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Residential heating with wood and coal:

health impacts and policy options in Europe and North America

Abstract

Residential heating with wood and coal is an important source of ambient (outdoor) air pollution; it can also cause substantial indoor air pollution through either direct exposure or infiltration from outside. Evidence links emissions from wood and coal heating to serious health effects such as respiratory and cardiovascular mortality and morbidity. Wood and coal burning also emit carcinogenic compounds. The results presented in the report indicate that it will be difficult to tackle outdoor air pollution problems in many parts of the world without addressing this source sector. A better understanding of the role of wood biomass heating as a major source of globally harmful outdoor air pollutants (especially fine particles) is needed among national, regional and local administrations, politicians and the public at large.

Keywords

AIR POLLUTION
BIOMASS
HEALTH POLICY
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Abbreviations and definitions[1]

BC	black carbon
BTU	British Thermal Unit
CCME	Canadian Council of Ministers of the Environment
CH_4	methane
CI	confidence interval
CO	carbon monoxide
CO_2	carbon dioxide
COPD	chronic obstructive pulmonary disease
CSA	Canadian Standards Association
DALY	disability-adjusted life-year
EC	elemental carbon
EC JRC	European Commission Joint Research Centre
EPA	United States Environmental Protection Agency
EU	European Union
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies [model]
GBD	Global Burden of Disease (Study)
HEPA	high-efficiency particulate air
IIASA	International Institute for Applied Systems Analysis
LPG	liquefied petroleum gas
NO_2	nitrogen dioxide
NO_x	oxides of nitrogen
NSPS	new source performance standard
OC	organic carbon
PAH	polycyclic aromatic hydrocarbon
PM	particulate matter
$PM_{2.5}$	PM with an aerodynamic diameter of less than 2.5 micrometres
PM_{10}	PM with an aerodynamic diameter of less than 10 micrometres
SO_2	sulfur dioxide
VOC	volatile organic compound

biomass	biodegradable products, waste and residues from agriculture, forestry, fisheries and related industries, as well as the biodegradable fraction of industrial and municipal waste
fossil fuel	carbon rich fuel other than biomass, including anthracite, brown coal, coke, bituminous coal and peat
hydronic heater	wood-fired boilers, often located outside the building (in a shed, for example) from which the heat is being generated and then circulated into the building as heat source
solid fuel	a fuel that is solid at normal indoor room temperatures, including biomass and coal
solid fuel boiler	a device with solid fuel heat generator(s) that provides heat to a water-based central heating system, with heat loss of <6% of rated heat output to its surrounding environment
solid fuel local space heater	an open fronted or closed fronted space heating device or cooker that uses solid fuels to emit heat by direct heat transfer with or without heat transfer to a fluid
woody biomass	biomass originating from trees, bushes and shrubs, including log wood, chipped wood, compressed wood in the form of pellets, compressed wood in the form of briquettes and sawdust

1 All definitions are taken directly or adapted from the draft European Commission Directive on requirements for solid fuel boilers (available at: http://ec.europa.eu/transparency/regcomitology/index.cfm?do=Search.getPDF&7YrbbCuiY/4ycAKX8F1akuCXCT-kEMvjCaXWhWTT3prm5SVAw47eF02NzJJLXFBE77kGvLzo2Pu5uyjPyPE0HGhn1Yyu8a5hceFqN5ixnqYI=, accessed 4 February 2015)

Executive summary

Wood, coal and other solid fuels continue to be used for residential cooking and heating by nearly 3 billion people worldwide at least part of the year, including many in Europe and North America. Residential heating with wood and coal is an important source of ambient (outdoor) air pollution; it can also cause substantial indoor air pollution through either direct exposure or infiltration from outside. The specific magnitude of the problem varies greatly by geography, prevalence of solid fuel use and the technologies used.

Across Europe and North America, central Europe is the region with the highest proportion of outdoor particulate matter with an aerodynamic diameter of less than 2.5 micrometres ($PM_{2.5}$) that can be traced to residential heating with solid fuels (21% in 2010). Evidence links emissions from wood and coal heating to serious health effects such as respiratory and cardiovascular mortality and morbidity. Wood and coal burning also emit carcinogenic compounds. Each year 61 000 premature deaths are attributable to ambient air pollution from residential heating with wood and coal in Europe, with an additional 10 000 attributable deaths in North America.

Measures are available to reduce emissions of solid fuels for residential heating in most places. Encouraging fuel switching (away from coal and other solid fuels) and use of more efficient heating technologies (such as certified fireplaces or pellet stoves) can reduce the emissions from residential wood and coal heating devices. Educational campaigns may also be useful tools to reduce emissions from residential solid fuel heaters. Furthermore, filters may reduce health effects from indoor air pollution.

Existing regulatory measures include ecodesign regulations and labels in the European Union (EU) and technology-based emission limits in the United States of America and Canada. Financial fuel switching and technology change-out incentives – as well as targeted "no burn" days and ecolabelling – are other tools available to policy-makers.

Given the substantial contributions to air pollution from residential heating with solid fuels, it will be difficult to tackle outdoor air pollution problems in many parts of the world without addressing this source sector. Nevertheless, the use of solid fuels for heating is expected to persist and probably even expand, especially within the EU, in the coming decades as a result of climate policies that favour wood burning. Better alignment is therefore needed between climate and air pollution policies in many countries. Information campaigns – especially those that increase knowledge about the energy efficiency of heating options – are encouraged.

1. Introduction and context

Residential heating is an essential energy service required by many people worldwide. Even with widespread availability of electricity and natural gas, the use of solid fuels for residential heating continues to be common practice in many places, including within European and North American countries. Solid heating fuels consist primarily of wood and coal but can also include forestry and agricultural residues and even garbage. Most fuels are burned in small-scale combustion devices, such as household heating stoves or small boilers for single houses, apartment buildings or district heating. Open fireplaces are popular in many parts of the developed world but do not actually provide net heating in most circumstances; they are therefore often characterized as for recreational use rather than space heating.

Currently, most burning of solid fuels for space heating is done in devices that incompletely combust the fuel owing to their low combustion temperature and other limitations. This results in relatively high emissions per unit of fuel, including many products of incomplete combustion such as $PM_{2.5}$ and carbon monoxide (CO) – two major air pollutants. Small-scale solid fuel combustion is also an important source of black carbon (BC) emissions. BC is a component of $PM_{2.5}$ that warms the climate. When coal is used for residential heating it can also result in emissions of sulfur and other toxic contaminants found in some types of coal; even with good combustion these contaminants are not destroyed.

The amount of heating fuel needed in a particular climate is dependent on the fuel efficiency of the stove, as well as the characteristics of the housing in which it is used (such as insulation infiltration – infiltration through the building envelope), an issue this publication does not address further. In developed countries nearly all space heating devices have chimneys; in some developing countries much space heating is done with open stoves inside the house. In both cases most of the emissions end up in the atmosphere and contribute to outdoor air pollution, which is the focus of this report (see Box 1).

Box 1. New WHO indoor air quality guidelines

WHO recently released indoor air quality guidelines for household fuel combustion (WHO, 2014a). The guidelines describe the household combustion technologies and fuels (and associated performance levels) needed to prevent the negative health effects currently attributable to this source of air pollution. Recommendations pertinent to household space heating include:

- setting emission rate targets (see the guidelines for specific target values) for both vented and unvented household stoves (for $PM_{2.5}$ and CO);
- encouraging governments to accelerate efforts to meet air quality guidelines, in part by increasing access to and encouraging sustained use of clean fuels and improved stoves, including maintenance and replacement of the stoves over time;
- preventing use of unprocessed coal as a household fuel, given that indoor emissions from household combustion of coal are carcinogenic to humans, according to the International Agency for Research on Cancer (IARC, 2010) – note that unprocessed coal is distinguished here from so-called “clean” or “smokeless” coal, for which less research on health effects has been done;
- discouraging household combustion of kerosene since there is strong evidence that heating with kerosene leads to indoor concentrations of $PM_{2.5}$, nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) that exceed WHO guidelines, and household use of kerosene also poses burn and poisoning hazards;
- encouraging governments to maximize health gains while designing climate-relevant household energy actions.

The dangers of coal burning for residential heating in cities in developed countries were slowly recognized over centuries, but a major policy response was triggered by the Great Smog of London in December 1952, which caused thousands of premature deaths within a short period (Brimblecombe, 2012) due to smoke from household heating with coal. Wood heating, while still a common practice even in some urban areas, has not received the same attention as coal, although it is also a major source of ambient air pollution during the heating season in nearly all parts of the world where wood is available (see Annex 1). For example, wood space heating was responsible for 11% of California’s annual average $PM_{2.5}$ and 22% of the state’s winter $PM_{2.5}$ emissions in 2012 (Air Resources Board, 2014). In the Helsinki Metropolitan Area, Finland, the contribution of wood heating to $PM_{2.5}$ emissions for the six-month cold season in 2005–2009 was 19–28% at urban and 31–66% at suburban monitoring sites (Saarnio et al., 2012).

Residential heating with wood is a sector in which $PM_{2.5}$ and BC emissions can potentially be reduced with greater cost–effectiveness than many other emission reduction options. Nevertheless, within Europe and North America only a few countries or states have set legal limits for minimum combustion efficiency or maximum emissions of PM and harmful gaseous compounds like CO and gaseous organic compounds (see section 6).

Parties to the United Nations Economic Commission for Europe's Convention on Long-Range Transboundary Air Pollution adopted emission reduction targets for $PM_{2.5}$ in participating countries in 2012. They decided to prioritize $PM_{2.5}$ mitigation measures, with a focus on BC reductions, primarily because of the strong climatic influence of BC and the opportunity to "provide benefits for human health and the environment" (UNECE, 2012).

Reasons for concern

The main reason for concern from residential heating using wood and coal is the effect it has on ambient air pollution and health. The types of fuel used for residential heating are an important determinant of both outdoor and indoor air quality in many countries. Burning solid fuel in homes produces more neighbourhood-level PM pollution than using electricity, gas or liquid fuels for heating. Burning conditions are often inefficient and household-level emission controls or regulations are often lacking.

WHO reports that 3.7 million premature deaths from exposure to ambient particulate air pollution occurred in 2012, including 482 000 in Europe and 94 000 in Canada and the USA (WHO, 2014b). Household use of solid fuels for heating is a contributor to this outdoor air pollution (see section 3).

Another reason for concern arises from climate and energy policies. Many countries in North America and Europe are actively encouraging residential heating with wood and other biomass (see Table 1). Biomass is touted, in some cases, as a renewable fuel that can assist with climate change mitigation and contribute to energy security. For example, the United Kingdom's Renewable Heat Incentive, introduced in 2014, explicitly includes payment to households using biomass boilers as part of the strategy to reduce the country's greenhouse gas emissions by 80% (from 1990 levels) by 2050 (Ofgem, 2014). Biomass fuels were also included in the European Commission's strategy for reaching the "202020" targets (20% reduction in greenhouse gas emissions, 20% of final energy consumption from renewable energy and 20% increase in energy efficiency by 2020), although much new biomass use in the EU has been for electricity production rather than household heating (ECF, 2010).

Table 1. Examples of government incentives and subsidies for residential heating with wood

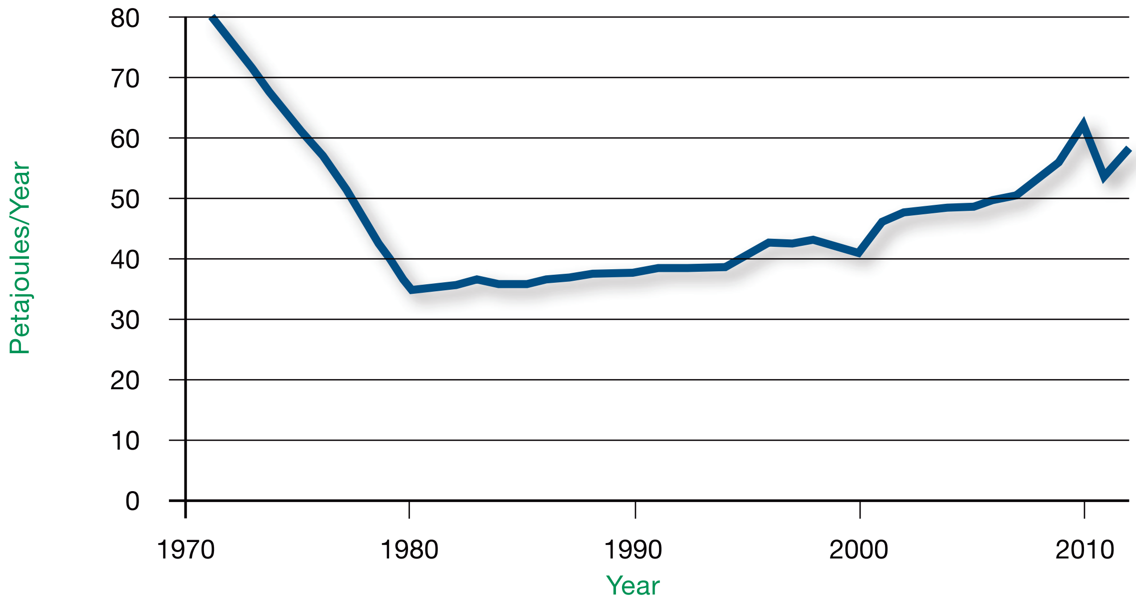
Country (scheme)	Incentive/subsidy	Notes on implementation
Denmark *(Incentive to scrap pre-1980 wood boilers)*	Grant of <€530 for households replacing old wood boilers with new boilers meeting an emissions limit (2008–2009)	3500 wood boilers have been replaced – about twice what would have been expected without the grant.
Germany *(Market incentive programme)*	Subsidy for installation of pellet boilers (over 150 kW) of >€2000 or €2500 when combined with solar panels	The programme is more than a decade old; designated funding has been adjusted downwards in some years.
Norway *(Ban on electrical and oil heating in new buildings; 40% of heat demand in new buildings must be supplied by non-grid electricity or non-fossil fuel energy)*	Subsidies of 20% for purchase of a new pellet stove (<€490) or new pellet boiler (<€1225)	The fund from which these subsidies come totalled €4.3 billion in 2013 and was managed in part by Enova SF, a state-run company.
United Kingdom *(2014 Domestic Renewable Heat Incentive)*	Household tariff from government of 12.2p (€0.15) per kW hour of energy generated when biomass boilers and pellet stoves used to heat home	As of August 2014 >1600 household biomass-fuelled home heating systems had been approved to participate in this programme.

Sources: IEA (International Energy Agency) (2013); Levander & Bodin (2014); Ofgem (2014).

Household wood combustion for heating seems to be rising in some countries thanks to government incentives and subsidies, the increasing costs of other energy sources and the public perception that it is a "green" option (see Table 1 and Fig. 1). As in many areas emissions from other sources (such as ground transportation, industry and power plants) are already controlled or legislation is in place to reduce them, residential biomass combustion is expected to gain prominence as a source of $PM_{2.5}$, especially if no efforts are made to encourage (or incentivize) use of modern and efficient residential wood-heating devices. The World Bank noted in 2013: "there is an urgent need to design and implement an effective approach to limiting black carbon emissions from home heating sources as their use continues to rise" (Pearson et al., 2013).

Further reasons for concern are economic downturns and fuel switching. Some families revert to heating with solid fuels (such as discarded furniture, wood scrap and coal) in response to economic hardship; this has happened recently in Greece and other European countries (Saffari et al., 2013). A 2012 study by the International Energy Agency concluded that, even in the absence of a global climate change agreement, biomass use in the residential energy sector will increase (quoted in Pearson et al., 2013). In the USA the number of households (especially low – and middle-income

Fig. 1. Residential use of wood in Finland, 1970–2012, according to national energy statistics



Note: A petajoule is 10^{15} joules.

Source: personal communication from Dr Niko Karvosenoja, Finnish Environment Institute (SYKE). Figure prepared on the basis of public data provided by Statistics Finland (2014).

households) heating with wood grew 34% between 2000 and 2010 – faster than any other heating fuel – and in two states the number of households heating with wood more than doubled during this period (Alliance for Green Heat, 2011).

Structure of the report

Motivated by the threat of increasing emissions from a push for more bioenergy combustion driven by renewable energy and energy security considerations and climate change mitigation policies (without proper consideration of health effects), this report addresses several concurrent factors:

- persistent levels of emissions from residential solid fuel combustion for heating (section 2);
- evidence of health effects from exposure to PM from this source sector in epidemiological studies (sections 3 and 4);
- measures available and policy needs to reduce emissions of solid fuel use for residential heating in most places (sections 5-8).

This publication does not represent a full systematic review of all relevant literature; the authors relied primarily on recent comprehensive reviews, reports and WHO guidelines to present a general policy-relevant overview of these topics. Seasonal space heating with wood is common in mountainous regions of many middle-income and poor countries – Chile and Nepal, for example – and coal is used for space heating in the parts of middle-income countries lying in temperate zones, such as Mongolia and China.

Owing to time and resource constraints, combined with the relative lack of data on usage and emissions in Asia and Latin America, however, this report focuses on Europe and North America (see Table 2).

Table 2. Focus of the report

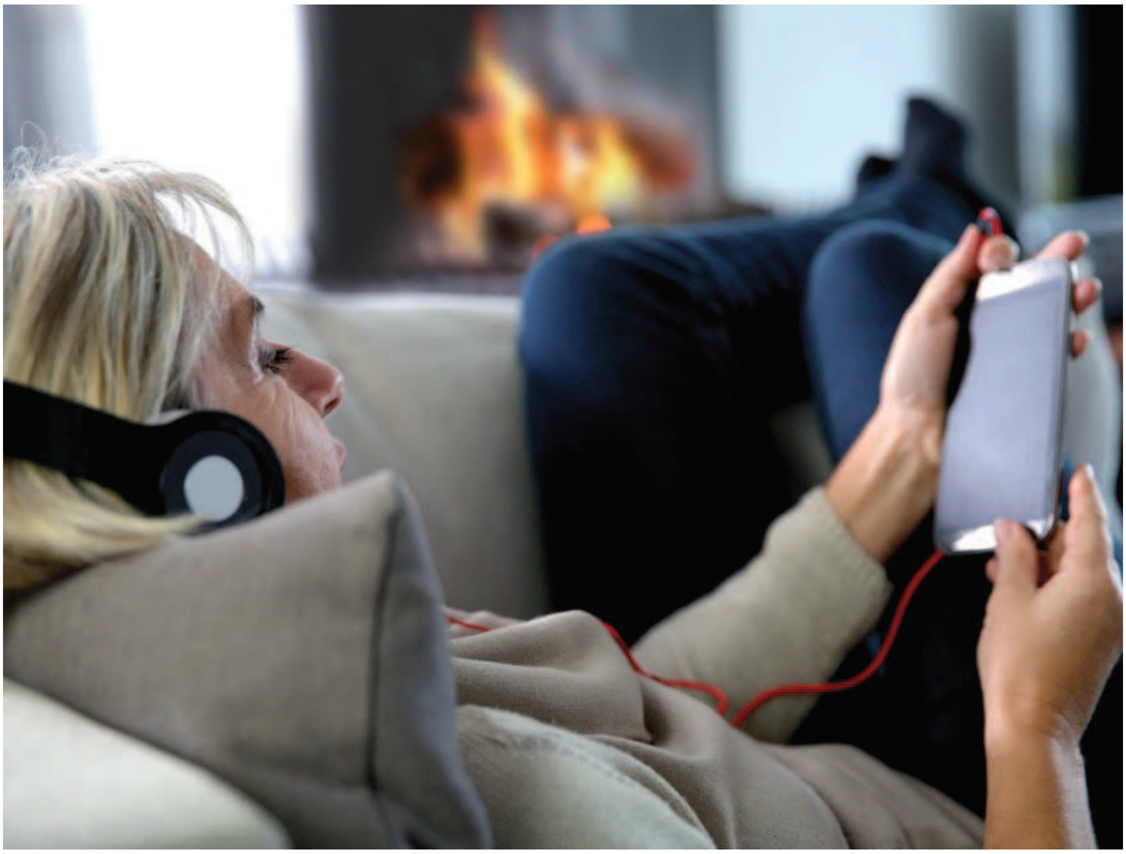
Category	Main focus	Less emphasis
Geographical scope (regions)	Europe and North America	Other countries where residential heating is required, including China and India
Type of fuel	Wood and coal	Other solid fuels, such as charcoal, peat, agricultural waste and garbage
Type of heating	Single-home residential heating	District heating
Type of exposure	Population-level exposure to ambient air pollution from heating appliances	Indoor (in-home) air pollution; emissions from cooking with solid fuels

2. Use of solid fuels for residential heating as a major source of air pollution

Residential heating with wood and coal is a significant source of ambient air pollution; it can also cause substantial indoor air pollution, through either direct exposure or infiltration from outside. The specific magnitude of the problem varies greatly by geography, prevalence of solid fuel use and the combustion technologies used. Nevertheless, use of solid fuels for heating is expected to persist and probably even expand within the EU in the coming decades as a result of climate policies that favour wood burning.

Residential combustion of solid fuels: a major source of $PM_{2.5}$

Worldwide, less than 10% of total ambient $PM_{2.5}$ (from both primary PM emissions and secondary PM formation) comes from residential heating stoves and boilers; about half of that comes from biomass heating, while most of the rest comes from household coal burning for heating (see Box 2). (These figures do not include district heating.)



Box 2. Residential heating with coal

Coal has been used for residential heating for centuries. In the 1960s coal and coke (a coal derivative) were the residential heating fuels of choice in Germany (84% of energy use in the residential sector) and France (68%), and were second only to oil in Denmark (33%) and Canada (22%). By the 1980s, however, residential coal/coke use was virtually nonexistent (<0.5%) in Canada, Norway and Sweden (Schipper et al., 1985). In the Netherlands coal was the major heating fuel in the 1950s and 1960s but disappeared from use by the mid-1970s, primarily due to domestically available oil and natural gas resources (Dzioubinski & Chipman, 1999).

In the USA 55% of homes used coal/coke for space heating in 1940, but this fell to 12% in 1960, below 5% in the early 1970s and below 1% from the early 1980s (Schipper et al., 1985; United States Census Bureau, 2011). One study estimates that reductions in the use of bituminous coal for heating in the USA from 1945–1960 decreased winter all-age mortality by 1% and winter infant mortality by 3%, saving nearly 2000 lives per winter month, including 310 infant lives (Barreca et al., 2014).

Coal typically requires a higher ignition and combustion temperature and has a higher content of sulfur and nitrogen than wood and other biomass. This means that residential coal combustion is a source of SO_2 and oxides of nitrogen (NO_x) (4% of SO_2 and 1% of NO_x emissions globally), as well as toxic pollutants adsorbed (adhering to the surface in an extremely thin layer) or absorbed to PM. In China (where residential coal combustion accounts for 7–8% of national SO_2 emissions) and some central European countries that use substantial amounts of coal for heating, the proportion can be much higher than average global emissions. To make matters worse, coals mined in certain geographical regions contain toxic elements (such as fluorine, arsenic, selenium, mercury and lead). Burning these types of coal in households has been associated with poisoning from the toxic compounds released during combustion.

Based on this and evidence that indoor emissions from household combustion of coal are carcinogenic to humans, the latest WHO indoor air quality guidelines strongly recommend against the residential use of unprocessed or raw coal, including for heating (WHO, 2014a). WHO currently makes no recommendation about the residential use of processed coal but calls for future research to examine the content of, emissions from and exposure to pollutants – including toxic contaminants – from the use of “clean” or “smokeless” coal.

While the residential sector as a whole represents about 40% of global anthropogenic $PM_{2.5}$ emissions, the majority of this portion (about 80% of the $PM_{2.5}$ produced directly by household combustion) comes from cooking rather than heating stoves in developing countries (see Box 3). In several specific regions of the world, however, residential combustion of solid fuels (biomass and coal) for heating makes a substantial contribution to total ambient $PM_{2.5}$ emissions, including Europe (13–21% in 2010, central Europe being the highest), the USA and Canada (10%) and central Asia (10%) (Chafe et al., in press) (see section 4).

Box 3. Residential cooking with solid fuels

Approximately 40% of the world's population – some 2.8 billion people – cook with solid fuels (Bonjour et al., 2013). The resulting household $PM_{2.5}$ air pollution, which shares the same constituents produced by residential heating with solid fuels, is associated with an estimated 3.5 million deaths per year. In addition, residential cooking accounts for approximately 12% of all outdoor $PM_{2.5}$ pollution worldwide (with a much higher proportion in some regions) and about 370 000 premature deaths each year from exposure to outdoor $PM_{2.5}$ pollution from this source worldwide (Chafe et al., 2014).

In two regions – east Asia (including China) and south Asia (including India) – a large proportion of $PM_{2.5}$ comes from both residential heating and cooking. When considered alongside their high population numbers, these two regions represent high-priority areas for shifting people away from residential solid fuel use and towards grid (electricity) connections or access to piped natural gas or liquefied petroleum gas (LPG).

Observed outdoor pollution levels from residential heating

In areas where wood combustion for residential heating is prevalent, studies have found relatively high short-term $PM_{2.5}$, PM with an aerodynamic diameter of less than 10 micrometres (PM_{10}) and volatile organic compound (VOC) concentrations.

In some places wood combustion is the major source of ambient $PM_{2.5}$, especially during the heating season (see Annex 1). Source apportionment studies, which identify the types of emission source contributing to measured air pollution levels, generally indicate that wood combustion accounts for 20–30% of local heating-season ambient $PM_{2.5}$ levels, although this estimate varies greatly by location. For example, a study in Italy found that in 2008 residential heating with wood caused 3% of PM_{10} in Milan, 18–76% in seven other urban areas and 40–85% in three rural areas (Gianelle et al., 2013).

In Austria during the winter months of 2004 wood smoke caused about 10% of PM_{10} near Vienna and around 20% at rural sites in two densely forested regions (Salzburg and Styria) (Caseiro et al., 2009). A study in a small village in the Czech Republic – where the only major wintertime source of particulate air pollution was residential combustion of wood, coal and household waste – found that average winter PM_{10} was higher in the village (around 40 μg/m^3) than in Prague (around 33 μg/m^3) in 1997–1998 and 1998–1999 (Braniš & Domasová, 2003).

In Seattle 31% of $PM_{2.5}$ measured at an outdoor monitoring site close to residential areas was apportioned to wood combustion and other vegetative burning (Kim & Hopke, 2008). During heating season the contribution has been as high as 62% at neighbourhood measurement sites (Larson et al., 2004).

Role of infiltration

Since residential wood combustion, by its nature, occurs in residential areas in close proximity to where people live, there is high potential for elevated exposure via emissions from a household's own appliance and/or those of neighbouring homes. Such exposure largely occurs indoors (due to indoor emissions from wood burning and infiltration of dirty ambient air), especially during the winter. A household with wood-burning appliances is likely to be surrounded by other homes with wood-burning appliances, and wood burning also tends to aggregate temporally; thus, on cold evenings and nights most homes in the area may be burning wood.

Given that most wood burning occurs in cold locations where homes are well insulated, buildings are expected to have low infiltration (meaning that relatively small amounts of outdoor air pollution, including wood-burning smoke, enter the house and contribute to indoor air pollution), especially during the heating season. Comparisons in European cities, however, do not show a strong relationship between annual climate and annual average infiltration: the infiltration rate does not vary much according to the climate when averaged over a year (Hoek et al., 2008).

In North America heating-season outdoor temperature is an important determinant of infiltration, and infiltration levels are generally lower in the heating than the non-heating season, when doors and windows are likely to be open more (Allen et al., 2012). In British Columbia the mean infiltration fraction of $PM_{2.5}$ in winter was found to be 0.28, compared to 0.61 in summer, although infiltration factors for individual homes in winter ranged from 0.1–0.6 (Barn et al., 2008); another study reported similarly low mean infiltration levels of 0.32 ±0.17 during the winter (Allen et al., 2009). Combustion of wood in residential areas and often under cold, calm meteorological conditions can nonetheless lead to high exposure compared to other pollution sources, owing to the principle of intake fraction (see Box 4).

Box 4. Intake fraction

Intake fraction describes the fraction of released emissions inhaled by humans; it is expressed in terms of the proportion of a pollutant taken in by humans of a given amount of a pollutant emitted. This fraction is dependent on the proximity of the population to the emitting source (and thus potential for dilution) and the density of the population exposed to the source (Bennett et al., 2002).

An analysis for the urban area of Vancouver, Canada, indicated a high intake fraction for wood smoke during the heating season (Ries et al., 2009), in part driven by the high population density in areas where wood was burned. Winter intake fractions of 5–13 per million were estimated, which is similar to estimated intake fractions for traffic emissions in North America. An analysis of the wood smoke intake fraction conducted for the entire population of Finland, however, reported a considerably lower intake fraction (2.9 per million compared to 9.6 per million for traffic sources), probably due to lower population density (Taimisto et al., 2011).

Indoor pollution levels

Modern wood stoves and fireplaces, when operated according to the manufacturers' instructions, release some PM and gaseous pollutants directly into indoor air, although in most cases the evidence for substantial indoor emissions from these modern stoves is very limited. With poor operation, poor ventilation or backdrafting, however, elevated concentrations of combustion products (such as PM, CO, VOCs, NO_x and aldehydes) may result indoors. Acute CO poisoning, which can sometimes even be fatal, may occur due to indoor emissions of wood combustion products when ventilation of the wood-burning appliance is not managed properly. In some situations exposure to ultrafine particles (PM with a diameter of less than 100 nanometres) may be high as well.

Indoor wood combustion sources are often closer to recipients than some outdoor sources; as a result, the intake fraction is higher. The composition of particles is different because of the shorter mixing time for atmospheric reactions and the typically higher indoor than outdoor temperatures. Exactly how these factors modify exposure and subsequent health effects is unclear.

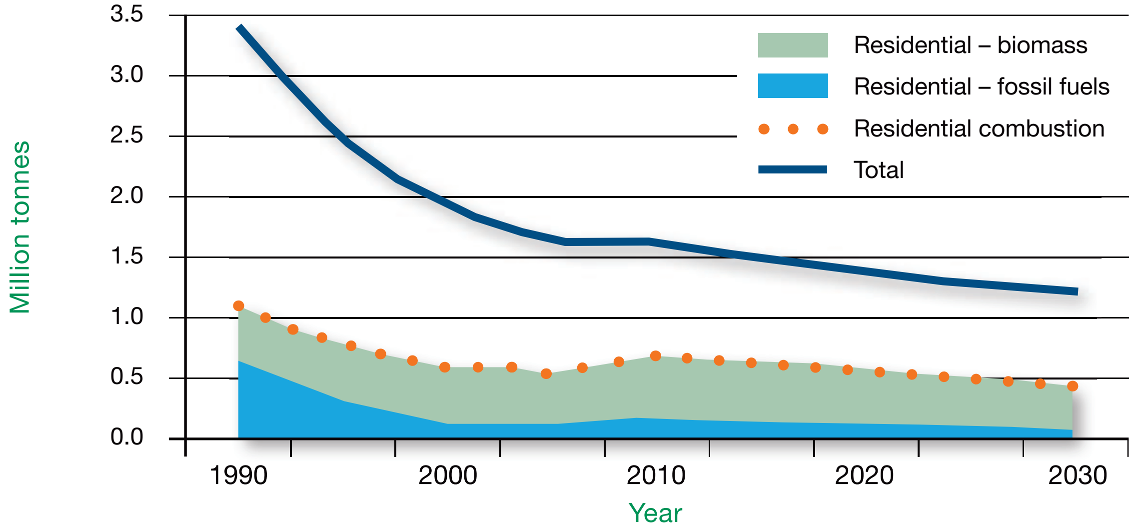
Residential heating emissions compared to other sectors

The fraction of total $PM_{2.5}$ emissions due to residential heating with solid fuels greatly increased in many regions between 1990 and 2005. This was due partly to much increased use of biomass fuels and partly to a reduction in emissions from other sources like industry, power plants and ground transportation in Europe and North America. This last sector has historically generated a significant amount of $PM_{2.5}$ (now partially controlled) and continues to be a major source of air pollutants, including those that contribute to the formation of tropospheric ozone (Chafe et al., in press).

Future trends in residential biomass emissions

In general, if current trends continue, the relative contribution of primary $PM_{2.5}$ emissions from biomass combustion for household heating are expected to increase in the future, although declining in absolute terms (see Fig. 2).

Fig. 2. Emissions of $PM_{2.5}$ from residential sources in the EU-28, 1990–2030

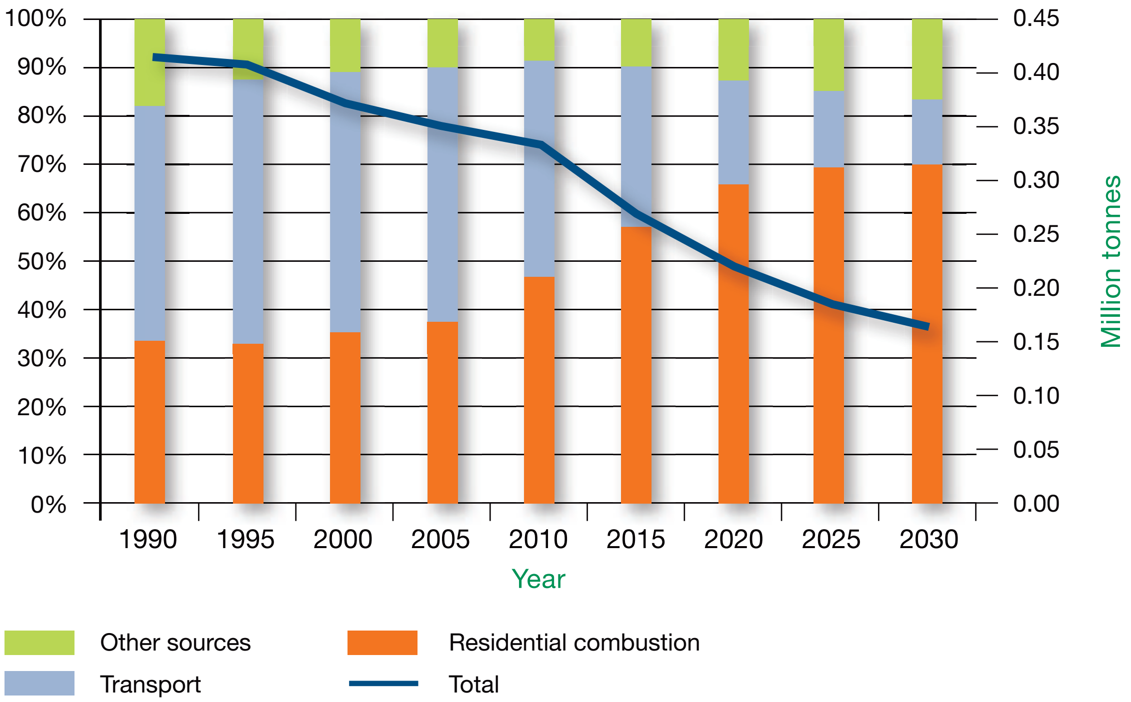


Notes: EU-28 is countries belonging to the EU after July 2013; current legislation scenario as in Amann et al. (2014), using the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model (Amann et al., 2011).

Source: reproduced with permission from the International Institute for Applied Systems Analysis (IIASA).

The reasons for this include the push for climate change mitigation (with biomass considered a renewable fuel under some climate policies), the potential for economic hardship to increase dependence on solid fuels, slow adoption of state-of-the-art technologies and the lack of strong incentives for exchanging current inefficient stoves and boilers. These $PM_{2.5}$ emissions include BC, which is a potent climate-warming substance (see Fig. 3). The net warming impact of BC-emitting sources, however, depends on the concurrent emissions of cooling aerosols, such as organic carbon (OC).

Fig. 3. Baseline BC emissions from the common major sources in the EU-28, 1990–2030



Note: EU-28 is countries belonging to the EU after July 2013; current legislation scenario as in Amann et al. (2014), using the carbonaceous particles module (Kupiainen and Klimont, 2007) of the GAINS model (Amann et al., 2011).

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Most residential stoves and boilers in use today are relatively inefficient, compared to the best models available for sale. Under ideal burning conditions, all the carbon in wood and other types of biomass, coal, kerosene, LPG, natural gas, diesel and gasoline would be completely converted to carbon dioxide (CO_2) while releasing energy. This is known as 100% combustion efficiency. Unfortunately, combustion efficiency of simple household stoves burning solid fuels is generally much lower than 100% (WHO, 2014a).

The less than ideal combustion conditions in most household fireplaces and stoves – including low combustion temperatures, suboptimal air circulation/oxygen availability, overloading of the firebox with wood, moist biomass fuel, and heat loss – cause emissions of harmful PM and gaseous compounds often referred to as "products of incomplete combustion". (see Box 5).

Box 5. Constituents of pollution from residential biomass and coal combustion

Particles: $PM_{2.5}$, BC, OC

$PM_{2.5}$ is one of the major air pollutants produced by burning solid fuels. Fine particles are generally considered to a good indicator of the health impacts of wood combustion sources: they have been the most broadly studied and are the focus of most emissions regulations.

BC is one constituent of $PM_{2.5}$ that has been associated with adverse health effects (see section 3) and is recognized as an important short-lived climate forcer (Bond et al., 2013; Janssen et al., 2012). (See section 8 for more on the climate implications of residential solid fuel use for heating.) As emissions from wood stoves or long-wood burners cool or “age”, a series of gaseous hydrocarbons adsorb onto the BC. When used correctly to optimize airflow, pellet stoves produce a much lower level of BC and polycyclic aromatic hydrocarbons (PAHs) than conventional wood stoves (Eriksson et al., 2014).

OC is another PM component that is emitted directly from combustion of many solid fuels; it also forms as a secondary pollutant. The organic and some inorganic emissions undergo rapid physicochemical transformation, followed by more delayed reactions in the atmosphere (Kocbach Bølling et al., 2009; Naeher et al., 2007). The speed of many reactions depends on the availability of sunlight (ultraviolet radiation) and on atmospheric temperature, which means that they are much slower in the cold and dark heating season than in the much brighter warm season of the year. In contrast to BC, which is light in colour, OC aerosols tend to be cooling for the climate.

Even as combustion efficiency of small-scale heaters is improved, the amount of BC emitted from a given amount of fuel will remain nearly constant. More complete combustion, however, will result in a much smaller amount of organic compounds and an increase in inorganic salts such as potassium sulfates, chlorides and carbonates and zinc, depending on the type of biomass (Larson & Koenig, 1994; Lighty et al., 2000).

Gases: CO, NO_x, PAHs, SO_2, VOCs

Wood (and other biomass) smoke also contains gaseous air pollutants linked with a range of potential health outcomes like CO, NO_x and VOCs such as acrolein, formaldehyde, benzene, gaseous and particulate PAHs, as well as other organic compounds including carboxylic acids, multiple saturated and unsaturated hydrocarbons, aromatics, PAHs and oxygenated organic compounds such as alhedydes, quinones, phenols and organic acids and alcohols. Combustion of biomass that contains chlorine, for example, which has been treated or transported via saltwater, can also emit chlorinated organic compounds. Burning coal often causes emission of SO_2 owing to its potentially high sulfur content (see Box 2).

Box 5. Contd

Levoglucosan

Levoglucosan is a tracer of biomass combustion and is often used as an indicator to determine exposure to biomass fuels or for source apportionment research. While it has proved useful as a marker of biomass combustion, more research is needed to evaluate the quantitative relationship between levoglucosan levels and PM mass concentration, given scenarios involving different wood types and combustion devices (Mazzoleni et al., 2007).

Other emissions

Burning coal can release elements and compounds that are particularly harmful to human health, such as fluorine, arsenic, selenium, mercury and lead; burning coal at the household level can release these into the indoor environment (see Box 2). When economic conditions are acutely bad, people often resort to burning furniture, plastics and garbage. Combustion of these products causes emissions that are of special concern to human health, such as dioxins and lead.

3. Health effects of solid fuel heating emissions

Evidence links emissions from wood and coal heating to serious health effects. Both short-term and long-term exposures to wood and coal smoke are harmful to health: they contain cancer-causing compounds and appear to act in the same way as PM from other sources. Respiratory problems are a common concern associated with exposure to wood smoke. Recent studies suggest that exposure to wood and coal smoke may also harm cardiovascular health. Studies of other biomass burning (such as forest fires) can help improve understanding of the health effects of residential wood burning.

Short-term exposure to particles from wood combustion appears to be as harmful to health as exposure to particles from the combustion of fossil fuels. At least 28 pollutants present in smoke from solid fuel use have been shown to be toxic in animal studies, including 14 carcinogenic compounds and four cancer-promoting agents (Smith et al., 2014). Undifferentiated PM was recently declared carcinogenic by the International Agency for Research on Cancer, including from household combustion of coal and household use of solid fuels (Loomis et al., 2013). The results of studies such as these were taken into account in the development of the WHO indoor air quality guidelines (WHO, 2014a; see Box 1) and are summarized in their supporting documents.

Several approaches have been taken to understand the effects of solid fuel heating emissions on human health. These include epidemiological studies that track the health effects of air pollution in human populations, studies of other biomass burning such as forest fire smoke and toxicological and clinical exposure studies.

Epidemiological studies

Hundreds of epidemiological time-series studies, conducted in different climates and populations, link daily increases in outdoor PM concentration with increased mortality and hospitalization. Long-term (years) PM exposure appears to influence health outcomes more strongly than short-term (days) exposure, although fewer studies have been done on longer-term exposure. Exposure to PM leads not only to acute exacerbation of disease, these studies suggest, but may also accelerate or even initiate the development of chronic diseases (WHO Regional Office for Europe, 2013). Long-term high-level exposure to wood smoke in low-income countries has been associated with lower respiratory infections (including pneumonia) in children; chronic obstructive pulmonary disease (COPD), reduced lung function and lung cancer in women; stillbirths and low birth weight of newborn babies (Smith et al., 2011; WHO, 2014a).

Although relatively few studies on the health effects of residential wood combustion specifically in developed countries have been undertaken, there is evidence of an association between wood combustion and respiratory symptoms. Ambient levels of particulate air pollution from wood combustion appear to be associated with exacerbation of respiratory diseases – especially asthma and COPD (Gan et al., 2013) – and including bronchiolitis (Karr et al., 2009) and otitis media (beginning as upper respiratory infection) (MacIntyre et al., 2011). A review of the health effects of particles from biomass combustion concluded that there was no reason to consider PM from biomass combustion less harmful than particles from other urban sources, but that there were few studies on the cardiovascular effects (Naeher et al., 2007). Recent epidemiological studies suggest that short-term exposure to particles from biomass combustion is associated with not only respiratory but also cardiovascular health (McCracken et al., 2012; WHO Regional Office for Europe, 2013).

Learning from other types of biomass burning

The health effects of ambient PM exposure from residential wood combustion can be assumed to resemble those of open biomass burning – including forest, brush and peat fires – because of the similar fuels. In many studies wildfires have been associated with severe respiratory effects, including:

- increased rates of respiratory hospital admissions and emergency room visits (Arbex et al., 2007; Duclos & Sanderson, 1990; Hanigan et al., 2008; Jacobs & Kreutzer, 1997; Johnston et al., 2007; Mott et al., 2005; Ovadnevaité et al., 2006);
- eye irritation and respiratory symptoms, such as cough and wheezing among children and teenagers (Kunii et al., 2002; Mirabelli et al., 2009);
- increased use of COPD medication and decreased lung function from PM exposure (Caamano-Isorna et al., 2011; Jacobson et al., 2012).

People with asthma or COPD seem to be especially threatened. A review of the respiratory effects of wildfires found an association between respiratory morbidity and exposure to bushfire smoke, which is consistent with the associations found with urban air pollution (Dennekamp & Abramson, 2011). Smoke from landscape fires causes an estimated 339 000 deaths annually (Johnston et al., 2012).

Burning of agricultural residues also seems to produce respiratory effects. In Winnipeg, Canada, a group of people with mild to moderate airway obstruction reported symptoms (cough, wheezing, chest tightness, shortness of breath, breathing trouble) during a smoke episode caused by burning of straw and stubble (Long et al., 1998). Burning of residues from rice farming in Iran was associated with increased prevalence of, among others, asthma attacks, use of asthma medication, cough and decreased lung function (Golshan et al., 2002).

Few studies have been done on the effects of long-term or prenatal exposure to residential wood smoke in developed countries. Exposure to wood smoke during pregnancy (number of days), however, was associated with small size for gestational age (Gehring et al., 2014); exposure to wildfire smoke during pregnancy slightly reduced average birth weight in infants (Holstius et al., 2012).

Toxicological and clinical exposure studies

The particles in wood smoke cause harm to human health through oxidative stress, direct cellular toxicity, impaired renewal of damaged cells, lung damage with secondary inflammation and genotoxicity (causing increased risk of respiratory cancer). Pulmonary inflammation may further lead to systemic inflammation. Particulate PAHs and their derivatives may cause many of these effects.

Fewer controlled human exposure studies have focused on residential wood combustion than have examined the effects of $PM_{2.5}$ or PM_{10} exposure from diesel engine exhaust. The particulate concentrations used in these studies (200–500 µg/m^3 $PM_{2.5}$ or PM_{10}) correspond to the highest hourly levels measured during wintertime temperature inversions in suburban residential areas of developed countries, where wood is used as the primary and secondary fuel for heating homes. Only one peer-reviewed journal paper provides data on $PM_{2.5}$ or PM_{10} at more than one exposure level (Riddervold et al., 2011). Comparison of results is hampered by inconsistent protocols. Different burning phases (start-up, optimal burning and burnout phases) may result in differences in exposure, and different handling of the burning device may alter exposure and possibly effects.

Experimental exposure of mainly healthy volunteers to diluted wood smoke aerosol (simulating high ambient outdoor $PM_{2.5}$ or PM_{10} concentrations found in densely populated wood-burning areas) has occurred in only a few controlled clinical studies, most lasting one to two hours. A couple of peer-reviewed studies found mild irritation in the respiratory tract, while others documented lung inflammation and systemic inflammation in blood. None of the studies, however, showed a change in lung function. In particular, studies using healthy volunteers found that exposure to wood smoke was associated with:

- systemic inflammation and bronchial and alveolar inflammation (Ghio et al., 2012);
- increased tendency towards blood coagulation (Barregard et al., 2006);
- inflammation in distal (lower) airways (Barregard et al., 2008);
- increased upper airway symptoms (Sehlstedt et al., 2010);
- higher self-reported mucous membrane irritation (Riddervold et al., 2011).

Three-hour exposure to smoke from wood combustion, with intermittent exercise, caused an acute increase in stiffness of major arteries and heart rate (Unosson et al., 2013).

Health effects of BC

Wood smoke is rich in BC: biomass fuels combusted for household heating and cooking contribute an estimated 34–46% of total global BC emissions (Bond et al., 2013). A recent review (Janssen et al., 2012) of epidemiological, clinical, and toxicological studies reported sufficient evidence of both short-term and long-term health effects of BC. The researchers found associations between daily outdoor concentrations of BC and all-cause mortality, cardiovascular mortality and cardiopulmonary hospital admissions. In addition, another study found an association between long-term BC concentrations and all-cause and cardiopulmonary mortality in a single-pollutant model (Smith et al., 2009). BC itself may not be a major toxic component of $PM_{2.5}$, but it rather acts as an indicator of other combustion-originating toxic constituents. BC may carry a wide variety of chemicals to the lungs, the body's major defence cells and possibly the circulatory system. Reducing exposure to $PM_{2.5}$ that contains BC should lead to a reduction in the health effects.

4. The burden of disease attributable to ambient air pollution from residential heating with wood and coal

Across Europe and North America, central Europe is the region with the highest proportion of outdoor $PM_{2.5}$ that can be traced to residential heating with solid fuels (21% in 2010). Each year 61 000 premature deaths are attributable to ambient air pollution from residential heating with wood and coal in Europe, with an additional 10 000 attributable deaths in North America.

Household space heating with biomass-based solid fuels (wood, crop residues and similar) creates outdoor air pollution that in turn results in an important public health burden (both in terms of premature deaths and in healthy life-years lost) across many regions of the world. Europe is among the regions with the most serious challenges in this regard: the proportion of outdoor $PM_{2.5}$ caused by household space heating with wood and coal is especially high across many parts of Europe (see Table 3).

In 2010 an estimated 61 000 premature deaths in Europe were attributable to outdoor $PM_{2.5}$ pollution originating from residential heating with solid fuels (wood and coal) – about the same number as in 1990 (Chafe et al., in press). This represents 55% of all deaths worldwide that can be attributed to exposure to outdoor air pollution from residential heating with wood and coal. Outdoor air pollution from household heating with solid fuels also is estimated to be responsible for 1 million DALYs (see Box

Table 3. Residential heating contribution to outdoor $PM_{2.5}$ and burden of disease, selected regions, 1990 and 2010

Region	$PM_{2.5}$ from residential heating (%)		$PM_{2.5}$ from residential heating (µg/m³)		Premature deaths/year		Disability-adjusted life-years (DALYs)/year	
	1990	2010	1990	2010	1990	2010	1990	2010
Central Europe	11.1	21.1	3.5	3.4	18 000	20 000	370 000	340 000
Eastern Europe	9.6	13.1	2.0	1.4	24 000	21 000	480 000	410 000
Western Europe	5.4	11.8	1.3	1.7	17 000	20 000	280 000	290 000
High-income North America	4.6	8.3	0.9	1.1	7 500	9 200	140 000	160 000
Central Asia	9.9	8.3	2.4	1.6	5 500	4 200	180 000	110 000
Global	3.0	3.1	0.9	0.7	120 000	110 000	2 800 000	2 200 000

6) across Europe in 2010 (47% of the global total), down from 1.3 million DALYs in 1990.

In North America exposure to outdoor $PM_{2.5}$ pollution from residential heating with solid fuels resulted in 9200 deaths in 2010, an increase from 7500 in 1990. This pollution also caused 160 000 DALYs in 2010, up slightly from 140 000 in 1990. Reducing the use of biomass for space heating or reducing emissions through better combustion or pollution capture would lessen this burden.

Box 6. DALYs

DALYs are a combined unit composed of mortality (premature death) in the form of years of life lost plus morbidity (injury and illness) in the form of years of life lost to disability in order to fully understand the ill health caused by a risk factor or disease. In the case of morbidity, a disability weight is assigned to each year lived with a specific affliction.

Globally, Europe has the highest proportion of outdoor $PM_{2.5}$ emissions attributable to household heating with solid fuels at 12% of total $PM_{2.5}$ in western Europe, 21% in central Europe and 13% in eastern Europe in 2010. This corresponds to average population-weighted $PM_{2.5}$ concentrations of 1.7, 3.4 and 1.4 µg/m^3, respectively. In comparison, 8% of the total ambient $PM_{2.5}$ in North America (Canada and the USA) comes from household heating with solid fuels (1.1 µg/m^3).

Methodology

The analysis in section 4 combines energy use and emissions estimates from the GAINS model hosted by IIASA, secondary PM formation calculated with TM5-FASST software at the European Commission Joint Research Centre (EC JRC), and health impact data from the 2010 Global Burden of Disease (GBD) Study (Amann et al., 2011; IIASA, 2014; EC JRC, 2014; Lim et al., 2012). All ambient air pollution estimates are population weighted and account for other sources of PM, such as open biomass burning (forest fires, agricultural burning) and dust. Health impacts are estimated by taking a proportion of the total impacts from outdoor air pollution, based on the proportion of total air pollution attributable to residential solid fuel combustion for heating. This procedure is in line with the approach taken by the Global Energy Assessment (Riahi et al., 2012) and a World Bank report on the burden of disease from road transportation (Bhalla et al., 2014). Although health impacts are presented by region here, the health benefits of reducing exposure to outdoor air pollution will vary significantly by country as a result of background health and pollution conditions.

An important consideration is to what extent results from epidemiological studies on urban PM can be generalized to PM from residential wood combustion. In the WHO air quality guidelines (WHO Regional Office for Europe, 2006) it was concluded that there was little evidence that the toxicity of particles from biomass combustion would differ from the toxicity of more widely studied urban PM. This same approach was followed in the analysis presented in section 4 and in the recent GBD Study (Lim et al., 2012), in which all combustion particles, regardless of source, were considered to be hazardous depending on the exposure level. This was based on the integrated exposure response curves developed for the GBD Study, which linked exposures to combustion particles across four sources – ambient air pollution, secondhand tobacco smoke, household air pollution and active smoking – to the health outcomes ischaemic heart disease, stroke, COPD, lung cancer and child pneumonia (Burnett et al., 2014).

5. Interventions shown to decrease emissions, improve outdoor and indoor air quality and improve human health

Encouraging fuel switching (away from coal and other solid fuels) and use of more efficient heating technologies (such as certified fireplaces or pellet stoves) can reduce the emissions from residential wood and coal heating devices. Filters may reduce health effects from indoor air pollution. Educational campaigns may also be useful tools to reduce emissions from residential solid fuel heaters.

National, state/provincial and local regulatory agencies have implemented a large number of regulatory air quality management efforts targeted at reducing ambient concentrations of pollutants emitted from residential wood combustion. These include actions focused on fuel switching, combustion technology (stove exchange), introduction of district heating and in-home high-efficiency particulate air (HEPA) filtration and educational efforts addressing burning practices. Comparatively few studies have assessed the effectiveness of these actions, and only a subsection of these assess the resulting health benefits.

Fuel switching

One study in Ireland found that banning the marketing, sale and distribution of coal (specifically bituminous coal) improved both air quality and health, and reduced deaths from respiratory and cardiovascular causes. Average concentrations of black smoke (fine PM measured by its blackening effect on filters) in Dublin declined by 35.6 $\mu g/m^3$ (70%) when coal sales were banned; adjusted non-trauma death rates decreased by 5.7%. Respiratory deaths fell by 15.5% and cardiovascular deaths by 10.3%. About 116 fewer respiratory deaths and 243 fewer cardiovascular deaths were seen per year in Dublin after the ban (Clancy et al., 2002).

In a subsequent reanalysis the original authors concluded that the statistical approach did not adequately control for a downward long-term trend in mortality, and that the results were therefore biased away from the null; however, the reanalysis still showed a significant decrease in respiratory mortality (Dockery et al., 2013). The work also showed that, where the ban was extended to other Irish cities, significant improvements in air quality were detected, as were reductions in morbidity and mortality, especially for respiratory outcomes. As noted earlier (Box 2), the WHO indoor air quality guidelines for household combustion now strongly recommend against the use of unprocessed or raw coal as a household fuel (WHO, 2014a).

One successful intervention in Launceston, Tasmania, combined fuel switching (via replacement of wood stoves with electricity) with community education and enforcement of environmental regulations (Johnston et al., 2013) to reduce the proportion of households heating with wood from 66% to 30%. Wood heating accounted for 85% of PM emissions at the beginning of the 13-year study; mean wintertime PM_{10} dropped 39% (from 44 to 27 μg/m^3) with the interventions.

This improvement in air quality was associated with reductions in annual mortality, after adjustment for general regional improvements in health that were charted in a nearby location (Hobart) over the course of the study. In winter months only, borderline significant reductions in cardiovascular (–19.6%; 95% confidence interval (CI):–36.3% to 1.5%) and respiratory (–27.9%; 95% CI: –49.5% to 3.1%) mortality were observed. Larger and statistically significant reductions in all-cause (–11.4%; 95% CI: –19.2% to 2.9%), cardiovascular (–17.9%; 95% CI: –30.6% to –2.8%) and respiratory (–22.8%, 95% CI: –40.6% to 0.3%) mortality were also observed in males compared to the whole population.

Heater and wood stove exchanges

A successful community wood stove exchange programme in Libby, Montana, replaced 95% (n = 1100) of older (not certified by the United States Environmental Protection Agency (EPA)) wood stoves with EPA-certified appliances or other heating sources over the course of four years. Before the exchange, residential wood stoves contributed about 80% of ambient $PM_{2.5}$ in the airshed (part of the atmosphere that behaves in a coherent way with respect to the dispersion of emissions) in winter months. Compared to the pre-intervention winter, average winter $PM_{2.5}$ mass was reduced by 27% and source-apportioned wood smoke-related $PM_{2.5}$ by 28% (Ward & Lange, 2010; Ward et al., 2008; 2010; 2011). Lower ambient $PM_{2.5}$ was also associated with reduced likelihood of reported respiratory infections. Compared to a two-year baseline period established prior to the stove exchange, the intervention produced a 26.7% (95% CI: 3.0% to 44.6%) reduced odds of reported wheeze for each 5 μg/m^3 decrease in $PM_{2.5}$ in schoolchildren.

A source apportionment study conducted in Golden, British Columbia, found that wood smoke-associated source contributions to ambient $PM_{2.5}$ levels decreased by a factor of four following a wood stove change-out programme (Jeong et al., 2008). During the programme the proportion of homes

using advanced (EPA-certified) wood stoves increased from 25% to 41%. In the same period, however, there was an overall increase (from 29% to 32%) in homes using conventional wood stoves. Health outcomes were not studied.

Results of studies evaluating the impacts of stove exchanges on indoor air quality have been inconclusive. In Libby, Montana, all homes in which stoves were changed showed reductions in $PM_{2.5}$ concentrations (of varying magnitude), including a mean 71% decrease in 24-hour indoor $PM_{2.5}$ concentrations and decreases in concentrations of OC and levoglucosan (Ward et al., 2008). A substantial difference in ambient temperature between the pre- and post-exchange sampling, however, might have affected infiltration rates and general wood-burning behaviour within the community. To address these concerns and to assess longer-term impacts of the stove exchanges, a follow-up study was conducted in the two subsequent winters, with sampling designed to match the temperatures of the pre-exchange measurements (Noonan et al., 2012). In this analysis a crude 53% reduction in mean $PM_{2.5}$ was observed (mean reduction of –18.5 μg/m^3 (95% CI: –31.9 to –5.2)) when adjusted for ambient $PM_{2.5}$, ambient temperature and several other household factors that might influence indoor PM levels. Reductions across homes and years were highly variable, and a subset of homes did not experience a reduction in $PM_{2.5}$ following the stove exchange. Similarly to the initial study, reductions were observed for OC, elemental carbon (EC) and levoglucosan.

A small stove exchange on a Native American reservation in Idaho improved indoor air quality (39.2 ±45.7 μg/m^3 median pre-exchange to 19 ±47.5 μg/m^3 post-exchange), with a 52% reduction in median indoor $PM_{2.5}$ (Ward et al., 2011). As in the Libby studies, reductions in levoglucosan and other compounds were observed. Five of the 15 homes did not show evidence of improvements in indoor air quality.

Another small wood stove change-out study in northern British Columbia found no consistent relationship between stove technology upgrades (from conventional to EPA-certified wood stoves) and outdoor or indoor concentrations of $PM_{2.5}$ or levoglucosan in homes where the stoves were exchanged (Allen et al., 2009). Measurements were conducted in 15 homes during the same heating season before and after the change-out (including approximately a one-month period for participants to become familiar with their new stoves) and results were controlled for infiltration and ambient temperature.

Such change-out initiatives have potential limitations. The Canadian Council of Ministers of the Environment (CCME) – the association of environment ministers from the federal, provincial and territorial governments – evaluated 12 stove exchange and educational efforts conducted in Canada and concluded that exchange programmes may have limitations relating to both the cost of new technologies and the long service life of appliances once installed. The assessment supported the use of regulation effectively to curb the sale of high-emission appliances. This approach is used in a number of Canadian provinces and American states.

The Canadian National Collaborating Centre for Environmental Health found that emissions standards (based on best available technologies) are needed to ensure that the newer devices installed through change-out programmes are among the cleanest available in the marketplace. Without these standards, change-out programmes may, in fact, be lost opportunities to install the cleanest available wood-burning devices, which will be in use for years to come. The study also found that removal of conventional noncertified appliances (through exchanges, time limits or prior to the sale or transfer of a property) was the most effective strategy included in a model municipal by-law for mitigation of residential wood smoke (Environment Canada, 2006) (see “Other regulations and voluntary measures” in section 6).

District heating

District heating is a system for distributing heat generated in a centralized location for residential and commercial heating requirements such as space heating and water heating. It was introduced for health, efficiency and comfort reasons in Sweden in the 1940s, both to avoid the use of coke and sulfur-containing oil close to where people live in cities and towns and to support the production of electricity (combined heat and power production). It was estimated in the 1970s that levels of SO_2 were two to five times lower in towns where district heating was common compared to similar towns without district heating (Boström et al., 1982). Since then, heavy oil as a fuel has been abandoned because of sulfur, energy and carbon taxes. With stringent emission controls, a number of different fuels have been introduced – predominantly biofuels. Today, Swedish district heating and cooling is mainly based on the use of excess heat from the production of electricity or industrial processes; it is considered one of the most environmentally friendly ways to use biofuels. Other energy sources are also used, such as heat pumps that use heat from sea/river or sewage water.

The most common heating method in multifamily dwellings and nonresidential premises in Sweden is currently district heating. As a result of this and other changes, the ambient air concentration of soot in the second largest city, Gothenburg, has decreased from almost 50 μg/m^3 in 1965 to about 5 μg/m^3 in 1995 (Areskoug et al., 2000). Another example is from central Stockholm, where SO_2 levels were dramatically reduced from over 200 μg/m^3 in 1965 to below 25 μg/m^3 in 1990. The environmental aspects of district heating have been described in detail and it has been estimated that the total energy requirement for heating in the EU could be met by using excess energy from power production for district heating (Frederiksen & Werner, 2013).

HEPA filtration

While household or individual-level strategies are not typically part of air quality management programmes, two studies from Canada indicate that in-home HEPA filtration might reduce health impacts from wood smoke. An initial single-blind randomized crossover study of 21 homes during winter, in an area affected by residential wood combustion as well as traffic and industrial sources, reported a mean 55% (standard deviation = 38%) reduction in indoor PM levels when HEPA filters were operated (Barn et al., 2008). This study was followed by a randomized intervention blinded crossover study, which included both exposure measures and assessment of potential health benefits associated with HEPA filter operation (Allen et al., 2011). Use of the HEPA filters reduced indoor $PM_{2.5}$ and levoglucosan concentrations by 60% and 75%, respectively. Use of HEPA filtration for one week was associated with improved endothelial function and decreased levels of biomarkers of inflammation in health adults (impaired endothelial function and systemic inflammation are predictors of cardiovascular morbidity). No associations were observed for urinary markers of oxidative stress. These studies indicate the potential for portable room air cleaners to reduce exposure and the health impacts associated with residential wood combustion.

Educational campaigns

EPA has set up a “Burn wise” programme to educate people to burn the right wood (dry, seasoned hardwood; no trash) the right way (hot and not smouldering fire, not overloading the appliance, not when outdoor air quality is poor) in the right efficient appliance. Educational campaigns run at the city, county and national levels can also encourage switching to alternative energy sources and avoiding unnecessary recreational combustion.

A study conducted in Armidale, a small university city in Australia with high PM pollution levels due to wood-burning heaters, found an educational campaign significantly decreased visible wood smoke emissions among 316 study participants (Hine et al. 2011); unfortunately, no air pollution measurements were taken. The main barriers to reducing wood smoke identified by the study were poor operation of wood heaters, mismanagement of firewood and lack of knowledge about the health effects of wood smoke. The campaign did not succeed in increasing knowledge among the study participants of the health risks of wood combustion.

In general, environmental educational campaigns have only moderate success in generating pro-environmental behaviour and there is little evidence of their effectiveness in peer-reviewed literature. No quantitative estimates describe how improved wood-burning practices – without exchanging combustion appliances – can reduce the health impacts of wood combustion. Very few studies have evaluated why even increasing awareness of the health risks of wood combustion does not always cause beneficial changes in behaviour (Hine et al., 2007; 2011).

Educational campaigns may fail if they only provide information on risks but do not try to affect the positive image of wood combustion. Many associate wood combustion at home with innate feelings of comfort, goodness, happiness and warmth (Hine et al., 2007). Decisions on whether to burn wood or not – when an individual has the ability to choose – may be based rather on intuitive positive feeling than on logical calculation of risks. Wood smoke seems to be perceived as less health-threatening than many other environmental stressors, although there is little evidence for or against this notion.

Increasing the perception of health risks associated with solid fuel heating can be one motivation to change behaviour, although awareness of risks does not automatically lead to beneficial changes in behaviour. Tobacco smoking, however, is an encouraging example of an activity whose image has been altered, at least in part, by active campaigning. Bans on smoking in bars have been shown to lead to beneficial changes in the respiratory and cardiovascular health of populations (Bartecchi et al., 2006; Goodman et al., 2007).

6. Regulatory and voluntary measures available to reduce emissions from wood heating in developed countries

Regulatory measures include ecodesign regulations and labels in the EU and technology-based emission limits in the USA and Canada. Financial fuel switching and technology change-out incentives, as well as targeted "no burn" days and ecolabelling, are other tools available to policy-makers.

This section focuses on the regulatory and voluntary measures now available or that hold the potential to reduce death or injury associated with residential solid fuel heating. Note that the section does not focus on interventions specific to coal burning because the WHO indoor air quality guidelines for household solid fuel use strongly discourage any coal use (WHO, 2014a); the assumption here is that any options available to reduce coal combustion in homes should be used.

Regulatory emissions limits

Over the past decade, the European Commission has worked towards the possibility of regulating solid fuel local space heaters and boilers, particularly those that use various forms of woody biomass fuel (wood logs, pellets and biomass bricks), to create proposed ecodesign emissions limits. Broader policy initiatives have now set the stage for the EU's work in this area and specific regulations to address energy efficiency and emissions are currently being developed for solid fuel space heaters (ENER Lot 20) and solid fuel boilers (ENER Lot 15) under the ecodesign directive (European Commission, 2009).

According to the Commission proposals, implementation of ecodesign standards would lead to significant reductions of $PM_{2.5}$ emissions from solid fuel local space heaters and boilers compared to baseline projections. The draft regulation for solid fuel local space heaters[2] states that in 2030 the proposed requirements for those products, combined with the effect of the energy labelling, are expected to save around 41 petajoules (0.9 million tonnes of oil equivalent (Mtoe)) per year, corresponding to 0.4 million tonnes of CO_2. They are also expected to reduce PM emissions by 27 kilotonnes per year, organic gaseous compound emissions by 5 kilotonnes per year and CO emissions by 399 kilotonnes per year. By 2030 the combined effect of the proposed

2 The proposed draft regulation sets a PM emission limit value of 50 mg/m^3 for open-fronted local space heaters, 40 mg/m^3 for closed-fronted local space heaters using solid fuel (but not pellets) and solid fuel cookers and a PM emission limit value of 20 mg/m^3 for pellet heaters by 2022 (PM measurement based on "dry" particles).

requirements for solid fuel boilers[3] and the energy labelling are expected to save around 18 petajoules (0.4 Mtoe) of energy each year – corresponding to about 0.2 million tonnes of CO_2 – and resulting in annual reductions of 10 kilotonnes of PM, 14 kilotonnes of organic gaseous compounds and 130 kilotonnes of CO.

Some countries in Europe (including Austria, Denmark, Germany, Norway and Sweden) have issued national emission standards for small residential heating installations, which are already in effect. The most comprehensive at this time is a German law of 2010 (quoted in Bond et al., 2013).

Canada also has countrywide standards in effect, limiting emissions for $PM_{2.5}$ and ozone pollution levels, and residential wood burning has been prioritized as a sector in which contaminant emissions can be reduced. CCME participated in an initiative to update the Canadian Standards Association (CSA) standards for new wood-burning appliances (CSA Group, 2010). These standards were adopted in 2010, lowering the PM emission rate to 4.5 g/h for noncatalytic wood-heating appliances and to 2.5 g/h for catalytic wood-heating appliances. They also established emissions limits of 0.4 and 0.13 g/megajoule for indoor boilers/furnaces and outdoor hydronic heaters, respectively.

In the USA, EPA established a new source performance standard (NSPS) limiting emissions for residential wood stoves under the Clean Air Act in 1988 (7.5 g/h for noncatalytic wood-heating appliances and 4.1 g/h for catalytic wood-heating appliances). This is expected to be updated in 2015 to reflect current best systems of emission reduction.

Note that the 1988 NSPS cover only new wood stoves and not devices installed prior to implementation of the standards, nor do they encompass many increasingly popular residential wood-burning devices, including fireplaces, masonry heaters, pellet stoves (see Box 7), indoor and outdoor wood boilers, furnaces and heaters. The EPA has had voluntary qualification programmes in place for hydronic heaters since 2007 and for fireplaces since 2009. Phase 2 qualifications of hydronic heaters is at 0.32 pounds parts per million British Thermal Unit (mmBTU) heat output and Phase 2 qualifications for fireplaces is 5.1 g/hr. The proposed NSPS revisions also include masonry heaters (2.0 g/h daily average; 0.32 lb/mmBTU (around 0.14 g/megajoule).

A hydronic heater is a wood-fired boiler, often located outside the building for which it is generating heat – in a shed, for example – that heats a liquid (water or water/antifreeze mix) and then uses this to circulate heat. To promote the production and sale of cleaner and more efficient outdoor hydronic heaters, EPA currently runs a voluntary certification programme for manufacturers. Certified outdoor hydronic heaters at the most stringent certification level ("phase 2") are about 90% cleaner than uncertified models. Even outdoor hydronic heaters qualifying for phase 2 certification, however, still emit one to two orders of magnitude more $PM_{2.5}$ on an annual average emission rate basis than residential oil or gas furnaces. Under the proposed revisions to the NSPS, a limit of 0.32 lb/mmBTU (around 0.14 g/megajoule) for indoor and outdoor hydronic heaters is proposed for 2015 and of 0.06 lb/mmBTU for both indoor and outdoor hydronic heaters in 2020. A number of state and local jurisdictions have also adopted setback distances (distances from buildings or other structures deemed to need protection) of 30–150 m, depending on emissions certification, for outdoor hydronic heaters.

All the above standards are focused on PM emissions, but the proposed American standard also includes minimum efficiency and CO testing and reporting requirements for wood-burning appliances, with the aim of also reducing CO emissions.

3 The proposed draft regulation sets a PM emission limit value of 40 mg/m³ for automatic and 60 mg/m³ for manual solid fuel boilers by 2020.

Box 7. Pellet stoves

Pellet stoves use processed biomass (in pellet form) as a fuel. Some are equipped with automatic pellet-feeding systems, which often run on electricity but are occasionally gravity-fed and require little attention from the user. They were developed in the 1980s and have become quite popular in Europe, although less so in the USA and Canada.

Significant growth in the installation of pellet stoves and boilers in residential and commercial sectors has been observed in several European countries over the last decade. Annual sales growth rates of 20–30% per year have been reported in Austria, France, Germany, Italy, Sweden (currently the largest market in the world) and Switzerland, varying a little from year to year owing to changes in the price of fossil fuels compared to stove pellets (UNEP & WMO, 2011).

Pellets were originally produced in some European countries as a way of using the waste products from sawmills. Pellet production increased fourfold in the EU between 2001 and 2009 and trade is fluid both within the EU and with external producers, particularly Canada, the Russian Federation and the USA (FAO, 2010). There is some concern about the overall carbon footprint of heating with pellets in Europe as many pellets are currently produced in North America or other regions and exported to Europe to sustain its thriving pellet market.

Pellet stoves are cleaner than many other options (Kjällstrand & Olsson, 2004; Olsson & Kjällstrand, 2006), but they may not be cost-effective for users who harvest their own wood for fuel. Prices for these kinds of stove are in the range of US$ 1000–3000. One estimate suggests that the cost–effectiveness of reductions for replacement of a wood stove ranges from US$ 130/megagram PM for a noncatalytic stove to almost US$ 1000/megagram PM for a pellet stove, but is highly dependent on the fuel price and the type of stove or boiler being replaced (Bond et al., 2013; Houck & Eagle, 2006).

In Sweden a 52% CO_2 tax on fossil fuels shifted consumer choice and led to increased penetration of modern biomass boilers and pellet stoves. In addition, public incentive programmes in several countries support modern biomass heating in households to reduce greenhouse gas emissions. For example, in France value-added tax on pellet stoves and boilers was reduced from 19.4% to 5.5%, a tax refund of up to 50% of the installation costs was made available and public campaigns were organized. Subsidies in Germany for the installation of pellet boilers of >150 kW were increased in 2008 from €1500 to >€2000 or even €2500 when combined with solar panels (UNEP & WMO, 2011).

Fuel switching

Several financial incentives for fuel switching are in place in Europe. In Austria biomass combustion (in pellet or wood chip boilers) is incentivized by a flat rate of €120/kW for 0–50 kW appliances and €60/kW for every additional kW up to a maximum of 400 kW. A maximum of 30% of the purchase value of the installation may be covered by this policy.

Germany provides grants for buyers of wood-burning appliances, with incentives to guide the purchase of automatically fuelled pellet-burning devices. Minimum rebates are in the range of €500–2500 for pellet ovens and boilers, depending on the specific model.

In Northern Ireland a grant of <€1260 is available to help low-income households replace an inefficient boiler (at least 15 years old) with a new wood pellet boiler (Brites, 2014).

Between 2006 and 2011 the Greener Homes Scheme in Ireland paid out €19 million in grants for the installation of nearly 6000 new biomass boilers and stoves (SEAI, 2014).

The Swedish government grants up to 30% of the costs of the labour, materials and installations for heating with biomass. A maximum of 14 000 Swedish krona (US$ 2000) per household applies. For apartment owners switching from direct electric heating to systems using district heating, biomass fuels or a geothermal/ground/lake heat pump, a maximum of 30 000 Swedish krona (US$ 3150) applies (Alliance for Green Heat, 2014).

"No burn" days (regulatory and voluntary)

Mandatory "no burn" regulations are used in many parts of the USA (and beyond) to reduce residential heating emissions when unfavourable meteorological conditions (low wind speed, temperature inversion) occur. For example, the Bay Area Air Quality Management District in California bans burning when "Spare the Air Tonight" advisories are issued (BAAQMD, 2014a). Bernalillo County (Albuquerque), New Mexico, has a winter advisory regulation/"no burn" programme from October to February, restricting use of non-EPA-certified fireplaces or stoves (City of Albuquerque, 2014). Denver, Colorado, has mandatory bans on "red" advisory days during the annual high air pollution season, with some exceptions. In Puget Sound, Washington, air quality burn bans temporarily restrict some or all indoor and outdoor burning, usually called when weather conditions are cold and still. San Joaquin County in southern California limits wood burning on days when air pollution approaches unhealthy levels. Santa Clara County, near San Francisco, uses a two-stage system to issue burn bans: at stage 1 residents can only use certified stoves; at stage 2 they may only use a wood stove if it is a primary heat source (EPA, 2014).

Voluntary "no burn" advisories are also in place in the USA. Lagrande, Oregon, asks for voluntary curtailment of wood stove use for heat based on daily advisories. The Yolo-Solano Air Quality Management District has initiated a voluntary programme called "Don't Light Tonight", which encourages residents not to use wood stoves and fireplaces when air pollution approaches unhealthy levels. The district also encourages cleaner burning techniques and switching to cleaner burning technology (EPA, 2014).

Heater exchange regulations

Mandatory regulations for heater exchange are in effect in parts of the USA. In San Joaquin County in southern California, existing wood stoves must be rendered inoperable or replaced with an EPA-certified wood stove when a home is sold; only pellet stoves, gas stoves and EPA-certified wood stoves can be sold. There are limits on the number of wood stoves or fireplaces that can be installed in new residential units. Santa Clara County in northern California has banned the installation of new wood-burning stoves or fireplaces. In addition, the Bay Area Air Quality Management District requires that only cleaner burning EPA-certified stoves and inserts be sold in the Bay Area and that only pellet stoves, gas stoves and EPA-certified wood stoves be installed in remodelled or newly constructed buildings. Emissions labelling for firewood, wood logs and wood pellets sold is also required (BAAQMD, 2014b).

Other regulations and voluntary measures

A model by-law and code of practice are in place in Canada. CCME produced a code of practice for residential wood-burning appliances; this focuses on reducing the impacts of emissions to air quality and climate, while recognizing the appliances' importance for domestic heating. The code includes a model by-law that municipalities or provinces can adopt for regulatory purposes, as well as guidance on wood-burning curtailment in response to air quality advisories, emissions testing for individual sources and complaint response strategies. The code provides advice and regulatory guidance for six best practices for consideration by jurisdictions in designing policies and programmes to reduce wood smoke emissions:

- regulating appliance efficiency;
- air quality advisories and "no burn" days;
- limits on installation or operation of wood-burning appliances;
- incentives to change;
- public outreach and education;
- performance management – planning for and measuring success.

Several European countries, such as Austria, Germany and Sweden, have introduced voluntary ecolabelling of stoves with standards for efficiency and emissions (Bond et al., 2013), such as the Nordic Swan label in Sweden (Pearson et al., 2013).

The 1999 Gothenburg Protocol under the Convention on Long-Range Transboundary Air Pollution, as amended in 2012, also includes recommendations on PM emission limit values for residential combustion installations with a rated capacity of less than 500 kW hours. The recommended emission limit values for PM depend on the type of fuel (wood: 75 mg/m^3; wood logs: 40 mg/m^3; pellets and other solid fuels: 50 mg/m^3) (UNECE, 2012).

The Wood Stove Decathlon, an initiative of the Alliance for Green Heat, was organized in 2013 to focus creativity and resources on designing next generation wood stoves. The main goal was to challenge teams of combustion engineers, engineering students, inventors and stove manufacturers to build wood stoves that are low-emission, high-efficiency, innovative and affordable, in a common process that may point to commercially attractive next generation stove production (Alliance for Green Heat, 2013).

7. Policy needs regarding future use of biomass for heating and energy production

Better alignment is needed between climate and air pollution policies in many countries. Information campaigns – especially those that increase knowledge about the energy efficiency of heating options – are encouraged.

Residential solid fuel combustion for heating is likely to persist in many parts of the world in the near future. The following is a summary of the policy needs regarding biomass and other solid fuel use for heating and energy production.

Any renewable energy or climate change-related policies that support combustion of wood for residential heating need to consider the local and global ambient **air pollution impacts** and immediately promote the use of only the lowest emission or best available combustion technologies.

Legal regulations for wood combustion efficiency in new heating appliances are urgently needed throughout the world. These will both slow down the current rapid speed of global warming (relating to BC in fine particles and VOCs that promote ozone formation) and reduce the great burden of disease caused by wood combustion-derived particles (especially organic compounds carried by BC). Such regulations should include tight – but technically achievable – limits in particular for the primary emissions of particulate mass, gaseous hydrocarbons and CO from new boilers and heaters.

Education on energy efficiency is needed. Improved efficiency of wood combustion in small-scale heating appliances greatly reduces emissions of major greenhouse gases, such as CO_2 and methane (CH_4), per unit of energy required for heating purposes. There is

an urgent need for education around this issue, including active outreach by air pollution, energy and health ministries.

As new wood-burning devices become more energy efficient and emit less pollution (especially PM), national governments need to prepare **heater exchange regulations** or voluntary programmes. Municipalities, counties and states should consider requiring heater exchanges at the time of home remodels or sales. In many cases, these regulations will be most successful if financial compensation is offered to assist with the cost of replacing old heaters with those meeting tight energy efficiency or emission limits regulations.

"No burn" areas are needed. Especially with current combustion technologies, it is important to define urban areas with dense populations and/or geographical features (such as valleys between mountains) where residential heating or cooking with small-scale appliances burning solid fuels (wood and coal) is not permitted at all or is at least limited to registered models of low-emission wood combustion devices. Residential heating with coal in small-scale appliances should also be permanently prohibited, at least in communities of developed countries, as should the use of wood log burners for central heating without a sufficiently large water tank (which otherwise leads to badly incomplete combustion and very large emissions).

Regulatory use of **"no wood burning" days** or morning and evening hours during unfavourable meteorological conditions (low wind speed, temperature inversion) needs to be introduced in vulnerable, densely populated areas, and more generally in valleys of mountainous areas. This can be introduced rapidly both to alleviate local air pollution episodes in vulnerable areas with prevalent wood burning and to reduce the risk of acute adverse health outcomes among the fast-growing susceptible population group of people aged over 65 years with chronic respiratory or cardiovascular disease. This would also be favourable in health terms for newborn babies and pre-schoolchildren, who also spend much time in the home and are more susceptible than older children and adults to respiratory symptoms and infections.

Local and regional authorities, with patient organizations, need to create community-wide **information campaigns** to inform residents about the climate and health benefits of local emission-free alternatives for house heating. These may include district heating by controlled combined heat and power plants, geothermal energy for single houses or as a larger local installation and heat pumps for single houses or apartments. Authorities could arrange distribution of leaflets and personal information to residents on how to arrange proper drying and storage of wood logs and how to use current small-scale heaters properly during annual chimney sweeps. An example of this is the information campaign implemented by chimney sweeps in Finland (Levander & Bodin, 2014). The most challenging task is to change the attitudes of people who are attached to the tradition of burning wood for house heating and comfort, and who often get their wood cheaply or without charge from their own or relatives' and friends' forests by harvesting small trees and making the wood logs in their spare time.

8. Co-benefits for health and climate of reducing residential heating emissions

Co-benefits are win–win outcomes for sectors other than the one from which a policy originates. Reducing emissions from residential heating can have significant benefits for both climate and health, especially in the short term.

Co-benefits include health benefits that arise from actions that are primarily motivated by an interest in mitigating climate change and climate mitigation benefits produced by actions that are primarily motivated by an interest in improving public health. Reducing emissions of health-relevant air pollutants – especially those that are also climate-active pollutants (such as CH_4 and BC) – can have short- and medium-term co-benefits for health; it can also immediately reduce exposure to associated particulate air pollution. Accounting for these health co-benefits can produce a more complete economic picture of the costs and benefits associated with efforts to reduce heating-related emissions, such as wood stove change-out programmes.

Increasing efficiency and tightening restrictions on emissions from wood and coal heating throughout the world would both slow down the current rapid speed of global warming (relating to BC in fine particles and VOCs and CH_4 that promote ozone formation) and reduce the burden of disease caused by combustion-derived particles (especially organic compounds carried by BC and contaminants in coal). The public needs to be better educated about the facts that improved efficiency of wood combustion in small-scale heating appliances greatly reduces emissions of major long-lived greenhouse gases (such as CO_2) and short-lived climate forcers (such as BC and CH_4); and that coal heating should be discontinued for both health and climate reasons.

Coal is an extremely greenhouse gas-intensive energy source. Coal produces 1.5 times the CO_2 emissions of oil combustion and twice the CO_2 of burning natural gas (for an equal amount of energy produced) (Epstein et al., 2011). When burned in homes rather than power plants, coal is also a major source of BC and other $PM_{2.5}$ (see Box 2). Wood and other forms of biomass are often considered renewable and climate-friendly fuels because trees take up CO_2 as they grow and store it in the form of carbon. As wood is burned, however, this carbon is released back to the the atmosphere, not only as CO_2 but in most household combustion also in the form of short-lived greenhouse pollutants such as BC, CO and VOCs including CH_4. Thus, to be perfectly "carbon neutral", wood fuel has to be not only harvested renewably but also combusted completely to CO_2.

For both climate and health purposes, the form these fuels' carbon takes when it is released matters greatly, since BC and CH_4 are both strongly climate-warming. BC is a climate-relevant component of fine particles, whether they are derived from tailpipe emissions of cars or residential heaters burning wood or other biomass. It is also harmful to health (see section 3). Note that although the toxicity behind the health impacts is indirect, via organic and inorganic constituents attached to BC, the impact on climate change is more direct, via increased light absorption of BC in atmospheric aerosol and on snow and ice (Bond et al., 2013; Smith et al., 2009).

A World Bank study found that replacing current wood stoves and residential boilers used for heating with pellet stoves and boilers and replacing chunk coal fuel with coal briquettes (mostly in eastern Europe and China) could provide significant climate benefits. It would also save about 230 000 lives annually, with the majority of these health benefits occurring in Organisation for Economic Co-operation and Development nations (Pearson et al., 2013). (The continued use of coal for residential heating is not recommended; however, the use of coal briquettes was factored into the scenario detailed here.)

Another study coordinated by the United Nations Environment Programme and the World Meteorological Organization found that widespread dissemination of pellet stoves (in industrialized countries) and coal briquettes (in China) for BC mitigation could improve health, since these interventions lead to reductions in $PM_{2.5}$. Major reductions in annual premature deaths expected as a result of these interventions include about 22 000 fewer deaths in North America and Europe, 86 000 fewer deaths in east and southeast Asia and the Pacific, and 22 000 fewer deaths in south, west and central Asia (UNEP & WMO, 2011).

If Arctic climate change becomes a focus of targeted mitigation action (because of threats from rising sea levels, for example), widespread dissemination of pellet stoves and coal briquettes may warrant deeper consideration because of their disproportional benefit to mitigating warming from BC deposition in the Arctic (UNEP & WMO, 2011). The World Bank found that replacement of wood logs with pellets in European stoves could lead to a 15% greater cooling in the Arctic (about 0.1 °C). For Arctic nations the modelling strongly indicates that the most effective BC reduction measures would target regional heating stoves for both climate and health benefits (Pearson et al., 2013).

9. Conclusions

The results presented here indicate that it will be difficult to tackle outdoor air pollution problems in many parts of the world without addressing the combustion of biomass for heating at the household level along with other sources of air pollution. To protect health policy-makers in regions that have relatively high levels of outdoor air pollution from household heating-related combustion need to provide incentives to switch from solid fuel combustion for heating to gas- or electricity-based heating.

Given that residential wood combustion for heating will continue in many parts of the world because of economic considerations and availability of other fuels, an urgent need exists to develop and promote the use of the lowest emission or best available combustion technologies.

There is also a need for renewable energy or climate change-related policies that support combustion of wood for residential heating to consider the local and global ambient air pollution impacts and immediately promote only the use of lowest emission or best available combustion technologies.

Policy-makers in regions where the proportion of $PM_{2.5}$ emissions attributable to household space heating with biomass-based fuels is high might wish to consider incentives to assist with a transition to more efficient technologies that encourage more complete combustion, and thus reduce $PM_{2.5}$ and other health-relevant emissions.

It may be preferable in many cases to focus on making biomass-based home heating more efficient and less polluting rather than transitioning away from biomass to fossil fuels, given the climate change implications of using fossil fuel for heating.

A better understanding of the role of wood biomass heating as a major source of globally harmful outdoor air pollutants (especially fine particles) is needed among national, regional and local administrations, politicians and the public at large.

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Annex 1. Residential wood combustion contributions to ambient PM concentrations

Location	Estimated contribution to ambient PM	Estimated ambient wood smoke $PM_{2.5}$[a] (µg/m³)	Notes	Reference
Australia and New Zealand				
Christchurch, New Zealand	90% heating-season $PM_{2.5}$ (SA)[b]	–	–	McGowan et al. (2002)
Tasmania, Australia	77% annual $PM_{2.5}$ (SA)	~20 (winter)	Elemental carbon (EC): 2.27 ±0.74 µg/m³; organic carbon (OC): 12.49 ±3.68 µg/m³; levoglucosan: 6.02 ±1.99 µg/m³	Reisen et al. (2013)
Tasmania, Australia	–	90th percentile of estimated concentration: Launceston: 30[a]; Hobart: 15[a]	–	Bennett et al. (2010)
Launceston, Australia	95% winter air pollution	–	–	Jordan et al. (2006)
Armitage, Australia	–	200	Night-time (2-week) winter mean	Robinson et al. (2007)
USA and Canada				
San Jose, USA	42% heating-season PM_{10} (SA)	–	–	Chow et al. (1995)
Atlanta, USA	11% annual $PM_{2.5}$	–	–	Polissar et al. (2001)
Atlanta, USA	11% winter $PM_{2.5}$ (SA)	–	Consistent associations across methods between $PM_{2.5}$ from mobile sources and biomass burning with both cardiovascular and respiratory hospital emergency department visits	Sarnat et al., 2008

Location	Estimated contribution to ambient PM	Estimated ambient wood smoke $PM_{2.5}$[a] ($\mu g/m^3$)	Notes	Reference
Vermont, USA	10–18% winter $PM_{2.5}$	–	–	Polissar et al. (2001)
Montana (5 communities), USA	55–77% heating-season $PM_{2.5}$ (SA)	7–11	–	Ward et al. (2010
Rural New York, USA	–	4–22	Night-time, heating season, inversion conditions; short-term peak concentrations from mobile monitoring as high as 100 $\mu g/m^3$	Allen et al. (2011)
Rochester, New York, USA	17% winter $PM_{2.5}$ (SA)	3.2	Wood smoke contribution to $PM_{2.5}$ increased to 27% when the corresponding hourly $PM_{2.5}$ concentrations were greater than 15 $\mu g/m^3$	Wang et al. (2011)
Seattle, USA	–	11.2	Mean heating-season concentrations to $PM_{2.5}$ in a wood smoke-impacted area of Seattle (measured during panel study of 19 subjects): 11.2 (standard deviation = 6.5) $\mu g/m^3$; ambient-source $PM_{2.5}$ exposure: 6.26 $\mu g/m^3$ (standard deviation = 3.9)	Allen et al. (2008)
Seattle, USA	7–31% annual $PM_{2.5}$ (SA)	–	–	Kim & Hopke (2008a)
Seattle, USA	~30% heating-season $PM_{2.5}$ (SA)	4	Estimated wood smoke contribution to ambient $PM_{2.5}$	Wu et al. (2007)
Portland, USA	27% annual $PM_{2.5}$ (SA)	7	Proportional contribution to $PM_{2.5}$ may also include influence of wildfires	Kim & Hopke (2008b)
Fairbanks, USA	60–80% winter $PM_{2.5}$ (SA)	~25	Winter mean 24-hour $PM_{2.5}$	Ward et al. (2012)
Truckee, USA	11–15 winter $PM_{2.5}$ (SA)	–	–	Chen et al. (2012)
Las Vegas, USA	11–21 annual $PM_{2.5}$ (SA)	–	Individual sites: 11.3 ±9.8%, 15.9 ±12.9%, 11.1 ±8.0, 20.8 ±12.5% contributions to annual $PM_{2.5}$ OC: 8–16% contribution from residential wood combustion; EC: 3–7% contribution from residential wood combustion	Green et al. (2013)

Location	Estimated contribution to ambient PM	Estimated ambient wood smoke $PM_{2.5}$[a] (μg/m³)	Notes	Reference
23 sites in California, USA	24% winter $PM_{2.5}$	–	–	Chen et al. (2007)
Golden, British Columbia, Canada	31% winter $PM_{2.5}$	–	Winter 2006	Jeong et al. (2008)
Vancouver, Canada	–	8.8	Night-time, heating-season geometric mean wood smoke contribution to ambient $PM_{2.5}$	Ries et al. (2009); Larson et al. (2007)
Rural British Columbia, Canada	–	11 (heating season, 7-day average)	Estimated outdoor-generated $PM_{2.5}$ measured indoors: 3.5 μg/m³ (SD = 2.3).	Allen et al. (2009)
Europe				
Po Valley, Italy	Rural: Sondrio 16–23% and Cantù 11–24%; urban background (including Milan): 10–27% winter PM_{10} (SA) (positive matrix factorization)	–	15–35% contribution to EC; 19–50% contribution to OC	Piazzalunga et al. (2011)
Austria	10–20% winter PM_{10} (SA)	–	–	Caseiro et al. (2009)
Southern Germany	59% winter PM_{10} (SA)	–	–	Bari et al. (2010)
Duisberg, Germany	13% autumn $PM_{2.5}$ (SA)	1.9	Ambient concentration	Saarikoski et al. (2008)
Prague, Czech Republic	37% winter $PM_{2.5}$ (SA)	1.1	Ambient concentration	Saarikoski et al. (2008)
Amsterdam, Netherlands	11% winter $PM_{2.5}$ (SA)	2.8	Ambient concentration, including contribution from long-range transport of biomass aerosol	Saarikoski et al. (2008)
Helsinki, Finland	Urban sites: 18–29%; suburban sites: 31–66% heating-season $PM_{2.5}$ (SA)	1–3	Additional contribution to ambient $PM_{2.5}$ in six month cold period from residential wood combustion	Saarnio et al. (2012).

Location	Estimated contribution to ambient PM	Estimated ambient wood smoke $PM_{2.5}$[a] (μg/m³)	Notes	Reference
Helsinki, Finland	Urban background: 17% $PM_{2.5}$ (SA) in four seasons	1.6	Ambient concentration	Saarikoski et al. (2008)
Northern Sweden	36–81% winter PM_{10} (SA)	–	–	Krecl et al. (2008)
Kurkimaki, Finland	–	8	Small community (164 single family homes) in central Finland: 8 μg/m³ $PM_{2.5}$ over full sampling campaign, with daily values of 5–40 μg/m³ and hourly averages as high as 50 μg/m³	Hellen et al. (2008)
Lycksele, Sweden	–	–	EC accounted for 11% and OC for 35% of the 5-week mean PM_{10} of 12 μg/m³; local residential wood combustion contributed to 31–83% of PM_{10}.	Krecl et al. (2007; 2008b)
Residential area, small town, Denmark	–	4	6-week average ambient $PM_{2.5}$: 16 μg/m³	Glasius et al. (2006)
Duisburg, Prague, Amsterdam and Helsinki	up to 37% in wintertime Prague	–	–	Saarikoski et al. (2008)
Other locations				
China (urban and suburban sites in Beijing and Guangzhou)	3–19% 24-hour $PM_{2.5}$ from biomass burning	6–183	October 2004	Wang et al. (2007)

a Where PM_{10} but not $PM_{2.5}$ measurements were made, the level of wood smoke $PM_{2.5}$ was estimated, based on the contribution to PM10 and assuming a typical PM_{10}:$PM_{2.5}$ ratio of 0.65 for combustion-dominated aerosol.

b SA: source apportionment – literature identified using Web of Science and PubMed search [using "woodsmoke", "biomass", "smoke" and "residential combustion" as keywords].

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