LIFE11 /ENV/ES/584

AIRUSE

Testing and development of air quality mitigation measures in Southern Europe

ABATEMENT OF EMISSIONS FROM DOMESTIC AND AGRICULTURAL BIOMASS BURNING

REPORT 20

12/2016

Authors:

Xavier Querol (Project coordinator)

IDAEA-CSIC (Consejo Superior de Investigaciones Científicas)

A. Karanasiou
F. Amato
C. Vasconcelos
A. Alastuey
M. Viana
T. Moreno
F. Plana
N. Perez
M. Cabañas
R. Bartoli
S. Martinez
M. Sosa

AICE – ITC – Universitat Jaume I

E. Montfort

I.Celades
A. Escrig
V. Sanfelix
S. Gomar

University of Birmingham

R. Harrison

C. Holman
D. Beddows
M. Harding

DEMOKRITOS National Centre for Scientific Research

K. Eleftheriadis

L. Diapouli
S. Vratolis
M. Gini
E. Bairaktari
S. Dalaina
V. Galifianakis

Università degli Studi Firenze – Dipartimento di Fisica e Astronomia

F. Lucarelli

S. Nava
G. Calzolai
R. Udisti
S. Becagli
R. Traversi
M. Severi
S. Borselli
M. Giannoni

Universidade de Aveiro

C. Alves

C. Pio
T. Nunes
L. Tarelho
M. Duarte
M. Cerqueira
E. Vicente
D. Custódio
H. Pinto

ARPA Lombardia – Agenzia Regionale per la Protezione dell'Ambiente – Settore Monitoraggi Ambientali

V.L. Gianelle
C. Colombi

INDEX

1. INTRODUCTION

The burning of wood and other biomass is an important but often unrecognised source of air pollution in Europe where the focus over recent decades has been on emissions from road traffic. Exhaust emissions of particulate matter (PM) from vehicles are declining with the increasing use of diesel particle filters while emissions from wood burning are growing. Biomass burning can also impact on visibility and give rise to odour (e.g. Kistler et al., 2012).

Wood, including wood waste, is the largest source of renewable energy in Europe and is expected to make a major contribution to the 20% European Union (EU) renewable energy target to be achieved by 2020 (European Commission, 2014). Between 2000 and 2013 the use of biomass for energy doubled in Europe, and in some Scandinavian and Baltic countries biomass is already contributing almost one third of the energy consumed. Three quarters of the biomass energy is used to produce heat, mainly for the residential market (European Biomass Association, 2015)[1] with a smaller amount feeding small-scale commercial heating plants and district heating systems (European Commission, 2014). The latter typically use modern pellet and chip burning plant, which generally has well controlled emissions. Domestic appliances range from simple fireplaces with uncontrolled grates to fully automatic wood pellet boilers.

Climate change mitigation policies which favour the use of renewable energy sources including biomass is one reason for the growth in domestic wood combustion (e.g. van der Gon et al., 2015). Other reasons include the cost of fossil fuels and public perception that wood is a ‘green’ fuel (EEA, 2014). According to the European Pellet Council (2015a) wood pellets cost up to 50% less than heating oil in most EU member countries. In addition, there is some evidence of a rise in so called ‘recreational burning’ for aesthetic reasons (Fuller et al., 2013).

Many Member States are actively promoting biomass to help meet renewable energy targets and its use is expected to grow over the coming years including for residential heating (European Commission, 2014). For biomass to reduce greenhouse gas emissions it must be produced in a sustainable way. Currently there are no common EU wide sustainability criteria for solid biomass although there are national standards such as those introduced in the United Kingdom (Ofgem, 2015).

Emissions from residential wood burning include fine PM ($PM_{2.5}$) composed of elemental carbon (EC)[2], organic carbon (OC) such as polycyclic aromatic compounds (PAHs), and a range of metals. Emissions of sulphur (S) and nitrogen (N) compounds from biomass

[1] It is unclear as to whether these statistics include biomass burnt in homes, or just applies to biomass consumed in district heating and combined heat and power (CHP) plants.

[2] The term elemental carbon and black carbon are often used interchangeably. They are defined by the methods used to measure them in the atmosphere. In this report the term elemental carbon has been used.

combustion tend to be low compared to fossil fuel combustion. Sufficiently high temperatures to form NOx from atmospheric nitrogen (N_2) rarely occur during wood combustion (Salthammer et al., 2014). The chemical composition and physical properties of biomass varies hugely especially between agricultural and woody feedstocks. For example, in general agricultural feedstocks have higher chloride (Cl) content than woody biomass which can lead to the formation and emission of dioxins (Villeneuve et al., 2012).

The size of particles emitted during residential biomass combustion varies depending on the combustion appliance, fuel type, combustion phase and sampling method, but they are predominantly fine particles with a relevant diameter close to 1 µm or less (Vu et al., 2015; Bari et al,. 2011).

Residential wood combustion is the largest source of primary OC emissions in Europe. It is thought that the current emission inventories significantly underestimate PM emissions from residential wood burning and for $PM_{2.5}$ emissions may be 2-3 times higher than reported. This would increase total European $PM_{2.5}$ emissions by about 20% (van der Gon et al., 2015).

Most of the PM mass emitted from manual devices is carbonaceous matter. The OC/EC ratio depends on the combustion efficiency and is greater from a fireplace than a stove (Calvo et al., 2015). Automatic appliances have much higher inorganic content reflecting the combustion efficiency particularly when operated under full load conditions (Schmidl et al., 2011).

There is evidence that the switch to domestic biomass burning is giving rise to air pollution episodes during the winter in a number of European cities. For example, in the Greek city of Thessaloniki wood burning resulted in a 30% increase in $PM_{2.5}$ concentrations during the winter of 2013 compared to the winter of 2012 as the economic crisis drove households to switch from oil to wood to heat their homes (Saffari et al., 2013).

Official EU statistics on emissions from residential properties show that SO_2 emissions have halved since 1990 while emissions of $PM_{2.5}$ and BC are now at a similar level. Over the last decade, however, domestic emissions of $PM_{2.5}$, BC and PAHs have all increased (EEA, 2015). As mentioned above, this data is likely to under-estimate emissions because of the difficulty in quantifying the extent of domestic wood combustion.

According to the World Health Organization (WHO) epidemiological studies show that exposure to $PM_{2.5}$ is associated with both mortality and morbidity (WHO, 2013) and more than 90% of the EU population lives in cities with levels above the WHO guideline (EEA, 2014). Exposure to $PM_{2.5}$ causes cardiovascular mortality and morbidity, atherosclerosis, adverse birth outcomes and childhood respiratory diseases. There is also emerging evidence that suggests links between long-term $PM_{2.5}$ exposure and neurodevelopment and cognitive function, as well as other chronic disease conditions, such as diabetes (WHO, 2013). Epidemiological studies have started to assess the impact of the chemical composition of particles, but few studies have assessed the relationship between specific organic components and adverse health effects.

There are studies reporting acute and short term effects of wood smoke on human health but little is known of the long-term health effects (WHO, 2013). An important constituent of wood smoke is benzo(a)pyrene (BaP), a proven carcinogen. Several other species associated with wood smoke are probably carcinogens according to the International Agency for Research into Cancer (IARC, 2010).

The other major anthropogenic source of PM emissions from biomass combustion is from the burning of agricultural wastes, such as the burning of stubble from cereal crops. This practice has declined in many EU countries in recent decades. The amount burnt fell by 84% between 1990 and 2012 (EEA, 2015b). However, the practice is still widely used in eastern and parts of southern Europe. Large scale agricultural burning impacts on air quality over large areas, for example Karlsson et al. (2015) report the impact of biomass burning in southern Russia on air quality over large areas of northwest Europe. This practice, when poorly managed, can result in the large scale burning of vegetation including unintended destruction of forests.

This report draws on the experience in northern and central Europe of policy measures that can reduce emissions from residential wood burning that could be applied in the southern European countries. It also discusses controls on the burning of agricultural residues that have been introduced.

Other AIRUSE reports provide further information as well as the results of new studies on the emissions from a range of domestic fireplaces and stoves using woods principally used in southern Europe[3]. These show that there are large differences in the emissions between wood burning appliances and fuels, especially between old residential appliances and modern, more efficient woodstoves and boilers. A number of recommendations were made including the eco-labelling of small-scale combustion appliances, the use of certified pellets meeting defined quality specifications, requirements on the storage of fuels and support for the replacement or retrofitting of old wood stoves and fireplaces. Where ambient PM standards are exceeded, due at least in part to wood smoke, the local jurisdiction may consider banning the use of non-certified woodstoves. Public education and outreach programmes should be undertaken to support any ban or appliance replacement programmes.

2. IMPACT ON URBAN AIR QUALITY

Biomass combustion is an important source of air pollution in many urban and rural areas in Europe, particularly in winter, and can be a major contributor to exceedances of European PM_{10} and $PM_{2.5}$ limits (Crilley et al., 2015; Herich et al., 2014). It can also lead to significant health effects and economic costs (e.g. Haluza et al. 2012; Sargianis et al., 2015).

Studies have shown that biomass burning is a significant source of ambient PM in cities across the EU including Vienna, Graz, and Salzburg in Austria (Caseiro et al., 2009), Milan, Florence and several smaller towns in northern Italy (Piazzalunga et al., 2011; Bernardoni et al., 2011; Giannoni et al, 2012), Stuggart and Berlin in Germany (Bari et al., 2011; Wagener et al., 2012), Barcelona in Spain (Reche et al., 2012; Viana et al., 2013), Antwerpen, and Ghent in Belgium (Maenhaut et al., 2012); Paris in France (Crippa et al., 2013; Bressi et al., 2014), and London in England (Fuller et al., 2014; Crilley et al., 2015). PM emissions from

[3] http://airuse.eu/outreach-dissemination/reports/

biomass burning in major cities can exceed those from traffic in winter (Crippa et al., 2013; Fuller et al., 2013; Wagnener et al., 2013).

Wood burning takes place in many homes at the same time and emissions increase during evenings, weekends and public holidays suggesting that domestic wood burning is a supplementary fuel, often heating a single room (e.g. Maenhaut et al., 2012; Saffari et al., 2013; Fuller et al., 2014).

During winter there appears to be a regional biomass source with additional contributions from local domestic wood burning (e.g. Maenhaut et al., 2012; Reche et al., 2012; Crilley et al., 2015). This may be due to the long range transport of emissions from large scale burning of agricultural wastes (Reche et al., 2012).

The tracers[4] used to identify the biomass burning contribution to ambient PM concentrations are not able to differentiate between emissions from small scale domestic appliances and those from larger scale boilers such as those used in district heating schemes as similar fuels are used. Several studies have used tracers to identify the relative contribution from soft wood (typically from conifers). In northern and central Europe it seems that about 70% of the wood burnt is soft wood and the remaining hard wood (from broadleaved trees) (e.g. Maenhaut et al., 2012).

The main source of EC emissions is the combustion of fossil fuels throughout the year, while OC sources are primarily of biogenic origin with large seasonal differences. In winter, biomass burning is the main OC source, with some additional contribution from fossil fuel combustion. In contrast, in summer secondary organic aerosols (SOA) from non-fossil sources is the dominant source with some contribution from fossil fuel combustion. Other sources in the summer include wood burning in open fires for grilling and particularly wildfires which occur sporadically and may cover large areas (Gelencsér et al., 2007).

The OC emitted from the combustion of biomass contains PAHs. Exposure to high concentrations of BaP is widespread in central and eastern Europe. Approximately one quarter of the EU urban population was exposed to BaP concentrations above the target value[5] from 2010 to 2012, and nearly 90% above the WHO reference level[6] over the same period (EEA, 2014). Pietrogrande et al. (2015) found that during winter months biomass combustion contributed approximately three quarters of the ambient BaP measured in the Po Valley in northern Italy and a third of the OC.

The AIRUSE project (AIRUSE, 2015) found that biomass burning in southern European cities is an important source of PM. In Athens, Florence, Milan and Porto this source was estimated

[4] Levoglucosan and potassium (K) have been widely used as a biomass burning tracer in ambient air. ^{14}C is also used to differentiated between fossil and modern carbon, but cannot differentiate between natural and anthropogenic sources. The ratio of levoglucosan to other anhydrosugars such as mannosan and galactosan has been used to determine the proportion of soft and hard wood combusted. The use of aethalometers to quantify biomass burning emissions is considered to be unreliable (Harrison et al, 2013).

[5] Annual mean of 1.0 ng/m^3 to be achieved by 2013.

[6] Annual mean of 0.12 ng/m^3

to contribute from 7 to 16% and from 12 to 24% of annual average contributions PM_{10} and $PM_{2.5}$ concentrations respectively.

In Barcelona there seems to be very little biomass combustion, with natural gas the dominant fuel. Natural gas is also widely used for domestic heating in Florence and Milan. In Florence, however, biomass combustion contributed 16 and 21% of the annual mean $PM_{2.5}$ and PM_{10} concentrations respectively, but 30 and 20% on polluted days. Biomass combustion is thought to occur mainly in the hills outside the city. In Milan biomass combustion contributed 21-24% to annual mean PM concentrations, but up to 35% during polluted days. In Athens the biomass burning contribution is much less, contributing up to 11% to annual mean PM concentrations and virtually nothing during polluted days when Saharan dust dominates. In Athens biomass combustion is associated with tracers of waste combustion suggesting that much of the biomass burnt is waste wood. In Porto measurements were only undertaken at a traffic monitoring station, where the contribution of biomass combustion is expected to be lower than at urban background or suburban sites. Biomass burning contributed up to 18% of the annual mean PM concentrations and up to 33% of the PM concentrations during polluted days (AIRUSE, 2015). It is clear that in several of these cities biomass combustion is a very important source of PM, particularly during pollution episodes, and there is a need to abate emissions.

Haluza et al. (2012) assessed the impact on human health of a hypothetical change in the average energy mix for Austria today (mainly natural gas and fuel oil) to the use of biomass for residential heating. The results show that annual mean PM_{10} concentrations would increase by 12.2% in rural areas and 15.4% in urban areas, and result in 174 additional deaths in a total population of 1.4 million inhabitants. This includes the effects of increased NO_2 concentrations as well as PM. This is considered to be an underestimate as PM_{10} was used instead of $PM_{2.5}$, indoor exposures were not accounted for, and that in some area concentrations and hence exposure would be higher e.g. in congested urban area and valleys.

Kistler et al. (2012) calculated that the Austrian government plan for up to 400,000 households to have biomass heating systems would increase national $PM_{2.5}$ emissions by around 6% using an average emission factor of 30 mg MJ^{-1}.

Further information on the contribution of biomass combustion to ambient concentrations of PM (PM_{10} and $PM_{2.5}$), including the results of new research in the five AIRUSE cities (Athens, Barcelona, Florence, Milan and Port) are provided in the AIRUSE report 'Biomass burning in Southern Europe', available on the AIRUSE website (www.airuse.eu).

3. EMISSIONS FROM DOMESTIC BIOMASS BURNING

Biomass heating systems range from small-scale household appliances of a few kilowatts (kW) thermal output to 500 MW biomass district heating, combined heat and power or industrial plant. Household appliances are typically in the range 5 – 100 kW, and run on wood logs or pellets. Larger scale biomass combustion plants, in the range 100 kW to 500 kW, are used in agriculture, commercial buildings, and industry. These plants use a variety of feedstocks including wood chips and miscanthus[7]. Large heating plants for district heating or industrial use have capacities in the range 1 - 500 MW and typically use wood chips, straw or miscanthus (European Commission, 2014). Larger plant tends to have lower PM emissions. This is due to the higher combustion temperatures, more stringent emission limits and abatement technology being more affordable for operators due to the economies of scale.

The quantification of emissions from residential biomass combustion is challenging due to the influence of the appliance design, combustion conditions, and the type and condition of the fuel. The effects of these parameters on PM emissions are discussed below.

The emissions of PAHs are dependent on similar factors. The emissions of carcinogenic PAHs are lower in a pellet stove and log wood boilers when near complete combustion took place compared to incomplete combustion (Bari et al., 2011).

3.1. Appliance Type

Residential biomass burning takes place in different types of appliance. Simple solid fuel space heaters (open fireplaces, closed fireplaces and stoves) provide heating in a single room. More sophisticated systems incorporate boilers which provide residential central heating and/or hot water. These may have a heat storage system and incorporate solar water heating. There are also solid fuel appliances that are primarily used for cooking such as Rayburn range cookers in the UK. In rural Germany, for example, homes typically have log boilers, with or without a heat storage tank, for central heating. For additional heating, typically of a single room, manually fed chimney stoves, tiled stoves and open fireplaces are commonly used (Bari et al., 2011).

PM emissions and composition from domestic biomass combustion vary widely and depend on the combustion efficiency. This in turn depends on the oxygen availability, the air and fuel mixing in the combustion chamber, the combustion temperature and residence time (Villeneuve et al., 2012). Emissions of PM, as well as total hydrocarbons, CO and CO_2, tend to be highest from uncontrolled combustion appliances, which are less efficient. In general, the emissions decrease in the following order: open fireplaces > chimney stove > traditional woodstove > eco-labelled stove > pellet stove (AIRUSE, 2015). An open fireplace can have PM emissions approximately 15 higher than those from an efficient pellet stove. Emissions from the traditional woodstove are 5 to 6 times those of the modern combustion devices (AIRUSE, 2015). Due to the lack of control over the volume of air in the combustion process, fireplaces operate with higher levels of excess air resulting in the fuel burning quicker and at lower temperatures.

Boilers tend to have higher emissions (when expressed per mega joule; MJ) than space heaters. PM emissions from boilers typically decrease in the following order: conventional log boilers > modern log/chip boilers > pellet boilers. Emissions per MJ are also higher from boilers with no heat storage.

[7] Commonly known as Elephant Grass, miscanthus is a high yielding energy crop that grows over 3 metres tall. It resembles bamboo.

PM_{10} emissions from a manually operated appliance may be almost one order of magnitude higher than from the combustion of wood pellets and chips in automatically fired appliance operating under full load (Schmidl et al., 2011). However there can be a significant variation in emissions from nominally the same type of appliance. For example, Win et al. (2012) found that $PM_{2.5}$ emissions from five automatic 20 kW pellet boilers varied by 30%.

The carbonaceous content of the PM is typically high in the PM emission from manually operated appliances, while those from automated systems are predominantly inorganic (Schmidl et al., 2011). The latter are more efficient appliances which operate at higher temperatures, resulting in more complete combustion. The NOx emission from these devices tends to be higher. AIRUSE (2015) found that BaP emissions were lowest from the pellet stove.

Modern, efficient biomass appliances use a two-stage combustion process. In the primary combustion zone (on the grate) drying and solid combustion take place and in the secondary combustion zone the volatile gases are burned. There is electronic control of the combustion process including controlled feeding of the fuel and airflow into the combustion chamber, a sophisticated burner with electronic ignition, and automatic ash removal and combustion chamber cleaning. This results in very low emissions of PM because of the absence of unburned hydrocarbons in the flue gas. The PM emissions are primarily inorganic, while emissions from lower technology stoves and boilers are mostly OCs. There are three main types of burners, that vary according to the orientation of their fuel feeds (Egger et al., 2013).

- underfeed burners (underfeed stoker or underfeed retort burners): the fuel is fed into the bottom of the combustion chamber or combustion retort. These burners are best suited for fuels with low ash content (wood pellets, wood chips).
- horizontal feed burners: the combustion chamber is either fitted with a grate or a burner plate. The fuel is introduced horizontally into the combustion chamber. During combustion, the fuel is moved or pushed horizontally from the feeding zone to the burner plate or the grate. Horizontal feed burners can burn wood chips and pellets.
- top feed burners: developed for pellet combustion in small-scale units. The pellets fall through a shaft onto a fire bed consisting of either a grate or a retort. The separation of the feeding system and the fire bed ensures the effective protection against burn-back into the fuel storage. A dumping grate removes the ash manually or mechanically. This feeding system allows very accurate feeding of pellets according to the heat demand and therefore responds more like a gas or oil boiler.

AIRUSE (2015) tested the efficacy of two pollution abatement techniques: a catalytic convertor and an electrostatic precipitator fitted to a wood stove and a pellet stove. In most cases there was no significant impact on emissions. For the catalytic convertor the fuel gas temperature was too low for the catalyst to be effective and ash/soot clogging and creosote fouling may take place on the catalyst surface. For the electrostatic precipitator the PM formed during the cooling of the condensable organic compounds within the device may increase PM such that concentrations are higher at the outlet than the inlet. These devices cost €1,000 to 3,000, which is similar to the cost of a new appliance.

3.2. Fuels

There is also a large variation in PM emissions depending on the type of wood used. The physical properties of the fuels such as moisture content, density, porosity, size, surface area and chemical composition can all affect the emissions (Villeneuve et al., 2012). AIRUSE (2015) also found the PM emissions increased with moisture content.

Kistler et al. (2012) found that PM_{10} emissions from the combustion of European larch and black poplar in a modern 8 kW manually fired log stove were a factor of 10 lower than from sessile oak when normalised for energy content. PM_{10} emissions were highest during the combustion of dry leaves and the lowest from pine cones. Emission during the combustion of common Austrian trees in two manually fired appliances found little effect of tree species, especially from the more sophisticated eco-labelled stove (Schmildl et al., 2011).

A study of the $PM_{2.5}$ emissions from the combustion of common Portuguese trees found a factor of approximately 3 difference between tree species (in terms of g kg^{-1} biomass burned, dry weight) with the highest emissions during combustion of Portuguese oak on a woodstove, and from olive in a traditional fireplace. The lowest $PM_{2.5}$ emissions occurred during combustion of Maritime pine in both appliances (Gonçalves et al., 2012).

In general, the combustion of pine and beech generated the lowest PM emissions for all types of burning appliances, while the highest levels were produced when olive, followed by oak species, were burned. Further details of Portuguese studies is provided in the AIRUSE report 'Emission factors for biomass burning' (www.airuse.eu).

AIRUSE (2015) found the lowest BaP emissions were from the burning of pellets. The emissions from the combustion of the best performing wood were more than 8 times higher (based on energy consumed). Emissions from the burning of softwood in a modern eco-labelled stove were found to be very high due to the hot flame and reduced oxygen availability, although the PM emissions were low.

It was also found that the emissions of some heavy metals (e.g. zinc (Zn), lead (Pb), iron (Fe) and arsenic (As)) were higher in PM_{10} emissions from some non-certified pellets than for the certified pellets. Pellets made from recycled wood and wood waste especially from the furniture manufacturing industry may contain preservatives and leaded paint, which are emitted with the PM when burnt.

Few studies have studied emissions from the use of non-woody biomass in appliances such as straw, cereal seeds, animal manure and poultry litter. Although not commonly used these fuels may become important in the future. Schmidl et al. (2011) found very high PM_{10} and NOx emissions from the combustion of pellets made from corn seeds under full load operation in an automated 40 kW appliance, and further research is required to fully understand the reasons for these high emissions.

AIRUSE (2015) found that the lowest PM emissions occurred when using ENplus certified wood pellets, particularly class A1 pellets. This certification scheme, run by the European Pellet Council, provides fuel quality specifications to ensure the certified fuels have low emissions, high energy content and do not cause the appliance to malfunction. It guarantees that the pellets comply with the relevant international standard (ISO 17225-2) and in some cases exceed the Standard's requirements (European Pellet Council, 2015b).

3.3. Emissions in different combustion stages

There are three stages to biomass combustion as defined by Calvo et al. (2014):

1. Stage 1 (start-up): Initial heating accompanied by wood drying and the initial removal of the volatile components (known as devolatilisation) without a visible flame. This period lasts for less than 5 minutes, and is associated with little loss of fuel.

2. Stage 2 (operation): Devolatilisation, ignition and combustion of volatile compounds and char. During this stage there is a rapid loss of mass and a vigorous flame. At the end of this stage less than one third of the original mass of fuel (in the form of char) remains.

3. Stage 3 (end): Little loss of mass of fuel occurs as the char is combusted. There are only localised small visible flames over the char particles.

PM emissions mainly occur when the fuel is smouldering during start-up (Stage 1) and the end phase (Stage 3) yet often emissions measurements are only undertaken during steady state conditions (Stage 2). For example, the review of Obaidulah et al. (2012) only mentions one study out of nine that considered smouldering emissions from domestic sized appliances. Emission inventories may therefore underestimate emissions from these appliances.

However, if an automatic appliance is run continuously over a long period the contribution during smouldering is less important as illustrated by the average emissions from six 12-20 kW appliances measured over six days by Win et al. (2012). Over this period the average $PM_{2.5}$ emission during start, operation and end phases were 25%, 65% and 11% respectively. For manual appliances which are refuelled several times during the evening, smouldering emissions are much more important.

It has been found that using paper, kindling or twigs to initiated combustion results in higher PM emissions than when commercial fire lighters are used (Kistler et al., 2012).

Emissions during start-up and the end stages are not generally measured during Eco-label tests such as the Scandinavian Swan and the German Blue Angel labels. The eco-labels for domestic biomass appliances are based on the European Standard method during operation (EN 303-5; 2012, British Standards Institute, 2012) with PM sampled from the hot flue gas in the chimney. Many research studies sample PM emission from biomass appliances using a dilution tunnel which better represents the emissions to the atmosphere. Dilution with cold air increases measured concentrations due to the condensation of organic compounds (Win et al., 2014). These factors make it difficult to compare the PM emissions measured in research studies with emission criteria used to award eco-labels

.

3.4. User influence

The operation of appliances, in particular the amount of fuel used and the airflow, influence the emissions from manually operated appliances, however, there is little quantified data of the effect of these parameters on PM emissions. In addition, the storage of the fuel can have a significant impact on emissions if it is allowed to get wet or otherwise contaminated.

Vincente at al.(2015) investigated the impact of (i) ignition technique (lighting the fuel from the top or the bottom); (ii) hot and cold start; (iii) fuel load and, in the case of high load, size of logs; and (iv) secondary combustion air supply on PM_{10} emission from a 14 kW stove. They found little variation in emissions when burning hardwood (Fagus sylvatica; beech). The only parameter that seems to affect emissions was using a small load (1.0-1.2 kg).

For softwood (Pinus pinaster; pine) top-down ignition reduced PM_{10} emission by more than 50% compared with the traditional bottom-up technique. This is thought to be due to the traditional ignition technique igniting the entire batch of fuel leading to high combustion rates and area where there was insufficient oxygen. The top-down ignition results in gradual combustion of the fuel resulting in more complete combustion

The combustion of whole logs resulted in higher PM_{10} emissions that split logs. This is because the initial combustion phase when high emissions occur, lasts longer with larger logs. Density and moisture content can also affect the duration of this phase and the associated PM_{10} emissions.

The use of secondary combustion air also reduced emissions as it results in more efficient combustion.

Schmidl et al. (2011) undertook a series of ‘malfunction’ tests to investigate the effect of reducing air flow and changing the amount of fuel on the grate of two manual log stoves. Having a low airflow, but just sufficient to ensure there was still flaming combustion, increased emissions by a factor of up to approximately four. The reduction in airflow also increased the organic carbon content of the PM due less complete combustion. Increasing the wood on the grate by three times resulted in higher emissions from one stove and lower one from the other, more sophisticated, stove. This suggests that it is important to have detailed, high quality user instructions about the optimum operation of the stove.

For automatic pellet systems there is less operator influence on performance of stoves.

The German regulations require an annual visit from a professional chimney sweep, who checks the appliance is properly installed, serviced and has low emissions.

The moisture content of the biomass fuels affects the combustion efficiency and PM emissions. Fresh wood needs to be seasoned, i.e. allowed to dry before it is burnt. It is also important that the fuel does not get wet during transport or storage. In the US some air pollution control agencies have encouraged residents to use a wood moisture meter and in some areas it is illegal to sell, advertise or supply wood unless the wood moisture content is 20 % or less (USEPA, 2013). In Europe graded pellets and briquettes have a defined moisture content of less or equal to 10-15% depending on the fuel and grade (British Standards Institution 2014a and 2014b). There is no standard for wood logs, which are likely to have variable moisture content.

4. AGRICULTURAL RESIDUES

The burning of crop residues[8],is undertaken to clear land quickly and cheaply, prior to the preparation of the soil ready for re-planting. This source can give rise to significant emissions of PM over large areas. One extreme example occurred during April and May 2006, when a large number of fires occurred over almost 2 million ha across the Baltic countries, western Russia, Belarus, and the Ukraine. The fires, started by farmers burning their fields, became uncontrollable and spread to nearby forests including those in the Kuronian Spit nature reserve in Lithuania. Five people died in the fires in Latvia. The PM emitted from this event was detected as far north as Spitsbergen in the Artic and Iceland. The majority (55%) of the fires occurred on arable land and wooded grassland (24%) (Stohl et al., 2007). Satellite data suggests that there is significant year to year variation in the total area burnt in the Russian Federation (Karlsson et al., 2015), but this extreme event was not exceptionally large, but the meteorological conditions were conductive to long range transport of air pollution. The burning of agricultural residual is banned in the Russian Federation but there is poor enforcement of the legislation.

The burning of agricultural residuals is also widespread in Romania even though the practice only commenced around 1990 (Stan et al., 2014). This is thought to be due to the combination of a lack of suitable equipment for gathering the crop residues (particularly specialist machinery for bailing), transporting and storing them; the reduction in livestock after 1990, the lack good information for small farmers on alternative uses of the residues and the belief that soil tillage practice is better after straw burning (Stan et al., 2014). This suggests that there is an important role for educating farmers on alternative uses for these residues.

Quantifying emissions from the open burning of agricultural residues is difficult as the emissions depend on many factors including the type of residue, its moisture content; combustion conditions as well as meteorology, terrain and fire management techniques (e.g. Sanchis et al., 2014; Gonçalves et al., 2011; Dhammapala et al., 2007).

Few studies have investigated the emissions from European crop residue burning. Gonçalves et al. (2011) investigated $PM_{<10}$, $PM_{2.5-10}$ and $PM_{2.5}$ emissions from the open burning of agricultural wastes (potato haulm, weeds from arable fields, and collard green stalks/pruned green leafy twigs), in a field in Northern Portugal. The impact of burning these wastes with used lubricating oil in metal containers was also investigated. They found that the burning the stalks/leafy residue resulted in the highest emissions. Burning with used lubricating oil increased the emission particularly $PM_{2.5-10}$. Fog was present during the sampling and this is thought to have contributed to the formation of larger than expected particles. For all three types of residue the carbon was virtually all organic.

There is also little data available on the effect of agricultural burning on ambient PM concentrations in the EU. Viana et al. (2008) found that the burning of rice straw residues at rural site located close to Valencia (Eastern Spain) increased daily PM_{10} concentrations on a regional scale by 10–15 µg m^{-3} on average, with a maximum of 30 µg m^{-3} during the rice

[8] Emissions also occur during the burning of agricultural wastes such as from the pruning of trees and vines.

straw burning season in 2006. Papadakis et al (2015) used a chemical transport model to estimate the impact of burning olive tree branches in winter, a common practice in Mediterranean countries, on $PM_{2.5}$ concentrations in Greece. The predicted effect was more significant on the most polluted days when hourly average $PM_{2.5}$ concentrations increased by more than 50% in most of the modelled domain and by up to 150% in Crete. Monthly average concentrations increased by 20% in Crete.

According to Kostenidou et al. (2013) almost 1 billion or 90% of the world's olive trees are located around the Mediterranean. In Greece the burning of the pruned branches from these trees was estimated to result in the emission of approximately 6,600 tons of $PM_{2.5}$ over a 3-4 month period, significantly more than emitted by passenger cars (2013).

Whilst burning may be useful to control pests and disease in certain crops, the incorporation of the residues into the soil has an important role to play in increasing the soil organic content and improving the soil structure, resulting in higher productivity. This is particularly important in those countries where there has been a significant decrease in livestock farming and available manure to improve soils and chemical fertilisers are relatively expensive. For example, the ploughing-in of straw accounts for as little as 11 per cent of the total straw resource in Poland, but 30-40 per cent of the total supply in England and the Czech Republic and as much as 60 to 70 per cent in France (Kretschmer et al., 2012).

In Southern and Eastern Europe, however, the over-incorporation of straw into the soil can affect the long-term soil fertility (Edwards et al., 2005). As a consequence it is common for farmers in these regions to incorporate straw into the soil in only two out of three years (Kretschmer et al., 2012).

In southern Europe permissions for agricultural burning is given by local or regional authorities when there is low wind speeds to prevent forest fires but these are the conditions when the impact on air quality are the highest.

There are alternative uses for straw including animal bedding, supplementary livestock fodder, as a mulch for vegetable production and as a substrate for mushroom production. It can also be used as a fuel on farms and elsewhere, where emissions can be more effectively controlled.

5. ABATEMENT OF EMISSIONS

5.1. Introduction

There are a number of generic measures available to reduce PM emissions from biomass combustion, most of which are applicable to the control of residential wood combustion. There are, however, no options for controlling emissions from agricultural residue burning other than banning or severely restricting the practice.

The mitigation measures include:

- Product standards i.e. setting emission limits for the combustion appliances;

- Fuel quality standards i.e. the mandatory use of certified fuels;
- Mandating maintenance;
- Public education including the use of eco-labels;
- Fiscal incentives; and
- Banning the emission source.

Many of these measures have already been adopted in certain Scandinavian and Alpine countries with a long tradition of residential wood combustion, and some measures have been agreed at the EU, but have yet to be fully implemented.

The state of Upper Austria close to the Austrian border with Germany and the Czech Republic has actively promoted the use of clean and efficient biomass combustion over a period of nearly three decades. Today about 15% of the state's primary energy comes from biomass, and there are 44,000 automatic biomass boilers in operation in residential, commercial, and public sector buildings. Of these, approximately half use pellets and the other half wood chips (Egger et al., 2013).

There are three reasons why advanced biomass systems have been widely adopted in Upper Austria. Firstly, in the early 1980s the farming and forestry industries were looking for new markets for forestry residues. Secondly, entrepreneurs saw a market opportunity for fully-automated, highly efficient and user-friendly biomass systems and launched the first automatic wood pellet heating system in 1996. Thirdly state policy has provided stable support to the market over a very long period (Egger et al., 2013).

Support for biomass heating in Upper Austria consists of financial incentives, legislation and promotional activities. Investment grants are available both for purchasing biomass boilers and for connecting buildings to biomass district heating plants. Strict emissions and efficiency standards, which have been progressively tightened, and early standardisation of wood pellets have supported the development of clean technology. Consumer confidence in the new heating system has been developed through awareness campaigns and independent technical advice from the state agency for energy efficiency and renewable energy (OO Energiesparverband).

This combination of measures and sustained support, has led to Upper Austria being a world leader in the manufacturer and use of clean biomass technology, and more than 25% of all modern biomass boilers currently installed in the EU were manufactured there. However, it should be noted that Austria has relatively high BaP concentrations due to biomass burning, although in general the concentrations are not as high as in some eastern European states where there is prevalent coal burning (EEA, 2015).

5.2. Emissions limits

Austria, Denmark, Germany and Switzerland have had national emissions limits for residential wood burning appliances for several decades. Since 1999 there has been a

European standard (EN 303-5) which includes emission limits for 'dust'[9] emitted from solid fuel boilers up to 300 kW. This was revised in 2012 with more stringent emission limits. Certain countries have agreed deviations from the main text including Austria, Denmark, Germany and Switzerland to enable the standard to be consistent with their national standards and law. The emission limits in the European standard and national legislation are shown in Table 1 and Table 2 respectively.

Table 1: European Standard Dust Emission Limits for biomass heating boilers up to 300 kW (EN 303-5)

Type of appliance		**Limit (mg m^{-3})**		
		Class 3	**Class 4**	**Class 5**
Manually loaded	≤50 kW	150	75	60
	>50-150 kW			
Automatically loaded	≤50 kW	150	60	40
	>50-150 kW			

The 'dust' limits in this Table are based on the gravimetric filter method. The method used needs to be referred to in the test report. The condensable organic compounds form PM when the flue gas is cooled as it mixes with ambient air. This is not included in the PM measurements, and therefore the values are not directly comparable with those measured using dilution tunnel methods.

European Standards (ENs) automatically become a national standard in each of the member countries. Standards are voluntary which means that there is no automatic legal obligation to apply them. However, laws and regulations may refer to standards and make compliance with them compulsory. Therefore the framework is in place for all EU members to introduce emission limits for these appliances.

Table 2: Dust Emission limits for biomass heating appliances in Denmark, Germany and Switzerland (Source: EN 303-5; Danish Government, 2015)

Country	**Fuel/appliance**	**Limit (mg m^{-3})**	**Notes**
Austria	Manual/room heater	35	From 01.01.2015
	Manual/central heater	30	
	Automatic/ room heater/pellets	25	
	Automatic central heater/ pellets	20	
	Automatic/other wooden fuels	30	
	Automatic/other standardised biogeneous fuels	35	

[9] The term 'dust' used in EN 303-5 is defined as "particles, of any shape, structure or density, dispersed in the gas phase at the sampling point conditions which may be collected by filtration under specified conditions after representative sampling of the gas to be analysed, and which remain upstream of the filter and on the filter after drying under specified conditions".

Country	**Fuel/appliance**	**Limit ($mg\ m^{-3}$)**	**Notes**
Denmark	Space heater	40	@ 13% O_2 From 24.07.2015 Alternatively average 5 g/kg sampled using a dilution tunnel
		30	@ 13% O_2 From 24.01.2017 Alternatively 4 g/kg sampled using a dilution tunnel
	Manual/boiler	60	@ 10% O_2 From 24.07.2015
	Automatic/boiler	40	@ 10% O_2 From 24.07.2015
Germany	All	20	From 4 kW
Switzerland	Wood logs/ manual)	50	13% O_2
	Wood chips/ automatic	60	
	Wood pellets/automatic	40	

The UK has adopted a different approach. Under national legislation dark smoke[10] is not permitted to be emitted from a chimney of any building, and local authorities can designate Smoke Control Areas (SCAs) in which it is an offence to emit smoke. Authorised fuels are permitted to be burnt in any appliance in SCAs. In addition, any class of fireplace shown not to produce a substantial quantity of smoke may be allowed in a SCA. A list of permitted biomass stoves, room heaters and boilers is published by the government. This approach was first introduced to control smoke from coal burning in the 1950s and is not designed to control $PM_{2.5}$ emission from biomass combustion.

In addition to the emission limits in Table 1, in April 2015 the EU agreed mandatory emission limits under the Eco-design Directive (Directive 2009/125/EC)[11] for PM, CO, and organic gaseous compounds[12] as well as minimum energy efficiency requirements for new small space heaters and boilers. These new Regulations come into force from the beginning of 2020 and 2022 respectively (see Table 3). The Eco-design requirements are less stringent than some national standards (Table 2), and do not apply to the combustion of non-woody biomass.

[10] Dark smoke refers to a shade on the British Standard BS 2742C Ringelmann Chart. It is smoke that appears to be as dark as, or darker than, shade 2. Black smoke means smoke which would be as dark as, or darker than, shade 4 on the chart.

[11] Commission Regulation (EU) 2015/1185 of 24 April 2015 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for solid fuel local space heaters ≤50kW and Commission Regulation (EU) 2015/1189 of 28 April 2015 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for solid fuel boilers.

[12] Commission Regulation (EU) 2015/1185 defines 'organic gaseous compounds emissions' as the emissions of organic gaseous compounds at nominal heat output expressed in mgC/m^3 flue gas calculated to 273 K and 1,013mbar at 13 % O_2.

The emissions limits apply to the approval of new types of appliance, which might be tested on one model in a series. The Regulations also require emissions testing of each model put on the European market.

There are also indicative benchmarks for the best-performing solid fuel boilers available on the market at the time of entry into force of the Regulations. For biomass boilers the PM benchmark is 2 mg m^{-3}, while for biomass pellet space heaters it is 10 mg m^{-3}, and for other biomass heaters the benchmark is 20 mg m^{-3} .

The introduction of these emission limits is likely to reduce emissions from new appliances. However they do not apply to existing appliances. Given the slow replacement of domestic combustion appliances it is likely that the effectiveness of the Eco-design Regulations will be minimal in the short term, especially in those parts of Europe with a long established tradition of burning firewood, unless there is incentivised replacement programme.

Table 3: PM emission limits for biomass space heaters and boilers under the Eco-design Directive (2009/125/EC)

Type		**Emission limits**			**Applicable from**	**Notes**
		mg m^{-3} (1)	g kg^{-1} (2)	g kg^{-1} (3)		
Space heaters ≤50 kW	Open fronted	50*	6**	-	01.01.2022	* 13% O_2 ** Dry basis
	Closed fronted	40*	5 **	2.4**		
	Close fronted using wood pellets	20*	2.5**	1.2**		
Boilers <500 kW	Manually stoked	60			01.01.2020	10% O_2
	Automatically stoked	40				

1. PM measurement by sampling a partial dry flue gas sample over a heated filter in the combustion products of the appliance shall be carried out while the product is providing its nominal output and if appropriate at part load.
2. PM measurement by sampling, over the full burn cycle, a partial flue gas sample, using natural draft, from a diluted flue gas using a full flow dilution tunnel and a filter at ambient temperature;
3. PM measurement by sampling, over a 30-minute period, a partial flue gas sample, using a fixed flue draft at 12 Pa, from a diluted flue gas using a full flow dilution tunnel and a filter at ambient temperature or an electrostatic precipitator.

To force the replacement of older appliances the German legislation provides a transition period depending on when they were first installed. Those installed prior to 1995 have to meet the current requirements by 2015; appliances installed 1995-2004 by 2019 and those installed 2005-2010 by 2025. Combustion plants using solid fuels may only be operated if they are in a good condition and are regularly checked by a chimney sweep. Open fireplaces may only be operated occasionally and new masonry heaters must be equipped with dust abatement.

In Italy there are no national emission limits for biomass burning on appliances less than 35 kW. However some regions have adopted restrictions for these smaller appliances. For example, Lombardy prohibits the use of wood burning fireplaces and stoves that are less than 63% efficient during the winter months in certain areas; but only in homes where there are alternative heating systems.

Other communes have restricted the use of biomass appliances in homes fitted with alternative heating systems when ambient PM_{10} concentrations exceed 50 µg m^{-3}. This type of restriction on residential biomass combustion is likely to be most effective when it is linked to air quality forecast, so the emission can be reduced before high concentrations occur. This approach has been adopted in some communities in the US. Depending on the severity of the emissions restriction often have two stages. In Stage 1 only EPA-certified wood stoves are permitted to operate, and in Stage 2 all wood-burning appliances are banned unless it is the household's only source of heat (USEPA, 2013).

An alternative approach has been adopted in the UK for biomass boilers, which links fiscal incentives to emission limits (see section 5.5). To ensure the complete combustion of the fuel, biomass boilers are required to have the following features:

- An adaptive fuel feed mechanism which adjusts the amount of fuel fed into the boiler in real time depending on the instantaneous load on the boiler.
- The monitoring of boiler flow and return temperatures, and their use via a control system to regulate the fuel feed rate and the speed of combustion air fans.
- Separately controllable primary and secondary combustion air (also tertiary air control on boilers above about 5 MW).
- A lambda sensor to monitor the oxygen content of the flue gas to ensure sufficient excess oxygen is supplied for complete combustion by regulating secondary (and tertiary) air fans.

In parts of the US the removal and destruction of old wood stoves is required when a home is sold. This is to encourage the replacement with newer, cleaner-burning appliances. In addition in some areas the fitting of fireplaces and other wood burning appliances in new built homes is banned, or the number and density of new wood-burning appliances in a given areas is restricted (USEPA, 2013).

The United Nations Environmental Programme (2011) has recommended that pellet stoves and boilers replace current wood-burning technologies in the residential sector in industrialized countries.

Fountoukis et al. (2014) used a chemical transport model to forecast the impact of replacing current residential wood burning appliances with pellet stoves. They predicted up to 60% decrease of OC in urban and suburban areas and decreases of 30-50% in EC over large parts of Europe during winter. The authors also predicted approximately 40% decrease in oxidised OC, mostly in rural and remote areas. $PM_{2.5}$ mass was predicted to decrease by 15-40% on average during winter in continental Europe.

5.3. Fuel quality standards

Some European countries (Austria, Germany, Switzerland and Sweden) have well established biomass quality standards covering the chlorine (Cl) and potassium (K) content as well as heavy metals such as Cd, Pb, Zn, Cr, Cu, As and Hg (Obernberger and Thek, 2003).

In 2010 an EN standard classification system was adopted (EN 14961) but was replaced by the international ISO standard 17225 in 2014 which provides a detailed scheme for different types of solid biofuels. A similar range of constituents are specified for three grades of fuels.

The voluntary ENplus quality scheme has three quality classes: EN*plus* A1, EN*plus* A2 and EN*plus* B based the ISO 17225-2 standard, but with some more stringent requirements. Each year the pellet production processes are audited and pellets analysed by accredited testing laboratories. Traders are also inspected annually. The fuel parameters specified include moisture, ash, sulphur, nitrogen, and metal content. EN*plus* was first introduced in Germany in 2010 and since then the scheme has been widely adopted across the EU and further afield. The aim of the ENplus certification scheme is to encourage the supply of wood pellets with a defined and consistent quality (European Pellet Council, 2015b). This quality scheme does not include sustainability criteria, and currently there are a number of different voluntary schemes operating in the EU.

The emissions of heavy metals from the certified pellets tested by AIRUSE (2015) were low. The study concluded that the lack of standards for raw materials inappropriate storage, poor handling, use of waste wood and as well as the use of binders probably all contribute to poor product quality. It is therefore important that mandatory standards for commercial wood pellets and chips are agreed to ensure that these fuels are not contaminated and are fit for purpose.

There are no quality schemes for wood logs in Europe. In parts of the US households are encouraged to measure the moisture content of their fuels to increase the likelihood of seasoned wood being used. Some areas also deem it illegal to sell, advertise, or supply wood for residential combustion with a moisture content greater than 20% (USEPA, 2013). The ISO 17225 standard limits the moisture content to 10% for pellets, and 12-15% for wood briquettes depending on the grade. For wood chips only the A1 and A2 grades have a moisture limit which varies between 10 and 35%.

5.4. Maintenance

In general, maintenance of biomass storage and combustion appliances is a safely issue. Tar can build up in the chimney and flue ductwork due to poor fuel management and prolonged low temperature operation. This tar usually burns off but if it ignites can cause a chimney fire. To avoid this occurring the flue should be checked and cleaned annually by a professional chimney sweep.

Inspection and maintenance of biomass appliances should be undertaken to the manufacturer's specification to ensure efficient combustion and low emissions. In some countries, such as Germany, chimney sweeps are required by law to inspect appliances on an annual basis to ensure that they are appropriately installed and certified, there is dry storage for the fuel, emissions limits are achieved, and the chimney is cleaned.

5.5. Fiscal incentives

Fiscal incentives have been used in a number of EU countries to encourage fuel switching to renewable energy sources, including residential wood combustion. None of these schemes appear to be specific to biomass and include solar heating and renewable other fuels.

The heating sector offers particular challenges for incentives. Heat is difficult to regulate as it is produced in millions of separate installations of widely varying sizes, at different temperatures, from several different fuels, and across the full range of end-users. Reliable data on heat production, its utilisation patterns and the costs of production are much more difficult to obtain than those for electricity and gas. Heat metering is also more costly. This makes the development of renewable energy heat policies, as well as the assessment of their effectiveness, much more difficult (IEA 2014).

The UK has the only heat based incentive system in the world. The Renewable Heat Incentive (RHI) was established in 2014 to encourage the use of renewable heat technologies by householders, communities and businesses. The domestic RHI scheme provides payments to households to compensate for the cost difference between installing and operating renewable heating and fossil fuel systems, including non-financial costs such as disruption, on the basis of 20 years of heat produced. The payments will be made quarterly for seven years and are currently 0.0643 £/kWh for biomass appliances. Biomass systems must provide space heating or space and water heating using a 'wet' central heating system like radiators. All biomass appliances must have an Emissions Certificate, issued by an accredited testing laboratory, showing the emissions when burning a specific fuel. The emission limits are 30 g GJ^{-1} for PM and 150 g/GJ for NOx. Only the fuel type(s) listed on the certificate can be used in the appliance, and householders may be asked to produce fuel receipts to prove the correct fuel has been used. All biomass fuel used by RHI participants must meet the Government's sustainability criteria and be sourced from a supplier on the Biomass Suppliers List. Early data suggests that most of the households that have benefited from the RHI support for biomass converted from oil. There is no evidence that they have converted from traditional biomass or sold fuel appliances. The domestic RHI is the first of its kind in the world and the UK Government expects it to play an important role in achieving its 2020 target of 12% of heating coming from renewable sources. It is too early to assess its effectiveness.

Biomass boilers require greater capital investment than fossil fuel boilers, but typically have lower fuel costs. Given this it may be that subsidising the installation of boilers is more effective than providing subsidies for the heat produced. Subsidies towards the capital cost of renewable heating systems are the most widely adopted financial mechanism for the support of renewable heat (IEA, 2014). This incentive can be in the form of a direct cash rebate or a tax credit, the latter being particularly important for businesses. In the US it has been found that incentive schemes to replace older technologies with most effective when accompanied by public education campaigns (USEPA, 2013).

Austria has taken a very different approach to the UK. In common with other countries it provides subsidies for the installation of technology, not its use. Grants to householders typically cover about 20% of the investment costs for an automatic heating system and are provided by the state government. A separate program exists for apartment buildings. New homes that receive funding from the state housing program (i.e. 95% of all new single-family homes) must also install a renewable heating system. The only fossil fuel-based heating systems allowed are gas condensing boilers, which must be combined with a solar thermal system. There has been a rapid growth in the number of residential biomass boilers due to these and other incentive programmes. The fact that wood for space heating is well-established in Austria has helped the rapid development of pellet boilers, as consumers were used to heating their homes with biomass (IEA, 2014). Similar fiscal incentives have been adopted

The Austrian Government has also provided incentives for the production of high quality wood pellets. The steady growth of the market resulted in over 10,000 new wood pellet boilers being installed in 2006 A short-term pellet price increase, however, caused uncertainty among consumers and led to a significant drop in new boiler installations in 2007. The expansion of the domestic wood pellet production capacity in 2007, supported by government subsidies, helped bring prices down and re-established consumer confidence, resulting in a continued growth of the market such that in 2013 more than 12,000 pellet boilers were installed (IEA, 2014).

Fiscal incentives can also pay an important role in discouraging farmers from burning agricultural residues. One of the reasons for the widespread practice in Russia is the weak economic state of its farms (Karlsson et al., 2015). Agricultural subsidies are very low in comparison with those available in the EU (IEEP, 2012). A number of EU Member States have used their Rural Development Programme, part of the Common Agricultural Programme (CAP) to provide fiscal incentives for straw to be left on fields following harvest and its incorporation either following the harvest or before cultivation in the spring (IEEP, 2012). New minimum standards for good agricultural and environmental condition (GAEC) of land were established by Regulation (EU) No 1306/2013 in 2013. GAEC 6 states "the maintenance of soil organic matter level through appropriate practices including ban on burning arable stubble, except for plant health reason". Member States can introduce a general ban on burning arable stubble, but may decide to prescribe further requirements. Therefore there is now a presumption that beneficiaries of the CAP should not burn agricultural residues, although national standards may include a number of exemptions, including for the control of pests and disease. Indeed, in the UK, the agricultural industry is lobbying government to remove the 20 year ban on stubble burning to address invasive black grass (e.g. Association of Independent Crop Consultants, 2015).

5.6. Eco-labels

The EU Eco-label is a voluntary scheme, established in 1992, to encourage businesses to market environmentally friendly products and services. It enables consumers to differentiate products based on their environmental impacts. It covers a wide range of products and services including water based heaters, but does not explicitly include biomass burning appliances. There are national eco-label schemes in Germany (Blue Angel) and the Nordic Countries (Nordic Swan). These have specific criteria for wood pellet heaters and solid biomass boilers and stoves respectively. It would be useful for the EU scheme to specifically include these appliances.

Some of the domestic biomass appliances tested in research projects (e.g. AIRUSE, 2015; Win et al., 2012) appear to exceeded the eco-label criteria. However, these have not been tested under the conditions specified by the eco-label, and therefore are not strictly comparable. The eco-label test procedure requires the PM to be sampled from the hot flue gases whereas research studies tend to take samples from a dilution tunnel to more closely represent the emissions into the atmosphere. In addition, the eco-labels only require testing of emissions during the steady state (stage 2) combustion, and do not include the significant emissions that occur during start-up and end of combustion. Win et al. (2012) found that the PM emissions from six appliances, that included the start-up and end stages, were approximately 3-6 times higher than the limit value of the Swan scheme for boilers and 2-7 times higher than the limit values of the Blue Angel scheme for boilers and stoves.

5.7. Public education

The provision of independent advice on emissions from biomass appliances can encourage consumers to invest in cleaner technology. The experience in Upper Austria suggests that awareness campaigns that are independent of the sales of a product are crucial for market growth; this is especially true for an emerging industry that has limited resources for marketing (Egger et al., 2013).

The OO Energiesparverband provides homeowners as well as public agencies and businesses with energy advice to inform their investment decisions. Each year, it provides 15,000 free face-to-face energy consultations to homeowners and public agencies. It has also undertaken a number of information campaigns to promote biomass heating utilising the media, billboards and other advertising strategies. Competitions have also been used to draw people‘s attention to heating with wood.

A trial in rural Italy has shown that sharing the results of local air pollution monitoring with households with biomass appliances increases the residents' perception of the health risk from emissions and their assimilation of information regarding good burning techniques. The data identified poor installations and fuel management practices as a significant cause of poor indoor air quality. The results were discussed with the homeowners. During the following winter indoor air quality improved despite colder outdoor air temperatures. The study concluded that the information provided to families resulted in the adoption of more effective practices to manage the emissions from their appliances (Piccardo et al., 2014).

In addition public education campaigns in the US have been shown to be affective at reducing emissions. By encouraging households to adopted good burning techniques and use well-seasoned wood emission can be reduced significantly (USEPA, 2013).

5.8. Banning biomass burning

It is considered unlikely that any EU government would introduce a ban on residential biomass combustion, although there could be limited bans during periods of high pollution such as those introduced in parts of Lombardy. Yap and Garcia (2015) investigated the effectiveness of a similar ban in the San Joaquin Valley in California when air quality was forecast to be poor (daily mean $PM_{2.5}$ concentration of approximately 65 µg m^{-3}). The effect of the ban was a reduction of 11-15% in wintertime average $PM_{2.5}$ concentrations.

The use of inefficient traditional wood burning appliances could, however, be banned. This would require implementation over a long period in a similar manner to the German transitional arrangements for the replacement of old biomass burners.

The burning of agricultural stubble has been implicitly banned in Member States by the Good Agricultural and Environmental Condition (GAEC) standards. Farmers need to follow these non-mandatory standards to receive funding under the Common Agricultural Policy. However Member State may allow derogations based on local conditions, such as those that permit it when wind speeds are low. Given the scale of these fires and their significant regional scale impacts on air quality there should be a total ban. The GAEC standards should make the ban on the burning of agricultural residues mandatory.

Some Member States also ban straw and stubble burning under national legislation. For example, in Denmark straw burning has been banned since 1991 and in England straw burning (of a significant scale) was banned in 1993. Such restrictions provide incentives for the incorporation of straw into the soil, and its use for other farming purposes or as a renewable fuel. The United National Environment Programme (2011) has recommended that the burning of agricultural residues be banned in all industrialised countries.

However, a mandatory ban will only be viable if the market for alternative uses of the residues develops and provides farmers with sufficient financial incentives to change their practices. This is likely to need financial and other government support, such as public education campaigns and outreach to farmers.

6. SUMMARY AND RECOMMENDATIONS

6.1. Summary

The emission of particulate matter (PM) from the residential burning of biomass for space and water heating has been shown to have a significant impact on air quality across Europe and to contribute to exceedences of the EU limit values. Emissions of PM and benzo(a)pyrene (BaP) from this source have increased over the last decade as policies to promote renewable energy have taken effect. Ambient concentrations are particularly high in central and eastern Europe, but also in the Po Valley, where biomass burning is widespread. Modern automatic pellet and wood chip appliances are significantly more energy efficient and have lower emissions than traditional fireplaces and wood log stoves, but most biomass burning is likely to take place in inefficient and polluting appliances.

PM emissions from residential biomass appliances are not regulated in most EU countries. Only in the Nordic and Alpine countries, where domestic wood burning is most widespread, have emission limits been adopted into national legislation. EU emission limits, however, were agreed in April 2015 for small scale solid fuelled space heaters and boilers which will be introduced from 2022 and 2020 respectively. These limits are less stringent that those in some national legislation.

There appear to be significant differences in the emissions depending on the type of biomass, particularly when burnt in traditional fireplaces and simple wood stoves. The available data suggests that emissions are lower (in mg MJ^{-1}) from the combustion of less dense woods such as pine than the more dense oak and olive. However, combustion is much faster, and therefore it is recommended that softwood is only used to initiate combustion. The burning of non woody biomass has the highest emissions, and these fuels are currently excluded from the Eco-design Regulations.

6.2. Recommendations

Biomass Appliances

The adoption of the EN 303-5 standard, first in 1999, and then revised in 2012, offers Member States an opportunity to mandate that all new biomass boilers meet these requirements. This, however, is considered unlikely to occur because the new Eco-design Regulation efficiency and emission limits will come into force within four (boilers) to six (stoves) years. Member States could however promote the use of appliances that meet the Eco-design benchmarks through a certification scheme, such as an eco-label or through linking fiscal incentives to appliances which achieve some or all the benchmarks. This would provide a clear incentive for manufacturers to invest in developing biomass combustion technology and abatement systems. If the use of non-woody biomass increases the Regulations will need to be extended to cover these fuels. The Eco-design Regulations are for new appliances. The typical lifetime of biomass appliances is likely to be many years if not several decades. Therefore this legislation will only be effective in a growing market, when a large number of new appliances are sold each year. As there is already air pollution resulting from the emissions from these devices, it seems appropriate to consider measures to reduce emissions of those currently in operation. Transitional arrangements, as in the German legislation, could be introduced to require the gradual replacement of the oldest devices over the next decade or so.

National and regional governments could support voluntary replacement/retrofit programmes to encourage households to replace older appliances with safer, more efficient, cleaner burning technologies. Financial incentives may be necessary to assist with the capital costs of replacement or retrofitting appliances.

It may be appropriate to ban the combustion of biomass in open fireplaces and simple wood burning stoves in areas where there are high PM concentrations. The United Nations Environmental Programme (2011) has recommended that in industrialised countries biomass should be burnt in pellet stoves and boilers, using fuel made from recycled wood and sawdust.

This is, however, likely to be meet with significant consumer resistance because of the emotional attachment to this practice (e.g. Piccardo et al., 2014; Reeve et al, 2013). However, it may be more acceptable if any was limited to periods of elevated PM pollution.

As emissions are dependent on operator practices it is important that there is greater public awareness of the risk of high PM emissions particularly from traditional devices with low energy efficiency. Emissions from open fireplaces adversely affect indoor as well as outdoor air quality.

Consumer advice should include using commercial fire lighters or a small amount of newspaper to light the fire; not to the appliance as a waste incinerator; maintain good control of the air flow (where possible), maintain the appliance according to the manufacturer's specifications; clean it regularly; and have the chimney professionally swept annually.

In addition, the thermal insulation of homes should be improved to reduce wood consumption and associated emissions.

Biomass fuels

Only certified pellets, briquettes and chips meeting high quality specifications should be permitted to be sold in Member States. The constituents of the pellets should be independently verified using an accredited laboratory, and not be made from contaminated waste wood.

It is more difficult to provide quality standards for wood logs and chips as they will vary depending on the source. Suppliers of these produced could be required to only sell seasoned wood that has been stored undercover.

Burning of agricultural residues

For controlling emissions from the open burning of agricultural residues the main mitigation measure is to ban the practice. This measure is supported by the United Nations Environmental Programme for industrialised countries (UNEP, 2011) as well as the GAEC of the EU Common Agricultural Policy. In reality Member State may allow exemptions in many areas. It is important that Member State understand the air quality consequences of wide scale burning of residues in fields and farm advisory services should educate farmers on this issue.

The GAEC standards should be modified to make the ban on the burning of agricultural residues mandatory and not subject to local derogations. As the current GAEC Standards have only recently been adopted this is unlikely to happen for some years. Therefore it is recommended that Member States introduce their own ban on this practice to improve air quality.

In addition, Member States should provide fiscal and other support for the development of the straw market for animal bedding, vegetable and mushroom production but also as an energy crop. Where there are alternative uses for straw with acceptable prices, a market will develop, providing farmers with an economic incentive to the incentive to stop the practice.

Public education

There is a need independent and authoritative advice for members of the public to fully understand the impact of different types of biomass combustion systems and fuels on emissions and air quality. Whilst this is important for those seeking to invest in a new system, it is possibly of greater importance for those that have an existing appliance. Few people have been taught the factors that affect emission and how to minimise them. This is especially important for the control of emissions from manually devices.

7. REFERENCES

AIRUSE, 2015, Summary Report. Available from http://airuse.eu/outreach dissemination/reports/ .

Association of Independent Crop Consultants, 2015. http://www.aicc.org.uk/minister-consider-stubble-burn-options. Accessed 25.11.2015.

Bari, M.A., Baumbach, G., Kuch, B., Scheffknecht, G. (2010). Temporal variation and impact of wood smoke pollution on a residential area in southern Germany. Atmospheric Environment. 44, 3823-3832.

Bari A., G. Baumbach, J. Brodbeck, M.l Struschka, B. Kuch, W. Dreher, G. Scheffknecht (2011). Characterisation of particulates and carcinogenic polycyclic aromatic hydrocarbons in wintertime wood-fired heating in residential areas. Atmospheric Environment 45, 7627-7634.

Bernardoni, V., Vecchi, R., Valli, G., Piazzalunga, A., Fermo, P. 2011. PM10 source apportionment in Milan (Italy) using time-resolved data. The Science of the Total Environment, 409, 4788– 4795.

Crilley L. R., W. J. Bloss, J. Yin, D. C. S. Beddows, R. M. Harrison, J. D. Allan, D. E. Young, M. Flynn, P. Williams, P. Zotter, A. S. H. Prevot, M. R. Heal, J. F. Barlow, C. H. Halios, J. D. Lee, S. Szidat, and C. Mohr (2015), Sources and contributions of wood smoke during winter in London: assessing local and regional influences. Atmospheric Chemistry and Physics, 15, pp. 3149–3171.

Bølling A.K., Pagels J., Yttri K.E., Barregard L., Sallsten G., Schwarze P.E., Boman C. (2009). Health effects of residential wood smoke particles: the importance of combustion conditions and physicochemical particle properties. Particle and Fibre Toxicology, 6, 29. doi:10.1186/1743-8977-6-29.

Bressi M., J. Sciare, V. Ghersi, N. Mihalopoulos, J.-E. Petit, J. B. Nicolas, S. Moukhtar, A. Rosso, A. Féron, N. Bonnaire, E. Poulakis, and C. Theodosi. 2014. Sources and geographical origins of fine aerosols in Paris (France). Atmospheric Chemistry and . Physics, 14, 8813-8839, 2014.

British Standards Institution, 2012. BS EN 303-5:2012 Heating boilers Part 5: Heating boilers for solid fuels, manually and automatically stoked, nominal heat output of up to 500 kW - Terminology, requirements, testing and marking. London.

British Standards Institution, 2014a. BS EN ISO 17225-2:2014. Solid biofuels — Fuel specifications and classes. Part 2: Graded wood pellets. London.

British Standards Institution, 2014b. BS EN ISO 17225-2:2014. Solid biofuels — Fuel Part 3: Graded wood briquettes. London.

Calvo A.I., V. Martins, T. Nunes, M. Duarte, R. Hillamo, K. Teinila, V. Pont, A. Castro, R. Fraile, L. Tarelho, C. Alves (2015). Residential wood combustion in two domestic devices: Relationship of different parameters throughout the combustion cycle. Atmospheric Environment 116, 72-82.

Calvo A.I., L.A.C. Tarelho, C.A. Alves, M. Duarte, T. Nunes (2014). Characterization of operating conditions of two residential wood combustion appliances. Fuel Processing Technology 126, 222–232.

Crippa, M., DeCarlo, P. F., Slowik, J. G., Mohr, C., Heringa, M. F., Chirico, R., Poulain, L., Freutel, F., Sciare, J., Cozic, J., Di Marco, C. F., Elsasser, M., Nicolas, J. B., Marchand, N., Abidi, E., Wiedensohler, A., Drewnick, F., Schneider, J., Borrmann, S., Nemitz, E., Zimmermann, R., Jaffrezo, J.-L., Prévôt, A. S. H., and Baltensperger, U. (2013). Wintertime aerosol chemical composition and source apportionment of the organic fraction in the metropolitan area of Paris, Atmos. Chem. Phys., 13, 961–981.

EEA, 2015. European Union Emission Inventory Report 1990–2013 Under the UNECE Convention on Long-Range Transboundary Air Pollution (LRTAP). Technical Report 8/2015. Annex I: European Union LRTAP emission data (EU-27).

Danish Government (2015). Order regarding air pollution from solid fuel combustion plants under 1 MW, unofficial translation. MST - 5230 – 00163. http://eng.mst.dk/media/131065/statutory-order-on-wood-stoves-2015.pdf,asccessed 25.11.2015.

Dhammapala, R., Claiborn, C., Simpson, C., Jimenez, J., (2007). Emission factors of PAHs, methoxyphenols, levoglucosan, elemental carbon and organic carbon from simulated wheat and Kentucky bluegrass stubble burns Emission factors from wheat and Kentucky bluegrass stubble burning: comparison offield and simulated burn experiments. Atmos. Environ. 41, 1512–1520.

Edwards, R, Šúri, M, Huld, T and Dallemand J F (2005). GIS-Based Assessment of Cereal Straw Energy Resource in the European Union. Proceedings of the 14th European Biomass Conference & Exhibition. Biomass for Energy, Industry and Climate Protection, 17.-21. October 2005, Paris. Available from http://iet.jrc.ec.europa.eu/remea/sites/remea/files/gis-straw_assessment.pdf.

EEA, 2015a. Annual European Union Greenhouse Gas Inventory 1990–2012 and inventory report 2014, Technical Report No 9/2014. Annex 2.8 CRT Tables Agriculture.

EEA, 2015b. Air quality in Europe - 2015 report. Copenhagen.

Egger C., C. Öhlinger, B. Auinger, B. Brandstätter, N. Richler, G. Dell (2013). Biomass heating in Upper Austria - Green energy, green jobs. OO Energiesparverband, Linz, Austria.

European Biomass Association, 2015, AEBIOM Statistical Report – European Bioenergy Outlook, Key Findings, Brussels,

file:///C:/Users/Public/Documents/Birmingham%20University/Biomass%20burning/AEBIOM-Statistical-Report-2015_Key-Findings1.pdf, accessed 16 November 2015.

European Commission, 2014, State of play on the sustainability of solid and gaseous biomass used for electricity, heating and cooling in the EU, Commission Staff Working Document, SWD(2014) 259 final Brussels, 28.7.2014.

European Pellet Council, (2015a). http://www.enplus-pellets.eu/wp-content/uploads/2011/12/ENplus-handbook-2.0-press-release_29.03.2013.pdf. Accessed 19 November 2015.

European Pellet Council, (2015b). http://www.enplus-pellets.eu/wp-content/uploads/2015/07/ENplus-V3-requirements-changes.png. Accessed 19 November 2015.

Fountoukis C., T. Butler, M.G. Lawrence, H.A.C. Denier van der Gon, A.J.H. Visschedijk, P. Charalampidis, C. Pilinis, S.N. Pandis (2014). Impacts of controlling biomass burning emissions on wintertime carbonaceous aerosol in Europe. Atmospheric Environment. 87, 175-182

Fuller G.W., A.H. Tremper, T.D. Baker, K.E. Yttri, D. Butterfield. 2014. Contribution of wood burning to PM10 in London. Atmospheric Environment 87, 87-94.

Fuller, G.W., Sciare, J., Lutz, M., Moukhtar, S. and Wagener, S., 2013. New Directions: Time to tackle urban wood burning?, Atmospheric Environment, 68, 295–296.

Giannoni M., T. Martellini, M. Del Bubba, A. Gambaro, R. Zangrando, M.o Chiari, L. Lepri, A. Cincinelli (2012). The use of levoglucosan for tracing biomass burning in PM2.5 samples in Tuscany (Italy). Environmental Pollution. 167, 7-15.

Gonçalves C., M. Evtyugina, C. Alves, C. Monteiro, C. Pio, M. Tomé. Organic particulate emissions from field burning of garden and agriculture residues. Atmospheric Research. 101, 666–680.

Gonçalves C., C. Alves, M. Evtyugina, F. Mirante, C. Pio, A. Caseiro, C. Schmidl, H.Bauer, F.Carvalho (2010). Characterisation of PM10 emissions from woodstove combustionof common woods grown in Portugal. Atmospheric Environment. 44, 4474-4480.

Harrison R.M., D.C.S. Beddows, A.M. Jones, A. Calvo C. Alves, C. Pio (2013). An evaluation of some issues regarding the use of aethalometers to measure woodsmoke concentrations. Atmospheric Environment. 80, 540-548.

Herich H., M.F.D. Gianini, C. Piot, G. Mocnik, J.-L. Jaffrezo, J.-L. Besombes, A.S.H. Prévôt, C. Hueglin (2014). Overview of the impact of wood burning emissions on carbonaceous aerosols and PM in large parts of the Alpine region. Atmospheric Environment. 89, 64-75.

IARC (2010). IARC Monographs on the Evaluation of Carcinogenic Risks to Humans VOLUME 92 Some Non-heterocyclic Polycyclic Aromatic Hydrocarbons and Some Related Exposures. Lyons, France.

Karlson P. E., L. R. Hole, H.Tømmervik and E. Kobets, 2015. Air pollution in the Nordic countries from biomass burning in Eastern Europe. Nordic Council of Ministers, Copenhagen.

Kistler M., C. Schmidl E. Padouvas H. Giebl, J. Lohninger, R. Ellinger, H. Bauer, H. Puxbaum,(2012). Odor, gaseous and PM10 emissions from small scale combustion of wood types indigenous to Central Europe. Atmospheric Environment 51. 86-93.

Kostenidou E., C. Kaltsonoudis, M. Tsiflikiotou, E. Louvaris, L. M. Russell, and S. N. Pandis (2013). Burning of olive tree branches: a major organic aerosol source in the Mediterranean. Atmospheric Chemistry and Physics. 13, 8797–8811.

Kretschmer B, B. Allen and K. Hart, 2012, Mobilising Cereal Straw in the EU to feed Advanced Biofuel Production. Report produced for Novozymes. IEEP: London.

Maenhaut, W., Vermeylen, R., Claeys, M., Vercauteren, J., Matheeussen, C., Roekens, E. (2012). Assessment of the contribution from wood burning to the PM 10 aerosol in Flanders, Belgium. The Science of the Total Environment 437, 226–236.

Ofgem, 2015, Domestic Renewable Heat Incentive (RHI) Essential Guide for Applicants, Version 2.1 June 2015, https://www.ofgem.gov.uk/sites/default/files/docs/2014/07/essentialguideforapplicants_web_june_2015_0.pdf, accessed 16 November 2015.

Palmer D., I Tubby, G. Hogan, W.Rolls (2011). Surrey. Biomass heating: a guide to feasibility studies Biomass Energy Centre, Farnham.

Piccardo M.T., M. Cipolla, A. Stella, M. Ceppi, M. Bruzzone, A. Izzotti, F. Valerio (2014). Indoor pollution and burning practices in wood stove management. Journal of the Air & Waste Management Association. 64 (11), 1309-1316.

Pietrogrande M.C., D. Bacco, S. Ferrari, J. Kaipainen, I. Ricciardelli, M.-L. Riekkola, A. Trentini, M. Visentin ~(2015). Characterization of atmospheric aerosols in the Po valley during the supersito campaigns - Part 3: Contribution of wood combustion to wintertime atmospheric aerosols in Emilia Romagna region (Northern Italy). Atmospheric Environment. 122, 291-305.

Piazzalunga A., C. Belisc, V. Bernardonid, O. Cazzulie, P. Fermoa, G. Vallid, R. Vecchi, 2011. Estimates of wood burning contribution to PM by the macro-tracer method using tailored emission factors. Atmospheric Environment. 45 (2011) 6642-6649.

Saffari A., N. Daher, C. Samara, D. Voutsa, A. Kouras, E. Manoli, O. Karagkiozidou, C. Vlachokostas, N. Moussiopoulos, M. M. Shafer, J. J. Schauer, and C. Sioutas. Increased Biomass Burning Due to the Economic Crisis in Greece and Its Adverse Impact on Wintertime Air Quality in Thessaloniki. Environental Science and Technology. 47, 13313-13319.

Sanchis E., M. Ferrer, S. Calvet, C. Coscolla , V. Yusa , M. Cambra-Lopez (214). Gaseous and particulate emission profiles during controlled rice straw burning. Atmospheric Environment. 98, 25-31.

Salthammer T., T. Schripp, S. Wientzek, M. Wensing (2014). Impact of operating wood burning fireplace ovens on indoor air quality. Chemosphere. 103, 205–211.

Sarigiannis D.A., S.P. Karakitsios, M. V. Kermenidou, 2015. Health impact and monetary cost of exposure to particulate matter emitted from biomass burning in large cities. Science of the Total Environment. 524–525, 319–330.

Schmidl C., M. Luisser, E. Padouvas, L. Lasselsberger, M. Rzaca, Carlos R.-S. Cruz, M. Handler, G. Peng, H. Bauer, H.s Puxbaum (2011). Particulate and gaseous emissions from manually and automatically fired small scale combustion systems. Atmospheric Environment 45. 7443-7454.

Stan V., G. Fîntîneru, M. Mihalache, Multicriteria analyusis of the effects of field burning crop residues. Notulae Botanicae Horti Agrobotanici Cluj-Napoca. 42(1), 255-262.

United Nations Environment Programme, (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decision Makers. Nairobi, Kenya.

USEPA, 2013. Strategies for reducing residential wood smoke. US Environmental Protection Agency, Research Triangle Park, North Carolina.

van der Gon H. A. C. D., R. Bergström, C. Fountoukis, C. Johansson, S. N. Pandis, D. Simpson, and A. J. H. Visschedijk, 2015. Particulate emissions from residential wood combustion in Europe – revised estimates and an evaluation. Atmospheric Chemistry and Physics. 15, 6503–6519.

Vicente E.D., M.A. Duarte, A.I. Calvo, T.F. Nunes, L. Tarelh, C.A. Alves. (2015). Emission of carbon monoxide, total hydrocarbons and particulate matter during wood combustion in a stove operating under distinct conditions. Fuel Processing Technology. 131, 182-192.

Viana M., C. Reche, F. Amato, A. Alastuey, X. Querol, T. Moreno, F. Lucarelli, S. Nava, G. Calzolai, M. Chiari, M. Rico (2013). Evidence of biomass burning aerosols in the Barcelona urban environment during winter time. Atmospheric Environment. 72 81-88.

Vianaa M., J.M. López, X. Querol, A. Alastueya, D. Garcı´a-Gaciob, G. Blanco-Herasb, P. López,Mahía, M. Pineiro-Iglesias, M.J. Sanz, F. Sanz, X. Chi, W. Maenhau (2008). Tracers and impact of open burning of rice straw residues on PM in Eastern Spain. Atmospheric Environment. 42 1941 – 1957.

Vu V.T.., J.M. Delgadon-Saborit, R.M. Harrison (2015). Review: Particle number size distributions from seven major sources and implications for source apportionment studies. Atmospheric Environment, 122, 114-132.

Wagener S., M. Langner, U. Hansen, H.-J. Moriske, W. R. Endlicher (2012). Source apportionment of organic compounds in Berlin using positive matrix factorization — Assessing the impact of biogenic aerosol and biomass burning on urban particulate matter. Science of the Total Environment 435–436, 392–401.

Win K.M., T. Persson, C. Bales (2012). Particles and gaseous emissions from realistic operation of residential wood pellet heating systems. Atmospheric Environment. 59, 320-327.

WHO 2013 Review of evidence on health aspects of air pollution – REVIHAAP Project Technical Report. WHO Regional Office for Europe, Copenhagen, Denmark.

Yap P.-S., and C. Garcia (2015). Effectiveness of Residential Wood-Burning Regulation on Decreasing Particulate Matter Levels and Hospitalizations in the San Joaquin Valley Air Basin. American Journal of Public Health. 05, 772–778.