source.

Humbert et al. (2011) determined the intake fractions of different emissions that take place in locations with different characteristics. The intake fraction represents the fraction of the emitted pollutant that is inhaled by humans. Humbert et al. (2011) differentiate these intake fractions along two dimensions:
- Stack height: The amount of pollutants that are inhaled by humans is higher when the emission occurs closer to the ground. For instance, traffic emissions are inhaled more than emissions that originate in the chimneys of a power plant.

[37] NH_3 damage costs were calculated in the DG MOVE project but were not published in the final report.

[38] We only adjusted for inflation and did not take changes in income levels between 2016 and 2020 into account, following CE Delft, (2018a). It is better to periodically adjust the valuation to new research rather than to update every year the valuation to new income levels.

— Population density or the distinction between urban, rural and remote areas:
  The amount of pollutants that are inhaled by humans also differ depending on how many people are situated in the area. In large cities/urban areas where population density is high, more of the pollutants are taken up by humans present in the area. The reverse holds for rural and especially remote areas, where very few people live.

Depending on the pollutant, the intake fractions are differentiated on one or both of these dimensions. For $PM_{2.5}$ and PM_{10}, the intake fractions are differentiated by both stack height and population density. SO_2, NO_x, and NH_3 are only differentiated by population density, as the influence of the stack height on the intake fractions of these pollutants is less well-known. For all pollutants, the weighted average intake fraction for each dimension is also calculated.

The intake fractions by Humbert et al. are based on the characteristics of an unspecified world continent, and partially on data for the United States. These characteristics are, however, not all applicable to the situation in Europe. For instance, in Europe a substantially smaller part of the land surface can be considered as 'remote'.[39] Moreover, the composition of emissions differs location to location. We therefore recalculated the intake fractions from Humbert et al. based on specific parameters for European characteristics, such as population density in urban and rural areas and the fraction of emissions that are emitted on each given stack height.

The next step is to use these differentiated intake fractions, applicable to the European setting, to differentiate in the environmental prices as given in the previous paragraph. To this end, we start by setting the average environmental price from the DG Move handbook to correspond to the weighted average intake fraction for the specific pollutant. Next, for each differentiated price, we take the relative intake fraction for the given stack height and/or location, as compared to the average intake fraction, and multiply it by the average environmental price. To demonstrate, the environmental price for $PM_{2.5}$ in an urban environment on the ground level is calculated as follows:

$$Price\ PM2.5_{[urban,ground\ level]} = Price\ PM2.5_{[average]} * \frac{IF_{PM2.5_{[urban,ground\ level]}}}{IF_{PM2.5_{[average]}}}$$

39 In this study, we do not present separate prices for remote areas, for this exact reason: very few areas in Europe can be considered 'remote'. Therefore, we distinguish between 'urban' and 'rural' prices only. The prices for remote areas are used for calculated population-weighted average prices though.

A.2 Environmental prices for human health per country

Table 13 provides an overview of environmental prices taken from Handbook of External costs of Transport for human health impacts. Table 14 shows the differentiated environmental prices for human health impacts.

Table 13 - Environmental prices derived from Handbook of External costs of transport for all EU27+UK countries, in €$_{2020}$/kg

Country	NH_3	NMVOC (all)	SO_2 (all)	NO_x (avg)	NO_x (urban)	NO_x (rural)	NO_x	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$ (metro-politan)	$PM_{2.5}$ (urban)	$PM_{2.5}$ (rural)	PM_{10} (non-exhaust; average)	CO (all)	CH_4 (all)
Location	All	All	All	All	Urban	Rural	All	All	All	Metropolitan	City	Rural	All	All	All
Source	All	All	All	All	All	All	Electricity	All	Electricity	Transport	Transport	Transport	All	All	All
EU Aggregate	18.5	1.3	11.4	14.0	20.9	11.6	10.3	40.9	20.5	402	130	73.9	23.5	0.013	0.058
Austria	19.7	2.4	16.6	27.4	40.8	22.7	20.3	56.9	28.3	492	159	91.8	32.6	0.025	0.111
Belgium	40.3	3.6	17.6	17.7	26.3	14.7	15.9	85.7	36.5	506	164	120.3	49.8	0.036	0.164
Bulgaria	5.9	0.0	4.4	6.5	9.8	5.5	5.3	9.8	7.5	202	64	31.7	5.7	0.000	0.000
Croatia	18.9	0.8	8.0	11.4	17.0	9.4	10.2	22.4	17.1	308	100	57.0	12.9	0.009	0.039
Cyprus	4.0	-0.5	8.2	5.7	8.4	4.8	5.6	14.9	11.5	na	75	17.9	8.7	-0.005	-0.024
Czechia	28.9	1.1	11.8	16.0	23.9	13.3	13.0	37.1	23.9	381	122	76.0	21.2	0.011	0.048
Denmark	14.8	1.5	9.8	10.7	15.8	8.8	9.6	27.2	14.7	496	159	62.3	15.8	0.015	0.067
Estonia	11.1	0.3	5.4	3.2	4.6	2.6	2.4	8.9	6.2	na	108	36.9	5.2	0.003	0.014
Finland	7.4	0.4	4.4	2.9	4.3	2.4	2.9	10.7	5.1	386	125	33.8	6.2	0.004	0.019
France	16.3	1.5	14.3	17.7	26.3	14.6	15.9	45.3	26.5	430	138	91.8	26.1	0.015	0.067
Germany	29.7	1.9	16.9	24.4	36.2	20.2	18.8	72.3	39.7	473	152	98.2	41.8	0.019	0.087
Greece	5.1	0.2	6.2	3.4	5.0	2.7	2.7	15.4	8.1	282	91	34.8	9.0	0.002	0.010
Hungary	20.0	0.7	10.2	17.6	26.2	14.6	14.1	34.8	21.4	335	108	62.3	20.1	0.007	0.034
Ireland	4.3	1.7	12.4	11.9	17.7	9.8	9.5	31.2	14.4	600	193	71.8	18.2	0.017	0.077
Italy	22.8	1.1	13.3	16.6	24.6	13.7	12.8	48.8	22.3	432	139	83.4	28.5	0.011	0.048
Latvia	9.2	0.4	4.9	4.4	6.5	3.7	4.1	10.1	6.0	265	86	29.6	5.9	0.004	0.019
Lithuania	8.3	0.5	6.5	7.9	11.7	6.5	7.0	14.7	8.1	317	103	40.1	8.4	0.005	0.024
Luxembourg	63.3	6.5	30.3	45.7	67.8	37.8	34.7	118.0	67.2	na	293	201.6	67.5	0.066	0.298
Malta	6.8	0.3	4.5	1.4	2.1	1.2	1.4	9.0	6.5	na	76	19.0	5.5	0.003	0.014

Country	NH_3	NMVOC (all)	SO_2 (all)	NO_X (avg)	NO_X (urban)	NO_X (rural)	NO_X	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$ (metro-politan)	$PM_{2.5}$ (urban)	$PM_{2.5}$ (rural)	PM_{10} (non-exhaust; average)	CO (all)	CH_4 (all)
Netherlands	31.7	2.7	20.9	18.2	26.9	15.0	14.1	85.8	39.4	484	156	106.6	49.9	0.028	0.125
Poland	15.2	0.6	8.3	9.3	13.8	7.7	6.8	29.5	17.2	298	96	54.9	17.0	0.006	0.029
Portugal	4.5	0.5	4.3	1.8	2.5	1.5	1.1	22.4	5.5	308	99	41.2	13.0	0.005	0.024
Romania	9.9	0.4	7.6	13.2	19.5	10.9	8.9	22.1	13.1	287	93	44.3	12.7	0.004	0.019
Slovakia	25.8	0.6	10.3	16.3	24.1	13.4	12.6	29.9	19.4	346	111	62.3	17.1	0.006	0.029
Slovenia	25.1	1.3	9.2	13.8	20.5	11.4	10.8	28.2	16.9	na	98	54.9	16.0	0.013	0.058
Spain	6.8	0.6	7.2	5.3	7.9	4.4	4.2	21.4	10.3	367	118	48.6	12.6	0.006	0.029
Sweden	11.2	0.6	5.3	5.7	8.4	4.6	5.7	18.6	6.5	395	127	40.1	10.8	0.006	0.029
United Kingdom	18.6	1.3	10.3	9.2	13.6	7.6	6.9	44.6	19.2	401	129	68.6	26.2	0.013	0.058

Table 14 - Differentiated environmental prices, human health impacts only, for all EU27+UK countries, in €$_{2020}$/kg

EU27+UK	Stack height	Urban	Rural	Weighted average
$PM_{2.5}$	High stack	24.9	22.0	20.9
	Low stack	32.4	26.5	27.2
	Ground level	94.0	50.3	78.8
	Emission-weighted average	48.8	32.2	40.9
SO_2	-	12.9	10.4	11.4
NO_x	-	20.9	11.6	14.0
NH_3	-	18.7	18.7	18.5
Austria	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	34.7	30.7	29.1
	Low stack	45.1	36.8	37.8
	Ground level	130.8	69.9	109.6
	Emission-weighted average	67.9	44.8	56.9
SO_2	-	18.7	15.1	16.6
NO_x	-	40.8	22.7	27.4
NH_3	-	19.9	19.9	19.7
Belgium	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	52.3	46.2	43.8
	Low stack	67.9	55.4	57.0
	Ground level	197.0	105.3	165.2
	Emission-weighted average	102.3	67.5	85.7
SO_2	-	19.9	16.0	17.6
NO_x	-	26.3	14.7	17.7
NH_3	-	40.7	40.7	40.3
Bulgaria	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	6.0	5.3	5.0
	Low stack	7.8	6.4	6.5
	Ground level	22.6	12.1	18.9
	Emission-weighted average	11.7	7.7	9.8
SO_2	-	5.0	4.0	4.4
NO_x	-	9.8	5.5	6.5
NH_3	-	6.0	6.0	5.9
Croatia	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	13.6	12.1	11.4
	Low stack	17.7	14.5	14.9
	Ground level	51.4	27.5	43.1
	Emission-weighted average	26.7	17.6	22.4
SO_2	-	9.0	7.3	8.0
NO_x	-	17.0	9.4	11.4
NH_3	-	19.1	19.1	18.9
Cyprus	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	9.1	8.0	7.6
	Low stack	11.8	9.6	9.9
	Ground level	34.2	18.3	28.7
	Emission-weighted average	17.8	11.7	14.9
SO_2	-	9.3	7.5	8.2
NO_x	-	8.4	4.8	5.7
NH_3	-	4.1	4.1	4.0

Czech Republic	Stack height	Urban	Rural	Weighted average
$PM_{2.5}$	High stack	22.6	20.0	18.9
	Low stack	29.4	24.0	24.6
	Ground level	85.2	45.5	71.4
	Emission-weighted average	44.2	29.2	37.1
SO_2	-	13.3	10.7	11.8
NO_x	-	23.9	13.3	16.0
NH_3	-	29.2	29.2	28.9
Denmark	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	16.6	14.7	13.9
	Low stack	21.6	17.6	18.1
	Ground level	62.6	33.5	52.5
	Emission-weighted average	32.5	21.5	27.2
SO_2	-	11.1	8.9	9.8
NO_x	-	15.8	8.8	10.7
NH_3	-	14.9	14.9	14.8
Estonia	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	5.4	4.8	4.5
	Low stack	7.0	5.7	5.9
	Ground level	20.4	10.9	17.1
	Emission-weighted average	10.6	7.0	8.9
SO_2	-	6.1	4.9	5.4
NO_x	-	4.6	2.6	3.2
NH_3	-	11.2	11.2	11.1
Finland	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	6.5	5.7	5.4
	Low stack	8.5	6.9	7.1
	Ground level	24.5	13.1	20.5
	Emission-weighted average	12.7	8.4	10.7
SO_2	-	5.0	4.0	4.4
NO_x	-	4.3	2.4	2.9
NH_3	-	7.5	7.5	7.4
France	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	27.6	24.4	23.1
	Low stack	35.9	29.3	30.1
	Ground level	104.1	55.7	87.3
	Emission-weighted average	54.0	35.7	45.3
SO_2	-	16.1	12.9	14.3
NO_x	-	26.3	14.6	17.7
NH_3	-	16.4	16.4	16.3
Germany	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	44.1	39.0	37.0
	Low stack	57.3	46.8	48.0
	Ground level	166.2	88.9	139.3
	Emission-weighted average	86.3	57.0	72.3
SO_2	-	19.0	15.3	16.9
NO_x	-	36.2	20.2	24.4
NH_3	-	30.0	30.0	29.7

Greece	Stack height	Urban	Rural	Weighted average
$PM_{2.5}$	High stack	9.4	8.3	7.9
	Low stack	12.2	10.0	10.2
	Ground level	35.4	18.9	29.7
	Emission-weighted average	18.4	12.1	15.4
SO_2	-	7.0	5.7	6.2
NO_x	-	5.0	2.7	3.4
NH_3	-	5.1	5.1	5.1
Hungary	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	21.2	18.8	17.8
	Low stack	27.6	22.5	23.1
	Ground level	80.1	42.8	67.1
	Emission-weighted average	41.6	27.4	34.8
SO_2	-	11.5	9.3	10.2
NO_x	-	26.2	14.6	17.6
NH_3	-	20.2	20.2	20.0
Ireland	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	19.1	16.8	16.0
	Low stack	24.8	20.2	20.8
	Ground level	71.8	38.4	60.2
	Emission-weighted average	37.3	24.6	31.2
SO_2	-	13.9	11.2	12.4
NO_x	-	17.7	9.8	11.9
NH_3	-	4.4	4.4	4.3
Italy	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	29.7	26.3	24.9
	Low stack	38.7	31.5	32.4
	Ground level	112.1	59.9	94.0
	Emission-weighted average	58.2	38.4	48.8
SO_2	-	15.0	12.1	13.3
NO_x	-	24.6	13.7	16.6
NH_3	-	23.0	23.0	22.8
Latvia	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	6.2	5.5	5.2
	Low stack	8.0	6.6	6.7
	Ground level	23.3	12.5	19.5
	Emission-weighted average	12.1	8.0	10.1
SO_2	-	5.5	4.4	4.9
NO_x	-	6.5	3.7	4.4
NH_3	-	9.3	9.3	9.2
Lithuania	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	8.9	7.9	7.5
	Low stack	11.6	9.5	9.7
	Ground level	33.7	18.0	28.3
	Emission-weighted average	17.5	11.6	14.7
SO_2	-	7.4	5.9	6.5
NO_x	-	11.7	6.5	7.9
NH_3	-	8.4	8.4	8.3

Luxembourg	Stack height	Urban	Rural	Weighted average
$PM_{2.5}$	High stack	72.0	63.6	60.3
	Low stack	93.5	76.3	78.4
	Ground level	271.3	145.0	227.4
	Emission-weighted average	140.8	93.0	118.0
SO_2	-	34.2	27.5	30.3
NO_x	-	67.8	37.8	45.7
NH_3	-	64.0	64.0	63.3
Malta	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	5.5	4.8	4.6
	Low stack	7.1	5.8	6.0
	Ground level	20.6	11.0	17.3
	Emission-weighted average	10.7	7.1	9.0
SO_2	-	5.1	4.1	4.5
NO_x	-	2.1	1.2	1.4
NH_3	-	6.8	6.8	6.8
Netherlands	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	52.3	46.3	43.9
	Low stack	68.0	55.5	57.0
	Ground level	197.3	105.5	165.4
	Emission-weighted average	102.4	67.6	85.8
SO_2	-	23.6	19.0	20.9
NO_x	-	26.9	15.0	18.2
NH_3	-	32.0	32.0	31.7
Poland	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	18.0	15.9	15.1
	Low stack	23.3	19.1	19.6
	Ground level	67.7	36.2	56.7
	Emission-weighted average	35.1	23.2	29.5
SO_2	-	9.4	7.6	8.3
NO_x	-	13.8	7.7	9.3
NH_3	-	15.4	15.4	15.2
Portugal	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	13.6	12.1	11.4
	Low stack	17.7	14.5	14.9
	Ground level	51.4	27.5	43.1
	Emission-weighted average	26.7	17.6	22.4
SO_2	-	4.9	3.9	4.3
NO_x	-	2.5	1.5	1.8
NH_3	-	4.6	4.6	4.5
Romania	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	13.5	11.9	11.3
	Low stack	17.5	14.3	14.7
	Ground level	50.7	27.1	42.5
	Emission-weighted average	26.3	17.4	22.1
SO_2	-	8.6	6.9	7.6
NO_x	-	19.5	10.9	13.2
NH_3	-	10.0	10.0	9.9

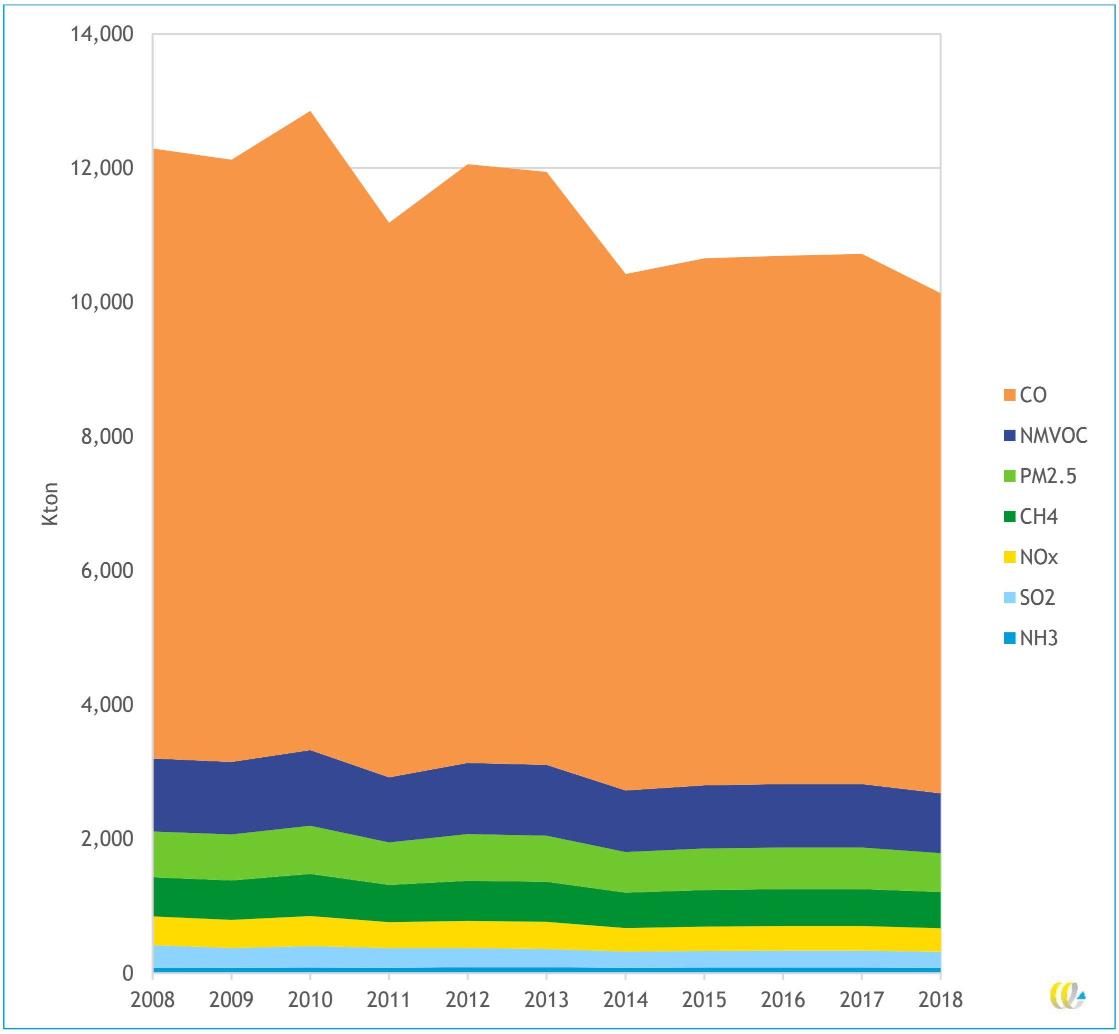
Slovakia	Stack height	Urban	Rural	Weighted average
$PM_{2.5}$	High stack	18.2	16.1	15.3
	Low stack	23.7	19.3	19.8
	Ground level	68.7	36.7	57.6
	Emission-weighted average	35.6	23.5	29.9
SO_2	-	11.7	9.4	10.3
NO_x	-	24.1	13.4	16.3
NH_3	-	26.0	26.0	25.8
Slovenia	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	17.2	15.2	14.4
	Low stack	22.3	18.2	18.7
	Ground level	64.8	34.6	54.3
	Emission-weighted average	33.6	22.2	28.2
SO_2	-	10.4	8.3	9.2
NO_x	-	20.5	11.4	13.8
NH_3	-	25.4	25.4	25.1
Spain	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	13.1	11.6	11.0
	Low stack	17.0	13.9	14.2
	Ground level	49.3	26.3	41.3
	Emission-weighted average	25.6	16.9	21.4
SO_2	-	8.1	6.5	7.2
NO_x	-	7.9	4.4	5.3
NH_3	-	6.8	6.8	6.8
Sweden	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	11.3	10.0	9.5
	Low stack	14.7	12.0	12.3
	Ground level	42.7	22.8	35.8
	Emission-weighted average	22.2	14.6	18.6
SO_2	-	6.0	4.8	5.3
NO_x	-	8.4	4.6	5.7
NH_3	-	11.3	11.3	11.2
United Kingdom	**Stack height**	**Urban**	**Rural**	**Weighted average**
$PM_{2.5}$	High stack	27.2	24.0	22.8
	Low stack	35.3	28.8	29.6
	Ground level	102.4	54.7	85.8
	Emission-weighted average	53.1	35.1	44.6
SO_2	-	11.7	9.4	10.3
NO_x	-	13.6	7.6	9.2
NH_3	-	18.8	18.8	18.6

B Input data

B.1 Total health-related costs of outdoor pollution

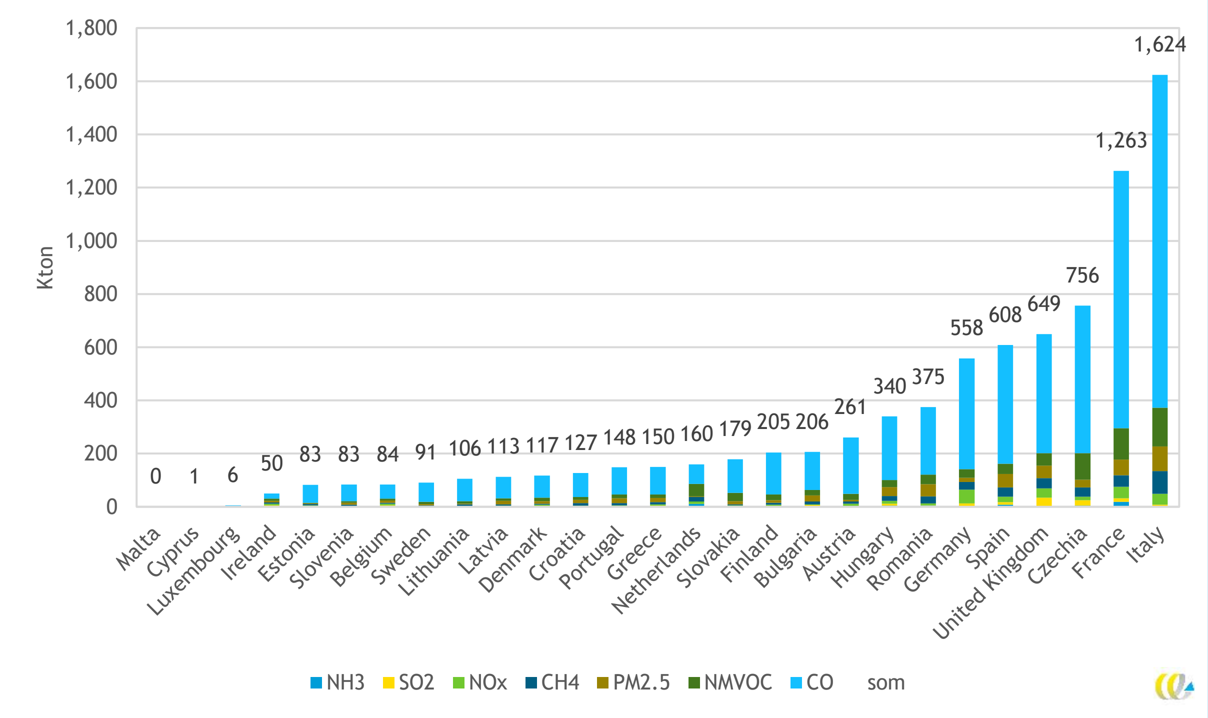
B.1.1 Direct emissions

Figure 22 - Direct emissions per substance, related to domestic heating and cooking (kton)



Note: Most emissions are related to the substance CO, but given it relatively low damage costs per unit of emission, CO is not dominant in the health-related cost figures.

Figure 23 - Direct emissions per substance per country, related to domestic heating and cooking (kton)



B.1.2 Indirect emissions

Approach

There were three methods identified to estimate direct emissions of electricity production in the EU27+UK countries:

- Life Cycle approach. Based on the Ecoinvent database in SimaPro it is possible to estimate total air emissions of electricity production, taking into account the national energy mixes used to produce electricity in the individual countries. However, it provides cradle to grave emissions related to electricity production, so including upstream emissions. Since we focus on direct emissions of domestic heating and cooking, such approach would not lead to a 'fair' comparison between electricity techniques and those based on other fuels. It was not possible to derive a 'rule of thumb' indication with share of total emissions could be attributed to electricity production phase only since production mixes and the technical state of electricity generators (filters) may differ substantially per country.
- Emission factors for electricity production applied to national energy mixes. EMEP-EAA provides (some) emissions factors per technique for public electricity and heat production. We could have combined these factors with IEA information on which energy carriers are used to produce electricity in the EU27+UK countries. In addition, assumptions must be made on the specific techniques used and average efficiencies of the generators. We don't know in advance whether this path would lead to reliable results and, within the scope of this study, we consider it not feasible.

— Emission intensities applied on total electricity consumption for domestic heating and cooking. EEA constructed SO_2 and NO_x emission intensities for public conventional thermal power electricity and heat production. These are calculated as the amount of pollutant produced (in tonnes) from public electricity and heat production (includes output from district heating plants and output from public thermal power stations[40]) divided by the output of electricity and heat (in toe) from these plants (EEA, 2011). However, EEA emission intensities only cover NO_x and SO_2 and are provided for the years 1990 to 2008 (EEA, 2011). Since then there have been substantial changes in the sector (also see Textbox 7)[41]. Therefore, we calculated emission factors for NO_x, SO_x[42], $PM_{2.5}$, NMVOC and NH_3 for recent years ourselves, based on the EEA described methodology and Eurostat emission- and gross production data. Since generators might produce both heat and electricity, we allocated the emissions based on the relative shares of heat (GHP) and electricity (GEP) in the total output. Subsequently, we combined the emissions factors with Eurostat data on electricity respectively heat demand for domestic heating and cooking in order to derive estimates for air pollution caused by electricity and heat production for use in homes for heating and cooking.
In our opinion, this approach for estimating indirect emissions yields the most reliable estimate currently available to us and best suits the scope and context of this study[43].

Textbox 7 - Emission intensities of electricity and heat production

Since the 1990, NO_X and SO_X emission intensity of public conventional thermal plants dropped significantly (with over 50% respectively 70%). Besides the increased use of end-of-pipe abatement techniques and other burners, this is due to the use of less SO_X and NO_X polluting fuels in many Member States (EEA, 2011). However, the increasing substitution of polluting fossil fuels for renewable energy increased other emissions. Particulate matter (PM) directly released into the air and emissions of volatile organic compounds (VOCs) increased because of the growth in biomass burning. Since 2005, $PM_{2.5}$ increased by 11%, PM_{10} by 7% and VOCs by 4%. In the EU27+UK (EEA, 2021c).

Results

Figure 24 shows the total indirect emission of electricity production for domestic heating and cooking, as used in our analysis. NO_x and SO_2 present the lion's share of indirect emissions, and have an almost equal share in the total emission calculation. NMVOC, $PM_{2.5}$ and NH_3 present a smaller part of the total emissions. However, the harmfulness of each substance differs, therefore no inferences can be made about the health consequences from this figure.

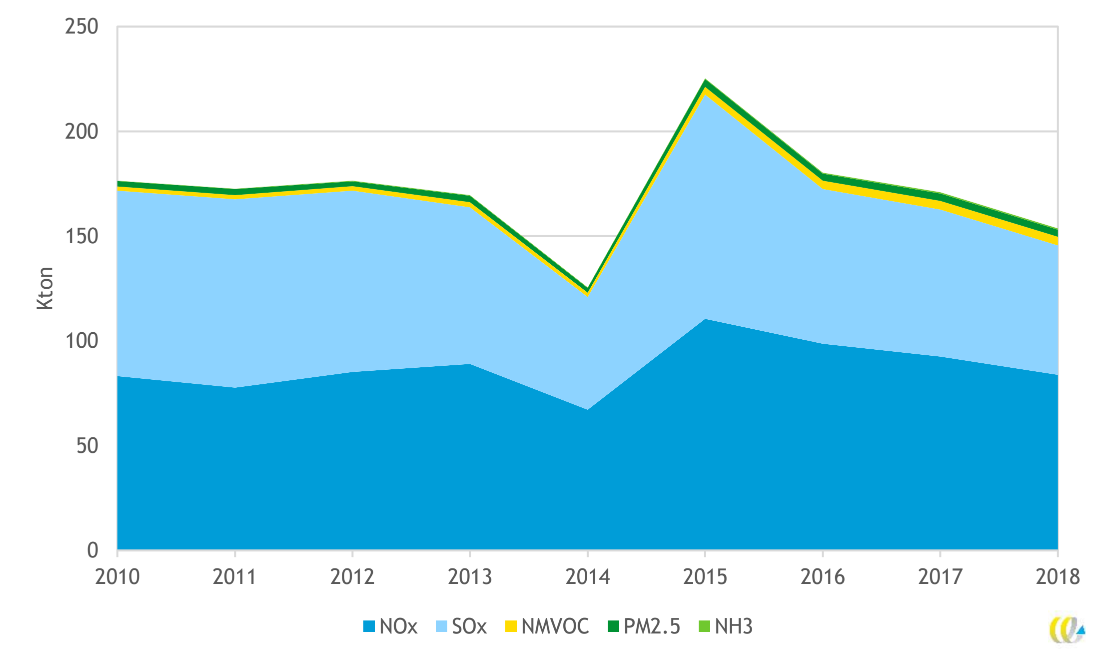
40 Autoproducers are excluded.

41 It is not realistic to calculated the trend over the period 1990-2008 and use that to estimate the emissions intensities for 2018, since the risk of trend break is high due to, among others, government regulations that cause shifts in national energy mixes or technical changes.

42 Emissions of the public electreicity and derived heat production cover sulphur oxides (SO_X). Since SO_X mainly consist of SO_2, so we interpret them as such in our social cost calculations.

43 Accounting for import and export patterns of electricity is outside the scope of the study. We assume that electricity demand leads to air polluting emissions of electricity production in the same country.

Figure 24 - Total indirect emissions due to heating and cooking, EU27+UK



B.2 Differentiation by technique and fuel combination

Description of technologies

Table 15 - Description of the heating technologies

Fossil based heating technology	**Description** based on: (EC, 2016)
Boiler - non-condensing	Boilers technologies burn fuels (heating oil, natural gas, coal) to generate hot water used for space heating and domestic tap water preparation. Pezzutto et al., (2019) classified furnaces in the category non-condensing boilers. A furnace is a closed vessel in which water or some other fluid is heated. The heated or vaporised fluid exits the boiler for use in various processes or heating applications. In households, the two main applications are: hot water and central heating.
Boiler - condensing	The main difference between the two categories of boilers is that condensing boilers contain a condensing unit, in which the water vapour in the exhaust gas is condensed. This enables the heat of condensation to be used for heating purposes. Because of this, condensing boilers have a higher efficiency than non-condensing boilers.
Stove	A stove is an enclosed box in which fuel is burned to provide heating, either to heat the space where the stove is situated, or to heat the stove itself and the items placed on it. The main difference to a boiler is the fact that there is no heated fluid in the system. The main function is space heating.

Combined Heat and Power – (CHP)	Internal combustion engines (ICs) are the most widespread Combined Heat and Power (CHP) technology for decentralised application in buildings. Usually, CHP-ICs are fuelled by natural gas, but there are also engines that are fuelled by heating oil, LPG or biogas. CHP-ICs are available for the application in buildings, but also for the application of district heating networks. Decentralised CHP-plants are not very widespread in the EU.
District heating	District heating can be described as a system in which heat is produced centrally by one or more larger units and then transported through a network of pipes to the final user. In Europe, most district heat is used in the residential sector and more specifically for domestic hot water preparation and space heating. A wide range of energy inputs can be used to supply district heating systems, such as heat from CHP units (e.g. steam turbines, gas turbines, IC engines, waste-to-energy plants), heat-only plants (e.g. boilers, geothermal, heat pumps, solar thermal) or waste heat from industrial processes.
Technologies using electricity	
Electric radiators	Decentralised electric heating systems usually consist of radiators installed in each room. Rooms can also be equipped with electric floor heating systems. The heat is generated by electric resistances.
Heat pump - aerothermal	A heat pump is a device used to transfer heat energy from one source of heat (air, ground or water) to another destination for several end energy uses (space heating, water heating, cooling). Some devices are reversible. This kind of heat pump works in either thermal direction to provide heating or cooling. Aerothermal devices use energy from the ambient air (indoor or outdoor).
Heat pump - geothermal	Geothermal devices extract energy from the ground. Geothermal heat pumps have a higher efficiency than aerothermal heat pumps.
Solar collectors	Solar collectors convert sunlight into heat and are used for domestic hot water and space heating. Pezzutto et al., (2019) consider three collector technologies: unglazed collectors, flat-plate collectors and evacuated tube collectors. Glazed flat plate collectors are the most prevalent technology in Europe.

Data verification

To our knowledge Pezzutto et al., (2019) provides the only dataset that includes data on both the type of techniques and energy carriers per country. Although information in the database has been checked by the authors and our first sanity check showed that the data is reliable, the country cases indicated that final energy consumption data might be inconsistent with information provided by national statistical/energy organisations.
This could be (partly) due to differences in classification/definitions. In some cases we were able to improve the database, for example with respect to the energy mix used for CHP and district heating.

Given these data reliability issues, we decided to rely on Eurostat data as much as possible. This means that in Paragraph 3.2 we used Eurostat's final energy consumption data per energy carrier and only used the Pezzutto database on the distribution of heating techniques over the energy carriers used in the countries.

To verify the robustness of the data, we collaborated with local experts in each of the countries. An overview of the local data sources that were checked is shown in Textbox 8. Due to the limited availability and consistency between the local datasets, we determined that our constructed dataset based on Eurostat and Pezzutto et al. (2019) provided the best approximation while being consistent between countries.

Textbox 8 - Data verification on consumption by fuel and heating technique

In each of the four countries used as case study, a contact person helped us in locating data sources for the consumption of energy by technique and fuel type in households. Below an overview for each country is given.

Italy

Estimated data for Italy is confirmed to be a sufficient estimate by Italian partners.

Poland

Our dataset has been approved. There was some alternative information, published by the Polish National Statistical Office. Given its origin, the dataset might be considered as representative, even though the data is based on a survey of ~4,000 households (only 0.02% of total Polish households). However, the classification of the data was different from the data we use in this study, which made it quite difficult to compare. In order to guarantee a consistent approach and promote comparability between countries, we decided to use our dataset for the analysis.

Spain

Spanish data on the household energy consumption by technique and fuel is available from a report on the long-term strategy for energy renovation in the building sector from the government (ERESEE, 2020). The estimated total energy consumption is reasonably similar to the estimated data based on Eurostat data and the dataset by (Pezzutto, et al. 2019). In Spain, biomass stoves and boilers are predominant for space and water heating. Gas and oil boilers are a close second. At a lesser amount, electric boilers and radiators are used.

United Kingdom

Data on household energy consumption by fuel for the UK is available from the National Statistics division (UK Government, 2020). Consumption by technique is not available. The data on relative fuel consumption is fairly similar to the estimated dataset based on Eurostat consumption and the Pezzutto et al. dataset. Gas is in both datasets approximately 65% of total consumption. Electricity, renewables and oil are less predominant, followed by coal as a minor contributor to energy consumption.

Estimated energy consumption by technique and fuel

Table 16 shows the share of each technique-fuel combination in the total final energy consumption by households for domestic heating and cooking activities. The classification of energy carriers is based on Eurostat, (2018b). Table 17 gives more specifics. Renewable and biofuels consist of primary solid biofuels, ambient heat, solar thermal and biogas. It should be noted that there has been a public debate on the definition of renewables; whether wood/biomass can be considered as ‘renewable’ or not.

NB. The category ‘wood stoves’ is included as a fuel-technique combination, ‘open fires’ are not considered separately, following Pezzutto et al. (2019). We do not have sufficient data to distinguish between them in our analyses. As a consequence, we treat open fires as stoves, even though EMEP air emission factors for open fires are indeed higher for most pollutants. This means that emissions and associated health-related social costs of open fires are included through the category ‘wood stoves' , but are likely to be underestimated.

Table 16 - Relative heating and cooking energy consumption by technique-fuel combination (in % total)

Technique	Fuel	EU27+UK	Spain	Italy	Poland	UK
Condensing boiler	Oil	1.3%	0.8%	1.1%	0.0%	0.5%
Condensing boiler	Gas	5.8%	0.7%	9.5%	1.0%	4.5%
Non-condensing boiler	Oil	10.6%	25.0%	6.2%	0.7%	7.0%
Non-condensing boiler	Gas	35.2%	23.4%	45.7%	15.1%	69.6%
Non-condensing boiler	Coal	3.8%	0.6%	0.0%	35.6%	1.6%
Non-condensing boiler	Wood	8.8%	22.6%	0.3%	2.0%	0.0%
Stove	Wood	8.6%	2.3%	22.3%	12.3%	6.0%
Electric radiators	Electricity	5.6%	9.2%	1.3%	2.2%	6.4%
Aerothermal heat pump	Electricity	1.8%	1.4%	0.4%	0.1%	0.3%
Geothermal heat pump	Electricity	0.3%	0.0%	0.0%	1.1%	0.0%
Solar	Solar	0.9%	2.6%	0.6%	0.3%	0.2%
CHP	Electricity and heat	0.4%	0.2%	0.0%	0.0%	0.5%
District heating	Electricity and heat	10.3%	0.1%	4.9%	20.6%	0.2%
Cooking	Oil	0.8%	1.8%	0.8%	2.8%	0.0%
Cooking	Gas	2.2%	3.0%	5.4%	4.0%	1.8%
Cooking	Coal	0.0%	0.1%	0.0%	0.4%	0.0%
Cooking	Wood	0.4%	0.3%	0.3%	0.3%	0.0%
Cooking	Electricity	3.3%	5.9%	1.2%	1.5%	1.6%

Note: Own calculations based on Eurostat, (2018b) and Pezzutto et al., (2019).

Table 17 - Classification of fuels for cooking and heating and related energy consumption (in % total, 2018)

Fuel	Eurostat category	EU27+UK	Italy	Poland	Spain	UK
Coal	Solid fossil fuels	3.8%	0%	36.0%	0.7%	1.6%
Gas	Natural gas	43.0%	60.6%	20.1%	27.1%	75.9%
	Biogas	0.1%	0%	0%	0%	0%
Oil	Oil and petroleum products	12.7%	8.1%	3.6%	27.6%	7.4%
Electricity	Electricity	10.6%	3.5%	3.2%	15.4%	7.8%
Heat	Heat	8.9%	4.0%	21.1%	0%	0.8%
Solar	Solar thermal	0.9%	0.6%	0.3%	2.6%	0.2%
Heat pumps	Ambient heat (heat pumps)	2.2%	0.4%	1.1%	1.4%	0.3%
Renewables (wood)	Primary solid biofuels	17.6%	22.8%	14.5%	24.9%	6.0%
Other renewables	Unknown remainder of renewables	0.2%	0.2%	0.1%	0.4%	0.0%

Note: It is unknown what the fuel source is of ‘other renewables’ category. Therefore, we proportionally dived the related energy consumption over the known renewable categories (biogas, solar thermal, solid fossil fuels and ambient heat).

Total health costs divided over technique/fuel combination

Table 18 – Total health costs divided over technique/fuel combination (mln €, 2018)

Technique (fuel)	Direct or indirect	EU27+UK	Italy	Poland	Spain	UK
Solar thermal	indirect	0	0	0	0	0
CHP	indirect	31	0	0	1	6
Cooking (coal)	direct	114	0	42	14	0
Cooking (oil)	direct	121	17	13	15	0
Heat pumps	indirect	173	1	13	5	4
Cooking (electricity)	indirect	221	3	12	22	22
Cooking (gas)	direct	262	100	14	16	26
Condensing boiler (oil)	direct	290	39	0	10	14
Electric radiators	indirect	447	4	25	34	89
Condensing boiler (gas)	direct	460	116	2	3	42
Cooking (wood)	direct	522	77	15	22	0
District heating	indirect	821	14	237	0	3
Non-condensing boiler (oil)	direct	2,451	220	5	322	219
Non-condensing boiler (gas)	direct	2,804	562	36	81	656
Non-condensing boiler (wood)	direct	3,320	19	25	445	0
Non-condensing boiler (coal)	direct	7,905	0	2,477	79	531
Stove (wood)	direct	8,822	3,494	419	133	1,064
Total		**28,764**	**4,666**	**3,336**	**1,203**	**2,676**

Emission factors

Table 19 – Selected EMEP emission factors in the residential and public electricity sector (g/GJ)

Technique (Pezzutto)	Energy carrier	EMEP category (residential or public electricity sector)	CO	NH_3	NMVOC	NO_x	$PM_{2.5}$	SO_x
Boiler - condensing	Oil	Small (single household scale, capacity <=50 kWth) boilers [Gas Oil]	3.7	-	0.17	69	1.5	79
	Gas	Small (single household scale, capacity <=50 kWth) boilers [Natural gas]	22	-	1.8	42	0.2	0.3
	Coal	Small (single household scale, capacity <=50 kWth) boilers [Solid Fuel (not biomass)]	4,787	-	174	158	201	900
	Wood	Pellet stoves and boilers [Wood]	300	12	10	80	60	11
Boiler - non-condensing	Oil	Small (single household scale, capacity <=50 kWth) boilers [Gas Oil]	3.7	-	0.17	69	1.5	79
	Gas	Small (single household scale, capacity <=50 kWth) boilers [Natural gas]	22	-	1.8	42	0.2	0.3
	Coal	Small (single household scale, capacity <=50 kWth) boilers [Solid Fuel (not biomass)]	4,787	-	174	158	201	900
	Wood	Pellet stoves and boilers [Wood]	300	12	10	80	60	11
Stove	Oil	Stoves [Gas Oil]	111	-	1.2	34	2.2	60
	Gas	Stoves, Fireplaces, Saunas and Outdoor Heaters [Natural gas]	30	-	2	60	2.2	0.3
	Coal	Stoves [Solid Fuel (not biomass)]	5,000	-	600	100	450	900
	Wood	Average of: Advanced/ecolabelled stoves and boilers [Wood] and Energy efficient stoves [Wood]	3,000	37	300	87.5	231.5	11

Note: For electricity and derived heat, calculated emissions factors are used, see Table 20.

Table 20 - Emission factor for electricity and derived heat, case study countries and EU27+UK (g/GJ, 2018)

	NH_3	NMVOC	NO_X	$PM_{2.5}$	SO_X
EU27+UK					
Emission factor electricity + heat	0.42	3.41	73.15	2.75	57.20
Emission factor electricity	0.36	2.87	61.60	2.32	48.16
Emission factor heat	0.07	0.54	11.56	0.43	9.04
Italy					
Emission factor electricity + heat	0.11	2.24	25.34	0.29	7.95
Emission factor electricity	0.10	1.93	21.81	0.25	6.84
Emission factor heat	0.02	0.31	3.53	0.04	1.11
Poland					
Emission factor electricity + heat	-	2.91	184.86	8.60	287.90
Emission factor electricity	-	1.95	124.17	5.78	193.37
Emission factor heat	-	0.96	60.69	2.82	94.52
Spain					
Emission factor electricity + heat	1.47	9.92	71.65	4.32	71.87
Emission factor electricity	1.47	9.92	71.65	4.32	71.87
Emission factor heat	-	-	-	-	-
United Kingdom					
Emission factor electricity + heat	0.11	1.90	99.12	2.28	22.76
Emission factor electricity	0.11	1.90	99.12	2.28	22.76
Emission factor heat	-	-	-	-	-

Note: emissions factors based on current electricity and heat mix.

Energy derived from fully renewable sources such as solar, geothermal are assumed to have no emissions.

Environmental prices

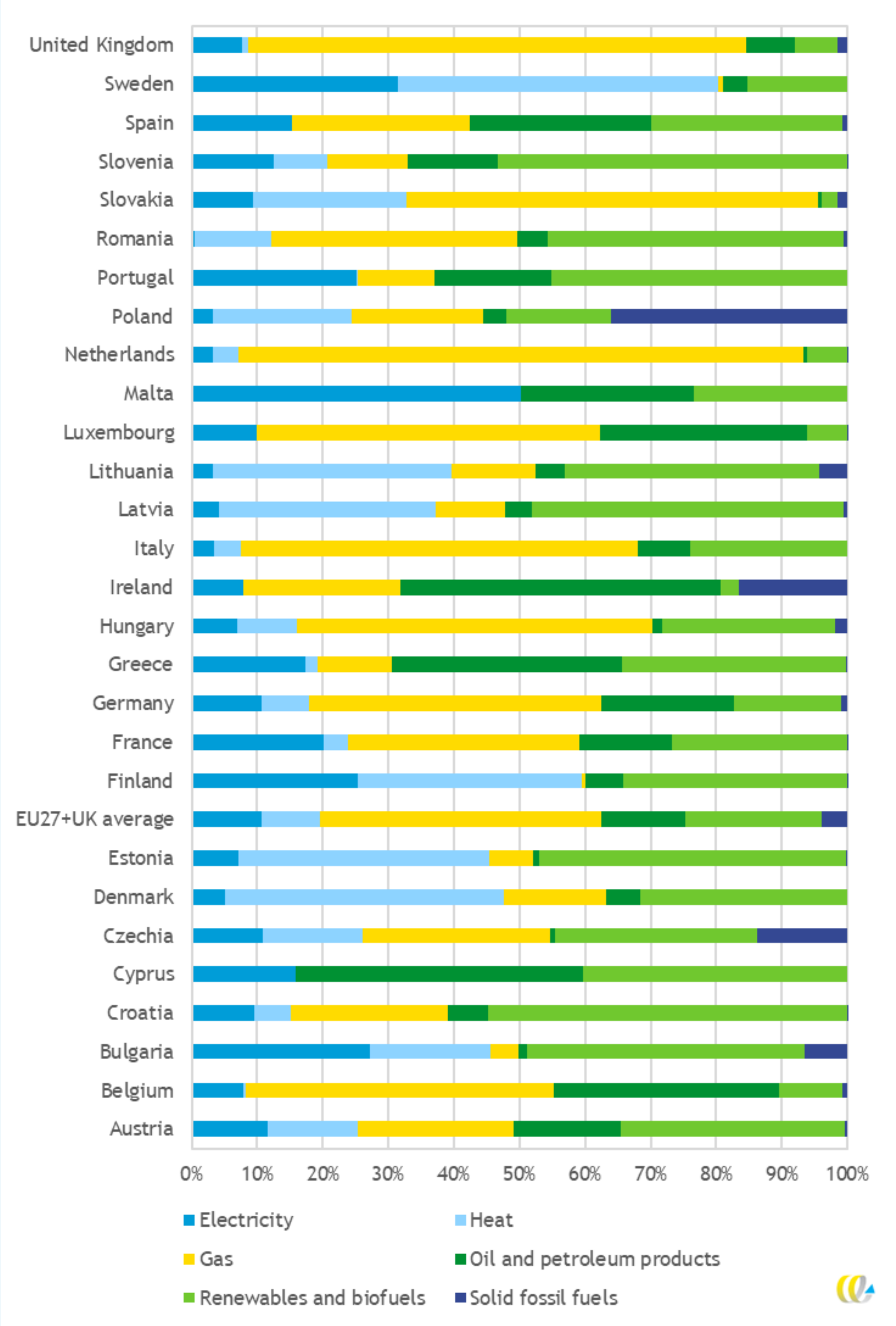
Table 21 - Environmental prices used for calculating health costs per technique-fuel combination

	CO	NMVOC	NO_X	$PM_{2.5}$	SO_2
EU27+UK	0.06	1.27	14.04	20.90	11.40
Italy	0.05	1.06	16.57	24.93	13.30
Poland	0.03	0.63	9.29	15.05	8.34
Spain	0.03	0.63	5.28	10.95	7.18
United Kingdom	0.06	1.27	9.18	22.77	10.35

Note: CH_4 and NH_3 are excluded, since no EMEP emission factors are available for the fossil fuel based technique-fuel combinations. The same holds for CO and NH_3 for electricity and derived heat techniques (see Table 19).

C Other data

Figure 25 - Share of fuels in the final energy consumption for domestic heating and cooking (%, 2018)



Source: Eurostat, (2018b).

Note: Heat covers CHP/district heating (derived heat). Renewables include heat pumps (ambient heat).

Figure 26 - Share of population living in urban or rural areas (%, 2018)

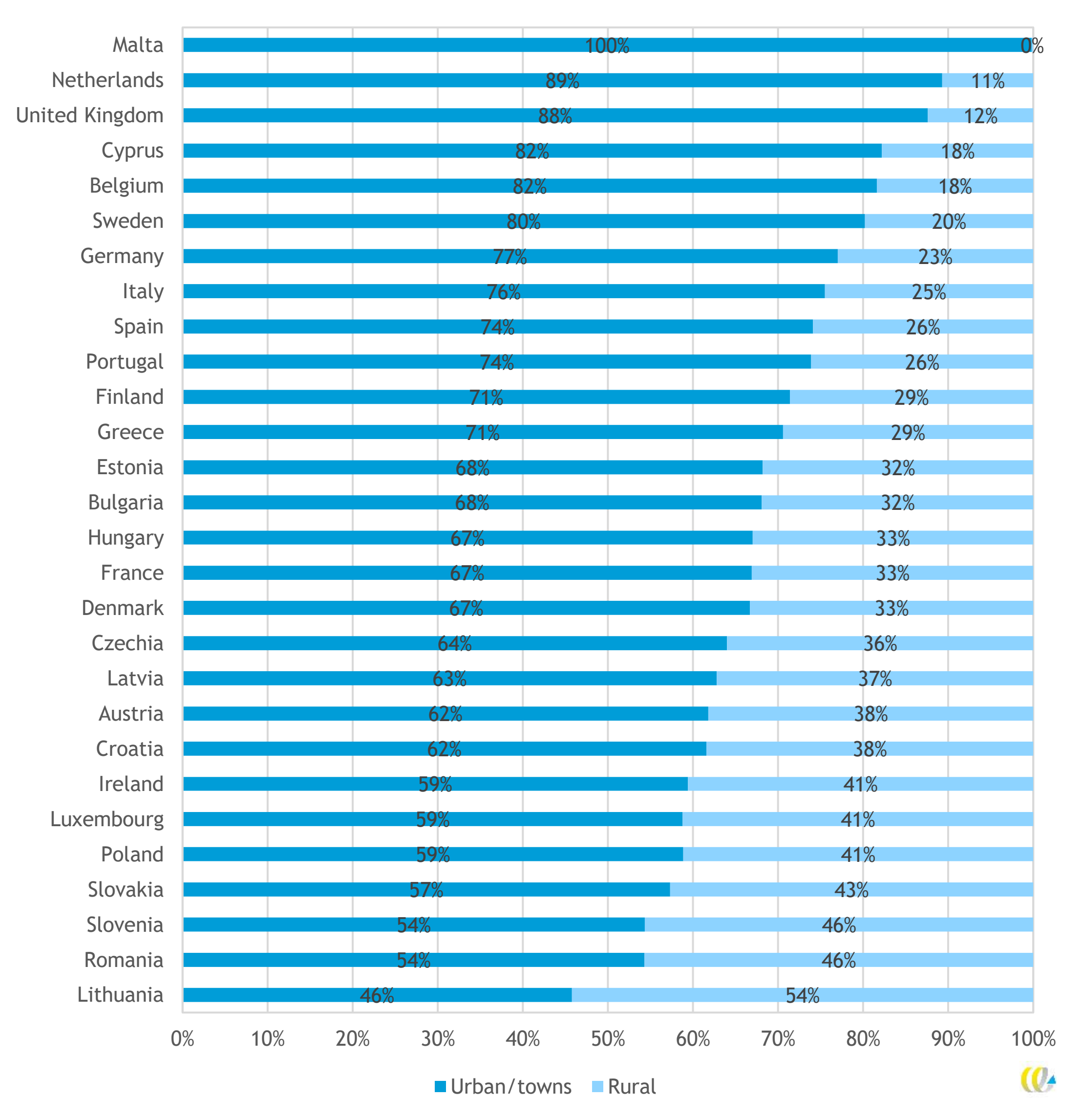
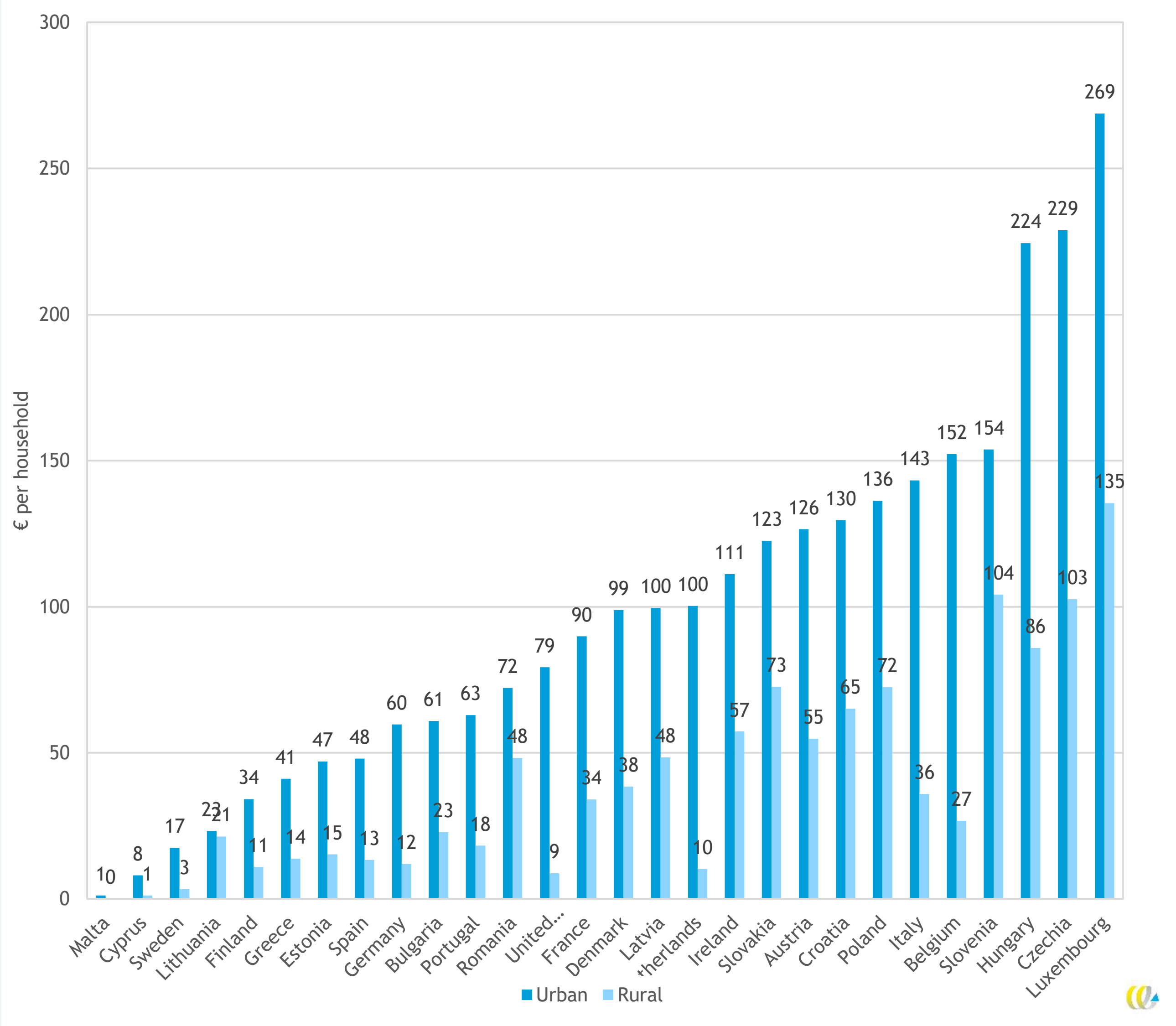


Figure 27 - Direct health-related costs per household in urban and rural areas in 2018



Note: This figure excludes the indirect costs. With indirect costs, it is unclear whether they occur in urban or rural areas, or even within the country.

In Luxembourg the health costs from pollution due to heating and cooking amount to 269 €/year/household in urban areas. Malta shows the lowest costs per household; the average household in an urban area suffers approximately € 1 per year due to pollution resulting from heating and cooking activities. The relative difference between health costs for urban and rural households differs substantially between countries. In countries such as Romania, Slovakia, Slovenia and Lithuania, the difference is limited. However, in for instance the Netherlands, UK, Belgium, Germany and Italy, the health-related impact per household is up to five to ten times higher in urban areas compared to rural areas.

Figure 28 - Total energy use for domestic heating and cooking (TWh, 2018)

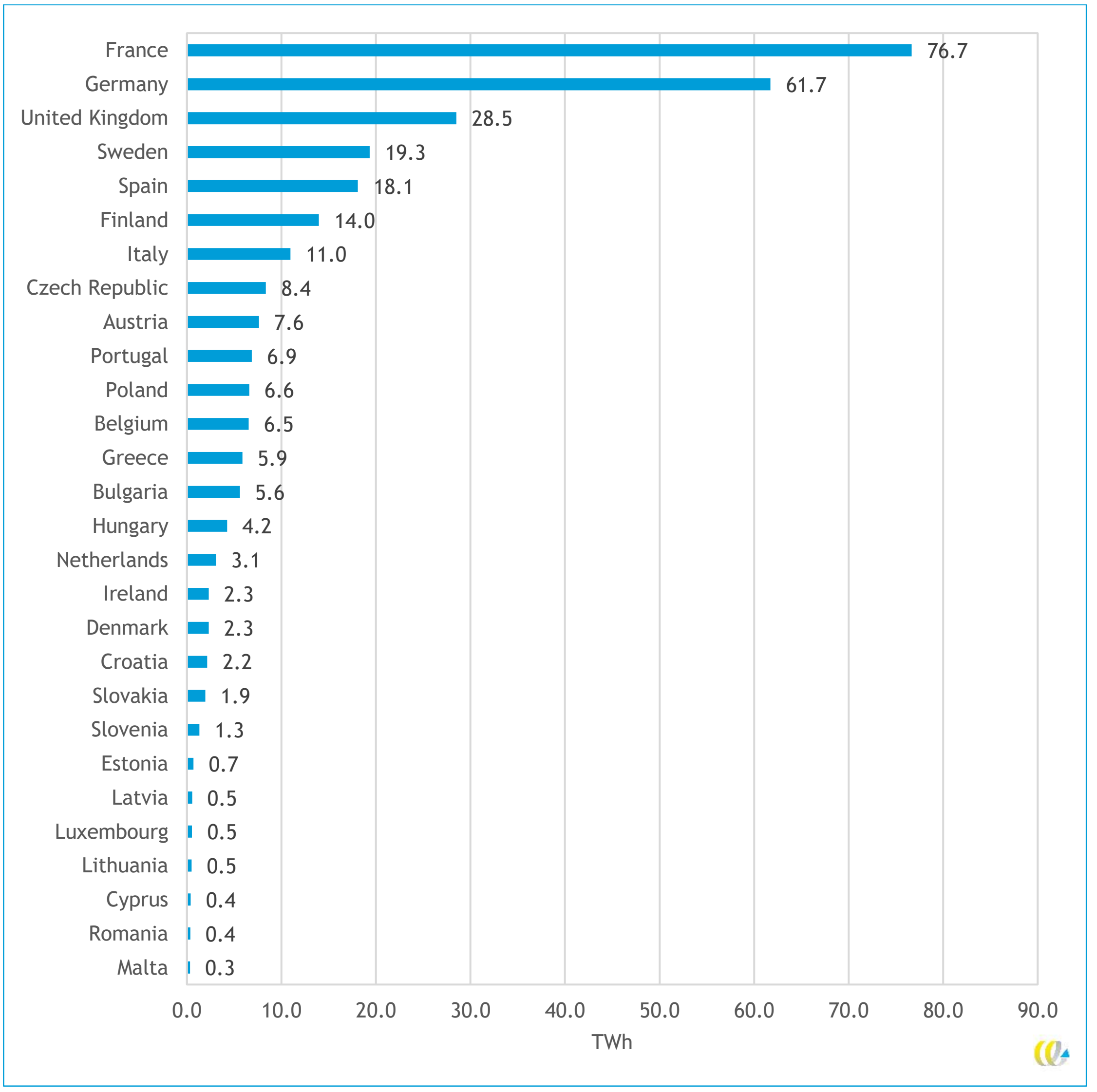


Figure 29 - Household energy use for heating and cooking (kWh/ household, 2018)

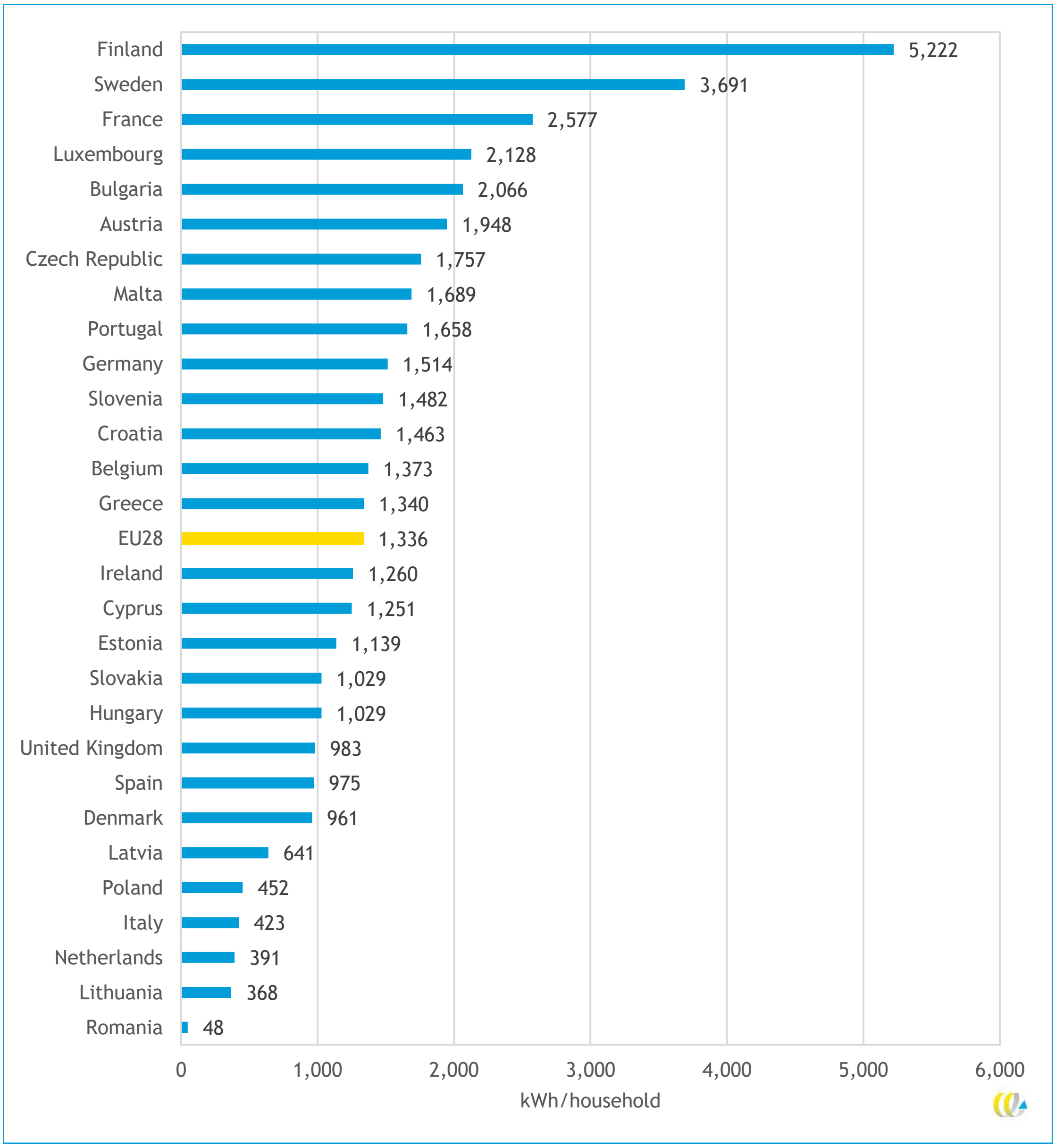


Figure 30 - Total indirect costs due to SO_2,NO_x, $PM_{2.5}$, NH_3 and NMVOC emissions from electricity and derived heat production used for heating and cooking, €/household 2018

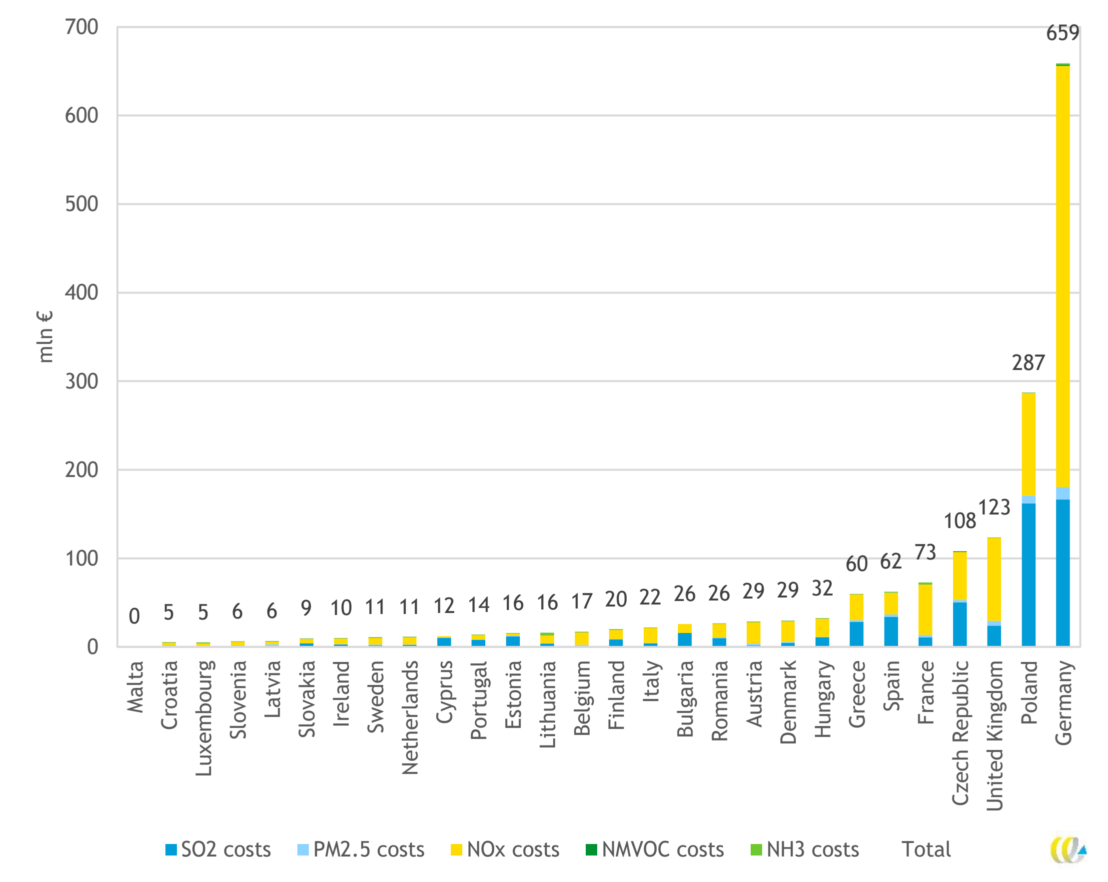


Figure 31 - Electricity production by source (%, 2018)

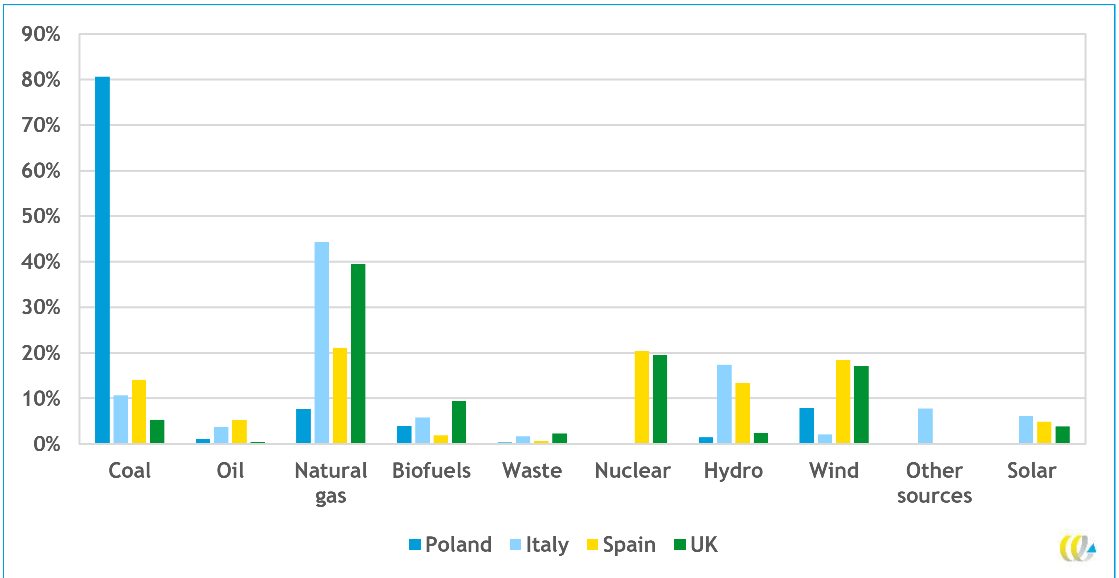


Figure 32 - Heat production by source (%, 2018)