Department of Mechanical and Aerospace Engineering

Biomass boiler emissions and chimney height - A review of practice in the UK and other EU countries

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ABSTRACT

The aim of this dissertation is to investigate the biomass combustion practice in Europe, particularly those areas related to emissions and chimney height calculation procedures. As the biomass industry keeps growing in Europe, especially for meeting the Europe’s 2020 targets and carbon reduction 2050 targets, the necessity of having a review of the most important environmental impacts and investigating the best practices for this impact reduction, increases. Therefore, this thesis also includes a revision of the main European legislation related to emission limits and chimneys, in order to perform an analysis of the differences existing among countries in Europe. Moreover, the chimney height calculation methodologies are investigated for five European countries by calculating the chimney height for some specifically created case studies following the different models, with the purpose of carrying out a comparison and to understand the differences existing in chimney height calculation.

Although most of the countries have developed complex air dispersion modelling software, this is hard to access and use, due to the high prices in the market and the complexity of the software. Therefore, this thesis is based on simple methodologies usually included in each country’s regulations.

The results from this dissertation show that there is a significant difference among the countries both in emissions legislation and chimney height calculation. In addition, it has been concluded that all of the available simple methodologies are not updated and are directed to large-scale biomass installations. Therefore, it seems necessary to develop a European agreement of the biomass combustion requirements, especially in terms of emission limits and a common simple methodology for chimney height calculation, primarily directed to small-medium scale biomass boilers that could be utilised by independent users.

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1. INTRODUCTION

1.1. Background

According to the UK Bioenergy Strategy published in April 2012 [Ref.14], biomass combustion for electricity, transport and heat production is meant to play a big role in meeting Europe's 2020 renewable targets and 2050 carbon reduction targets. However, there is a need of a wise control and development of these systems to assure that they do not in reality release more carbon to the atmosphere or risk food supplies. Bioenergy is a very useful renewable source that, in contrast with wind or solar sources, can be controlled and used when it is required. Moreover, as confirmed by the Energy Technologies Institute, excluding biomass combustion from the energy plans could increase the cost of decarbonising the actual energy system by about £44 billion. [Ref.14] Therefore, the development of biomass plants in Europe, and especially in the UK, is meant to be one of the key solutions to the energy demand.

One of the growing applications for biomass boiler systems is district heating, especially in countries such as Austria and Denmark. Similar district heating schemes are meant to be developed in the UK, following the success of these installations in the north European countries.

Biomass contributes significantly to the global energy supply, especially in heating applications. For some countries, in addition to its positive effect in climate change due to the reduction of CO_2 emissions, it gives energy security by diminishing the dependency on other countries for fossil fuels importation.

However, there are some risks and uncertainties regarding these systems, especially those related to air quality, compromising food security and actually reducing carbon emissions. Hence, there is a need of performing a wise control and development of biomass plants in order to ensure their benefits within the boundaries of UK's sustainable-sourced biomass.

One on the major impacts of this technology is the air quality disturbance due to the emissions. Therefore, since biomass plants are likely to be developed as Europe drives towards a renewable energised union, it is essential at this point to perform a review of the possible impacts of this development and the different methodologies to reduce the emissions and the implications in human health.

Really attached to this issue is the chimney height of the biomass boiler, which greatly influences the effects of the contaminants in the flue gases on the local population and nearby countries.

Due to this fact, the first part of this thesis will be a review of the emissions derived from biomass boilers, the different abatement and reduction methodologies applicable and the effects these contaminants might have on human beings.

Furthermore, and as the legislation applicable in the different European countries influences the biomass practice, this thesis will show a review of the relevant regulations for some European countries in the biomass technology regarding the calculation of the chimney height. It can be seen that chimneys in some Northern European countries usually have greater dimensions than those in the UK. Therefore, a comparison of the different methodologies for chimney height calculation will be carried out, in order to improve the current UK model as it has been recently proposed by the UK environmental expertises. Hence, the chimney height of some UK located case studies will be calculated following the different existing models in some European countries, obtaining different results that will allow us to perform a sensitivity analysis and a proper comparison.

The biomass technology is wide and its performance varies depending on the boiler type, the fuel used or the energy produced. Therefore, all the related aspects, including regulations and emission limits, rely on the different characteristics defining a specific system. Hence, for this project to be feasible, the biomass analysis will be constrained to medium biomass boilers (from 50 kW to 500 MW) fuelled by clean wood.

1.2. Project outline

Aims & objectives

To investigate emissions, their impacts and most efficient abatement technologies for wood fired biomass boilers.

•To identify the emissions regulations of the European Union and to make a review of the main national regulations for some European countries.

•To analyse different methodologies for chimney height calculation for some European states.

•To provide generalised recommendations for chimney height calculation from the previous analysis.

Scope

The biomass boilers investigated in this report are wood pellets and wood chips fuelled heating boilers. For simplification, the study is directed to small-medium boilers (from 50 to 500 kW) fired by clean wood.

Due to the inaccessibility to complex dispersion modelling software, the analysis of chimney height calculation methodologies has been constrained to mathematical equations or graphical calculations usually included in the national regulations of the studied countries. Moreover, these simplified methods are presumably more appropriate for small and medium scale applications, where detailed modelling would be too expensive.

Methodology

For the completion of this thesis the following work has been performed:

- General literature review of wood fired biomass boilers and their application.
- Detailed investigation about biomass boiler emissions, health impacts and the most common abatement techniques.
- Intense research about chimney height calculation methods for different European countries. This investigation was specially hindered by the language, since most of the used information had to be translated from other languages (German, Danish, Swedish, Finnish, Spanish, etc.)
- Investigation about specific wood fired biomass boilers of different sizes to be able to create case studies.
- Investigation about pollution within the UK to be able to select two locations for the creation of the case studies.

- Development of the different European chimney height calculation methodologies in Excel documents in order to simplify the calculations for the selected case studies.
- Calculation of the chimney height for the created case studies, sensitivity analysis to identify the most influencing parameters in chimney height determination and the derived conclusions and recommendations.

1.3. Biomass boiler operation

The biomass combustion process consists of consecutive heterogeneous and homogeneous chemical reactions carried out in different steps that include drying, de-volatilisation, gasification, char combustion and gas-phase oxidation. The characteristics of the process are highly dependent on the boiler type, temperature, fuel and other combustion conditions. [Ref.44]

Hence, the process, and therefore the limitation of the emitted pollutants, can be optimised by the control of these conditions. The following figure shows the main reactions carried out in a two stage combustion biomass boiler. This staged combustion is one of the possible improvements to reduce pollutant emissions, as it is detailed in Section 2.2.

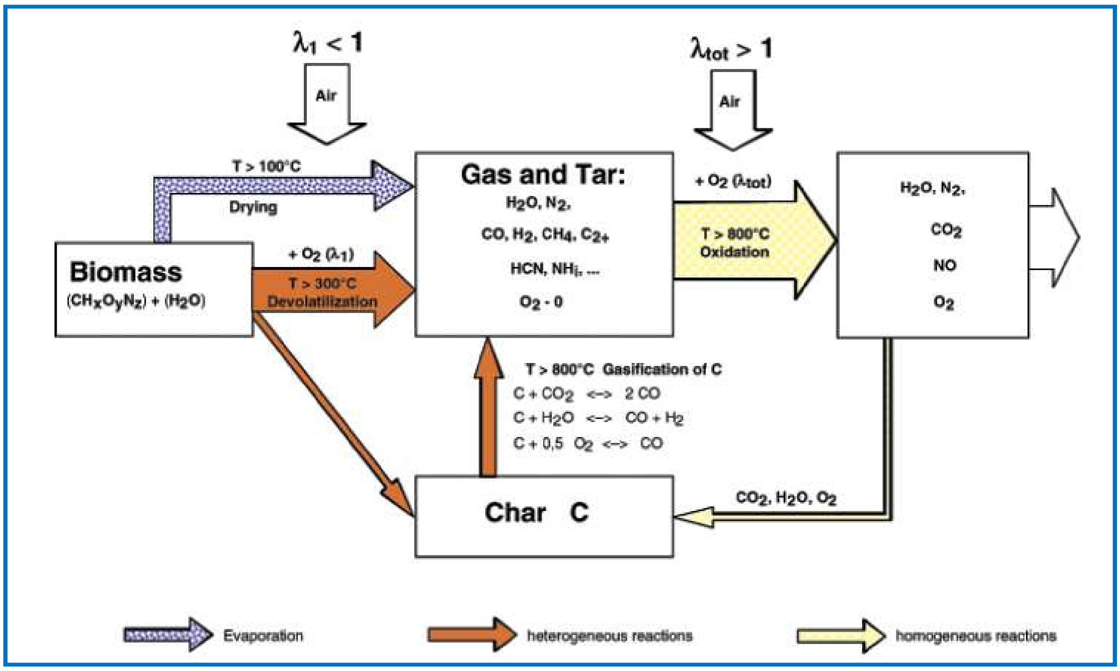

Figure 1: Main reactions during a two-stage biomass combustion process. ***SOURCE: [Ref.44]***

1.4. Biomass fuel types

The concept "biomass" includes a wide variety of fuel types with different characteristics that influences the boiler operation. In this Section, a summary of the main types known as biomass is described:

- Forestry: Wood obtained from conventional forestry working, such as thinning, felling and coppicing of sustainably managed forests, parklands and other green spaces. These processes leave waste timber and small pieces of wood that cannot be used for cellulose, furniture or other purposes, but can be fed as fuel in a biomass boiler system
- Agricultural crops, such as wheat, maize, sugar, rapeseed or oil palm and other crop types mainly grown for their use in energy generation (known as energy crops), such as short rotation coppice (SRC) or Chinese silver grass (miscanthus grass). These crops are cultivated on land that is unsuitable for food crops.
- Biodegradable wastes and residues: This group includes residues from the wood processing that are unsuitable for other wood purposes (also included in the first group), agricultural residues (straw, husks), sewage sludge, animal manure, waste wood from construction, and food waste.
- Algae: It includes microalgae and macroalgae, which can be grown in either fresh or saline water. This fuel is not yet available for industrial used but the advances in investigation can make it a reliable source for biomass energy.

2. BIOMASS BOILER EMISSIONS

"The air quality impacts of burning biomass depend on what fuel biomass is replacing, how it is burned, the quality of the fuel and to an extent where it is burned." (UK Bioenergy Strategy, 2012 [Ref.14])

Generally, the substitution of coal fired plants with biomass boilers has a positive impact on air quality as they contribute to reduce CO_2 emissions. However, these installations can also increase other pollutant emissions, what justifies the relevance of understanding how these emissions occur, and how their impacts can be reduced by the use of abatement methodologies or good chimney design.

The typical pollutants related to biomass combustion are: nitrogen oxides (NO and NO_2, represented as NOx), sulphur dioxide (SO_2), particulate matter (PM), carbon monoxide (CO) and carbon dioxide (CO_2).

However, the combustion of biomass also leads to other less frequent emissions, depending on the fuel composition and in the combustion process. Therefore, due to the wide range of possibilities in this field, this report will be only centred in wood fired boilers.

As it is pointed out by the US EPA in the AP-42, about wood residue combustion in boilers, there are 90 identified organic compounds and 26 trace metals emitted from this fuel type combustion. The Washington State Department of Ecology lists the pollutants of concern from wood-fired boilers. This table is included as Table A1 in the Appendix.

The pollutants result from biomass combustion process can be grouped as [Ref.44]:

- Unburnt pollutants: CO, PAHs (Polycyclic Aromatic Hydrocarbons), H_2, HCN, NH_3, N_2O, tar, soot and CxHy
- Complete combustion pollutants: NOx and CO_2
- Ash and contaminants: ash particles, SO_2, HCl, and heavy metals

SO_2 is not greatly emitted in wood combustion, as it is essentially a low sulphur fuel. In fact, in many of the wood fired boilers test reports there is no SO_2 emission specification since it is not usually measured. The US EPA estimates as a usual value for SO_2 emissions 10.8 g/GJ which, compared to other pollutants, is not significant.

This pollutant can be reduced in the flue gas by wet scrubbing mechanisms, but this abatement technique is not used in wood fuelled systems due to the low emissions.

If the biomass fuel is obtained sustainably, biomass combustion helps reducing the CO_2 emissions in comparison to fossil fuels burning, as biofuels are part of the natural process, creating a closed carbon cycle. “When wood, residues or energy crops are converted into energy, they only produce about as much CO_2 as they had previously fixed during their growth.” (UK Bioenergy Strategy, 2012 [Ref.14])

The next sections study in more detail the implications, emission conditions, health impacts and abatement methodologies of the most important pollutants related to clean wood combustion: NOx, CO and PM.

2.1. Particulate matter

Description and health impacts

Particulate matter, also known as dust in some countries, refers to the mixture of suspended particles and droplets composed by acids (such as nitrates and sulphates), ammonium, water, elemental carbon, organic chemicals, metals and soil materials. [Ref.43]

Biomass combustion, particularly in small-scale installations, can lead to high particulate matter emissions of great variety, such as: carbon particles and soot; unburned wood dust; polyaromatic hydrocarbons (PAH) compounds; semi-volatile organic compounds (e.g., tars and condensables); and ash (minerals, metals, dirt).

As combustion and cleaning equipment improves, the particulate matter emissions are reduced to small particles, with diameters lower than 10 µm (PM10). The “Emissions from Wood-Fired Combustion Equipment” report [Ref.6] points out that the size of uncontrollable particles emitted during an efficient wood combustion can be grouped as: 90% of particles with less than 10 µm in diameter, which can be inhaled; and 75% of particles with a diameter lower than 2.5 µm, which can penetrate deeply into the lungs.

The organic fraction of the particulate matter is very influenced by the combustion efficiency and poor combustion is related to high organic emissions and greater potential for toxic organic compounds. For example, the benzopyrene and the fluorene can be avoided by high combustion temperature, sufficient oxygen availability in the flame enhanced by good mixing and sufficiently long residence time in the combustion zone. [Ref.43]

The inorganic emissions, however, are influenced by the formation mechanisms and they can be increased with higher temperatures, since ashes can be converted to gases.

The EPA divides the particulate matter in two groups:

- Coarse particles (PM10), including all the particulate matter with diameters smaller than 10 μm and bigger than 2.5 μm. In practice, this name includes all particles with diameter lower than 10 μm, but the EPA has proposed this new standard to separate 2.5 μm from 10 μm particles. These are usually mechanically generated from agriculture, mining, construction and road traffic and they sediment in the ground due to the gravity within hours.
- Fine particles (PM2.5), for particles with diameters lower than 2.5 μm. They are known as primary if they are directly emitted to the air and secondary if they are the result of chemical reactions of gases such as SOx, NOx, NH_3 and NMVOC (Non Metallic Volatile Organic Compounds) in the atmosphere. This particle type can remain in the atmosphere for weeks and they are particularly emitted from combustion processes, such as motor vehicles and coal and wood burning.

The limit values for this pollutant are usually specified as mass concentration. However, apart from the concentration, there are many other parameters that influence the PM impact, such as the particle size (as it is explained above), particle shape and the chemical composition.

Dust can be harmful to humans, especially in long exposures. It can cause higher morbidity, affection of lungs and they can reduce the life expectancy, particularly if who inhales it already suffers from lung or heart disease. “Numerous time-series studies have observed associations between particulate air pollution and various human health endpoints, including: mortality, hospitalization for respiratory and heart disease, aggravation of asthma, incidence and duration of respiratory symptoms, and lung function.” (Nussbaumer, 2001 [Ref.40]). In addition to this, some studies reflect that exposure to high particulate matter concentration in air can also cause cardiovascular diseases.

Particle size can be a determinant factor in how the particulate matter affects health, since the distribution and sedimentation of it in the lungs is highly influenced by the size of the particle. While coarse particles are usually filtered in the upper airways (nose and throat), fine particle can settle in the lungs and even in the alveoli.

The differences in composition and health impacts of the particle size justifies that that the World Health Organisation sets different limit values for PM2.5 and PM10:

Table 1: WHO air quality guidelines and interim targets for PM10 and PM2.5 (annual mean concentrations).

	PM10 ($\mu g/m^3$)	PM2.5 ($\mu g/m^3$)	Basis for the selected level
Interim target- 1	70	35	These levels are associated with about a 15% higher long-term mortality risk relative to the AQG
Interim target- 2	50	25	In addition to other health benefits, these levels lower the risk of premature mortality by 2-11% relative to the previous level
Interim target- 3	30	15	In addition to other health benefits, these levels reduce the mortality risk by 2-11% relative to the previous level
Air quality guideline	20	10	These are the lowest levels at which total, cardiopulmonary and lung cancer mortality have been shown to increase with more than 95% confidence in response to long-term exposure to PM2.5

Abatement and reduction techniques

Due to the harmful impacts of the particulate matter, installations are often equipped with abatement technologies to reduce the PM emissions. This section will provide a summary of the most common techniques used for this purpose. To fulfil this section the US EPA website, among others, has been used for information gathering.

- **Combustion process**: Some aspects of this step can be designed to reduce PM formation. For example, the optimisation of the ignition method and the start-up of the process, as well as burning at nominal capacity, help reducing dust formation. In order to work always al full load, the plant can be implemented with heat storage which can store the heat when the heat demand is low, avoiding the operation at part-load, which is highly related to great PM emissions.

- **PM removal techniques**: There are many technologies that can be used to separate the particulate matter from the exhaust gas in a combustion plant. The most typical are explained below:

  ~ **Cyclone systems**

The basis of this technique is particle separation through mechanical forces. In this system, the exhaust gas acquires high rotational velocities and the particles are separated by inertial forces, grouping in the peripheral walls due to their greater mass while the gaseous content exits the system.

These collectors are applicable for dry particulate matter (as wet dust can be accumulated in the cyclone walls, obstructing the gas flow), when the required separation efficiency is low-medium (50-90 %) or as a pre-collector system.

The cyclone efficiency can be defined as [Ref.52]:

$$Eff = \frac{k \cdot \rho \cdot d^2 \cdot V}{u \cdot D}$$

Being:

k = constant for a given cyclone geometry

ρ = particle density

d = particle diameter

V = inlet gas velocity

u = gas viscosity

D = Cyclone diameter

Gas velocity increases with lower diameters, hence this technique can be divided in:

Large diameter cyclone (30-180 cm diameter): Used for separation of large particles which enter the cyclone tangentially and rotate, settling in the hopper located in the head of the cyclone body.

Small diameter multi-cyclone (7-30 cm diameter): Using the same mechanism, it is directed to separate small-diameter particles (down to 5 µm), as the diameter of the cyclones is smaller, generating a faster spinning and reducing the distance from the centre to the periphery. In fact, some especially designed cyclone systems are able to collect particles of 1 µm. Since one cyclone does not admit great gas flow rates, a parallel multi cyclone system equipped with a single collector is common for exhaust gas treatment. The following figure shows the configuration of this removal system in a small scale wood-fired boiler. (US EPA [Ref.59]).

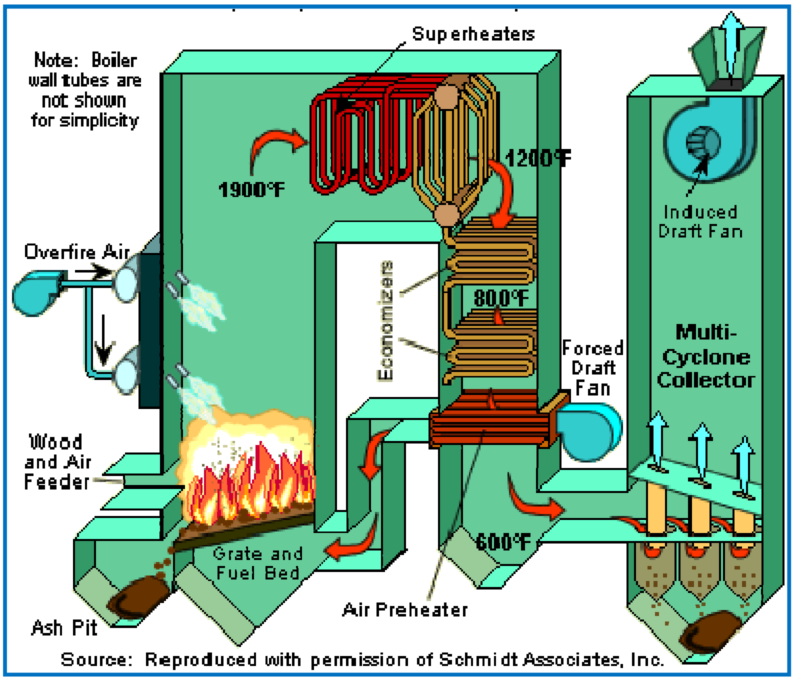

Figure 2: Multi-cyclone collector in a small wood fired boiler. *SOURCE: US EPA [Ref.59]*

~ **Wet scrubbers**

In these systems the particulate matter is separated from the gas by wetting and addition of droplets, increasing the mass of the particles which allows further separation from the gas in cyclones. Regardless of the scrubber vessel, a wet scrubbing system needs more appliances for complete particle removal. An example of a wet scrubbing system is included in the Appendix for consultancy as Figure A1. There are different types of wet scrubber vessels, some of which are described below:

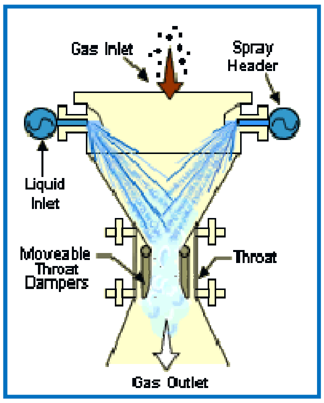

Figure 3: Venturi scrubber. *SOURCE: US EPA [Ref.59].*

Venturi scrubber: The gas enters the system and it is wet by scrubbing liquor sprayed in the top of the throat, where the wet gas accelerates generating droplets that trap the solid particles. After the tight section, these droplets agglomerate enlarging the droplets diameter which makes them separable from the gas. Figure 3 shows a typical venturi scrubber:

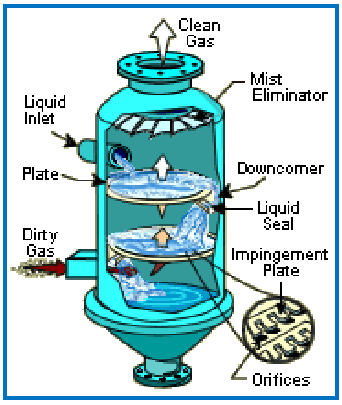

Figure 4: Plate scrubber. *SOURCE: US EPA [Ref.59].*

Plate scrubber: Working with the same mechanism, in this system the gas atomises the entering water by the acceleration caused by tiny holes in the horizontal plates. The gas-water contact is counterflow, as the water is scrubbed in the top and the gas flows from the base. Figure 4 shows a plate scrubber system:

Spray towers: Similarly to the other cases, in this system the liquor is sprayed with the help of atomised spray units into the gas generating liquor droplets that encapsulate the particles. It removes particles down to 2 µm. The following figure gives a view of this technique.

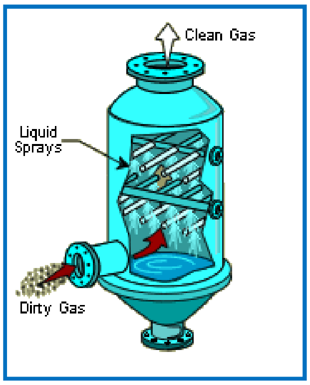

Figure 5: Spray tower scrubber. *SOURCE: US EPA [Ref.59].*

The efficiency of the particulate matter removal relies principally on the particle size, the velocity of the dust and the velocity of the sprayed water. Since these parameters differ depending on the scrubber, the efficiency to separate fine particles is highly dependent on the type and conditions of the system. The following graphic shows this efficiency variation for fine particles (less than 5 µm of diameter):

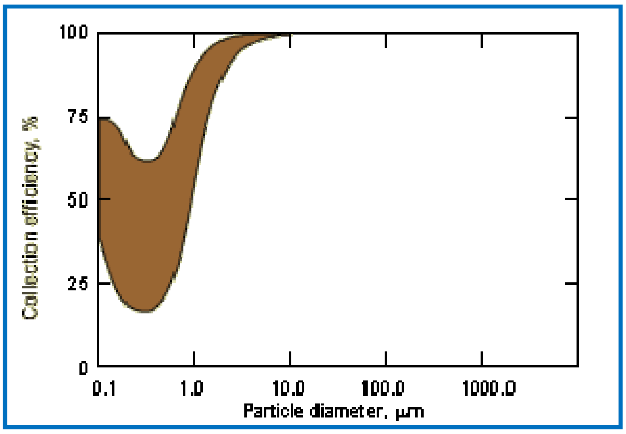

Figure 6: Particle size-Efficiency of wet scrubbers. *SOURCE: US EPA [Ref.59].*

Electrostatic precipitators:

The basis of this technique is to use electric forces to charge the particles that are moved by the high-voltage electric field to the electrode collectors, where they accumulate. This system is applicable for wet and dry particles and combines high efficiency with low operational cost, since the pressure loss is kept to a minimum reducing fan power.

The typical electrostatic precipitator consists of a series of parallel charged plates that act as particle collectors and some electrode wires to which high voltage is applied, generating an electric field between the wires and the plates. The gas flows through the electrodes and charges the particles that are afterwards collected in the plates. Therefore, the gas circulates into a number of fields in series which improves the efficiency.

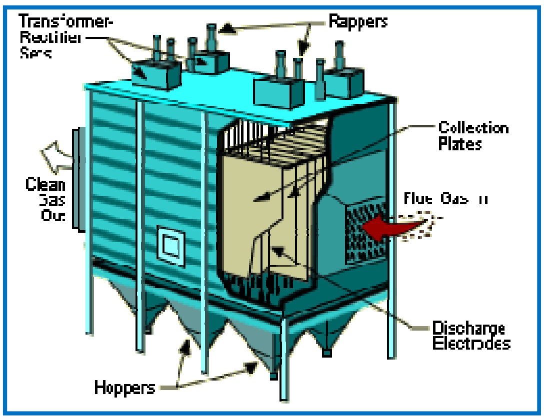

Figure 7: Electrostatic precipitator. *SOURCE: US EPA [Ref.59].*

To remove the accumulated particles from the collectors, vibration is applied to the plates when dry particles cleaning. In the case of wet particles, they are removed by water washing.

The following figure shows the efficiency of this removing system for different particle sizes:

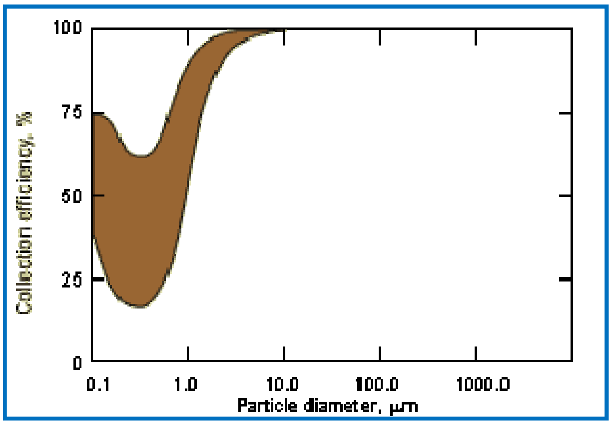

Figure 8: Particle size-Efficiency of electrostatic precipitators. ***SOURCE: US EPA [Ref.59].***

Fabric filters

This technology consists of a series of fabric tubes up to 5-7 m long and 100-150 mm diameter hanging together forming a block that retain the particles of the gas in its way through the structure. The incoming particles are filtered even when the already accumulated particles have formed a dust layer on the fabric bags.

It is a very efficient technique for particle removal, and it can be improved with the addition of electrostatic forces to favor the particle attraction to the bags. However, there is a great pressure lost during the process and high fan power is required to make the gas flow, which increases the operational cost. In addition this procedure is limited in its application with high temperatures and humidity as this can damage the fabric

When the selected time of operation is finished, the compartment is isolated and the bags are cleaned by vibration, a pressure pulse or a blast of air, which cleans the bags rapidly and lets the cleaning process continue whilst the particle cake is collected in the hopper.

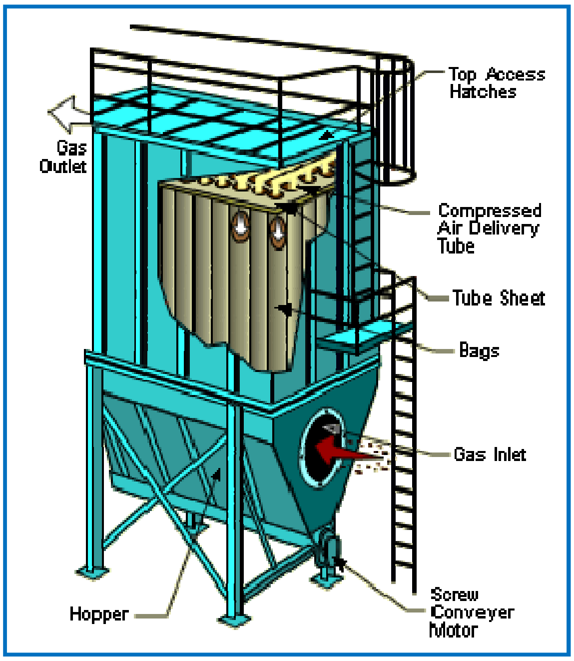

Figure 9: Pulse jet fabric filter. *SOURCE: US EPA [Ref.59].*

The following table summarises the main advantages and disadvantages of the abatement technologies for PM.

Table 2: Advantages and disadvantages of PM removing technologies.

	Advantages	Disadvantages
Cyclone	Low capital and operational cost Simple construction and low maintenance Applicable for high PM quantity Suitable for high temperature	Inefficient for small particles Susceptible for plugging Must operate above dew point Can suffer from abrasion
Wet scrubbers	Low capital cost Collects gases and particles Cools and cleans hot gases Can work at dewpoint Minimal explosion or fire hazard	Liquid effluent produced Corrosion Stack gases wet and cold High energy cost for fine particles
Electrostatic precipitator	Very high efficiency Collects ultrafine particles Low pressure losses- low operational cost	Not applicable when gas contains sticky material High capital cost Large space requirement
Fabric filters	High efficiency for ultrafine particles Produces dry dust Low capital cost	High pressure drop Not applicable with high temperatures High maintenance costs

Adapted from US EPA and other sources

The following figure shows the criteria for the selection of the optimal system for abatement of particulate matter:

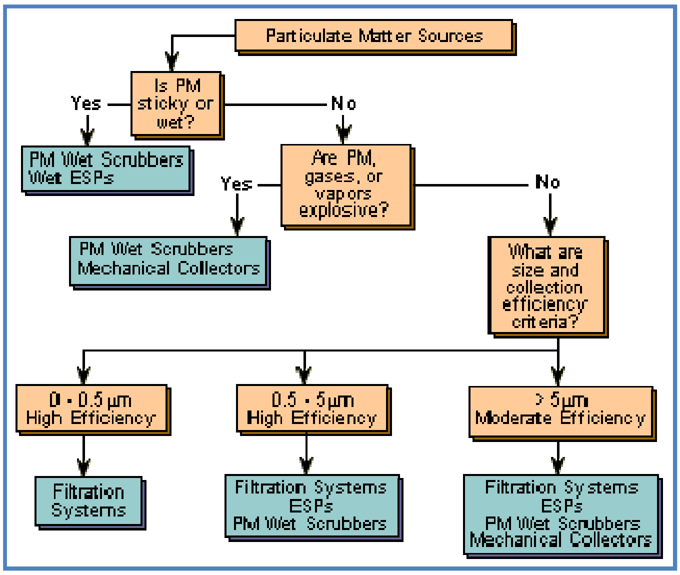

Figure 10: Guidance for PM removal system selection. ***SOURCE: US EPA [Ref.59].***

2.2. NOx

Description and health impacts

NOx emissions are one of the most concerning impacts of biomass combustion. It refers primarily to the sum of nitric oxide (NO) and nitrogen dioxide (NO_2). They are produced by the oxidation of nitrogen present in the fuel and in the air; although in the case of biomass combustion they are mainly caused by the nitrogen present in the fuel. NOx emissions are favoured by high temperatures.

One of the major impacts of this pollutant is the formation of nitric acid vapour and particles when reacting with ammonia, water and other compounds. The inhalation of these particles can cause lung and heart diseases, analogously to the effects described for PM. And the nitric acid contributes to the formation of acid rain, which has severe impacts on humans, animals and vegetation.

NOx can also react with volatile organic compounds to produce ozone, which has negative effects in the health, causing respiratory affections; and with other many compounds forming toxic products.

In practice, for its quantification all the nitric compounds present are converted to NO_2 and NOx is expressed as NO_2. The possible NOx formation mechanisms are:

- *Fuel NOx mechanism:* The following figure shows a simplified reaction path of the fuel nitrogen. It can be seen that during thermal degradation of the biomass, HCN and NH_3 are produced, which are afterwards converted to NO and N_2 by oxidation processes. The main oxide emitted is NO which is transformed to NO_2 in the atmosphere primarily by reaction with ozone.

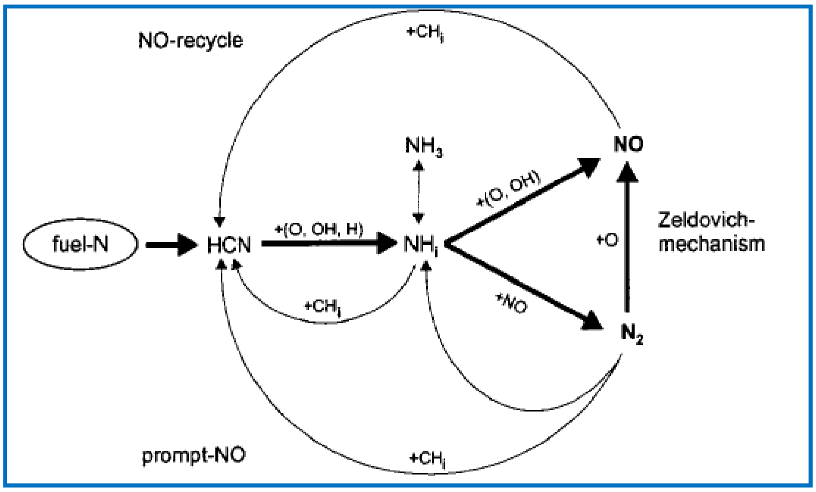

Figure 11: Reaction path diagram for NOx formation and destruction in the gas phase. ***SOURCE: [Ref.53]***

- *Thermal NOx mechanism:* It refers to the oxidation of the nitrogen present in the air to produce NO at high temperatures (usually above 1300 ºC). This NO formation increases with the temperature, the O_2 content and the residence time. However, this temperature ranges are not usually reached in biomass combustion and in these plants thermal NOx formation occurs primarily after the main combustion.
- *The prompt NOx mechanism*, which starts with the reaction of the nitrogen contained in the air with CH, producing HCN, which follows then the path described in the first mechanism. This mechanism is not significant in biomass applications, especially if compared to fossil fuel combustion. The following graphic shows the NOx formation mechanisms versus the temperature [Ref.63]

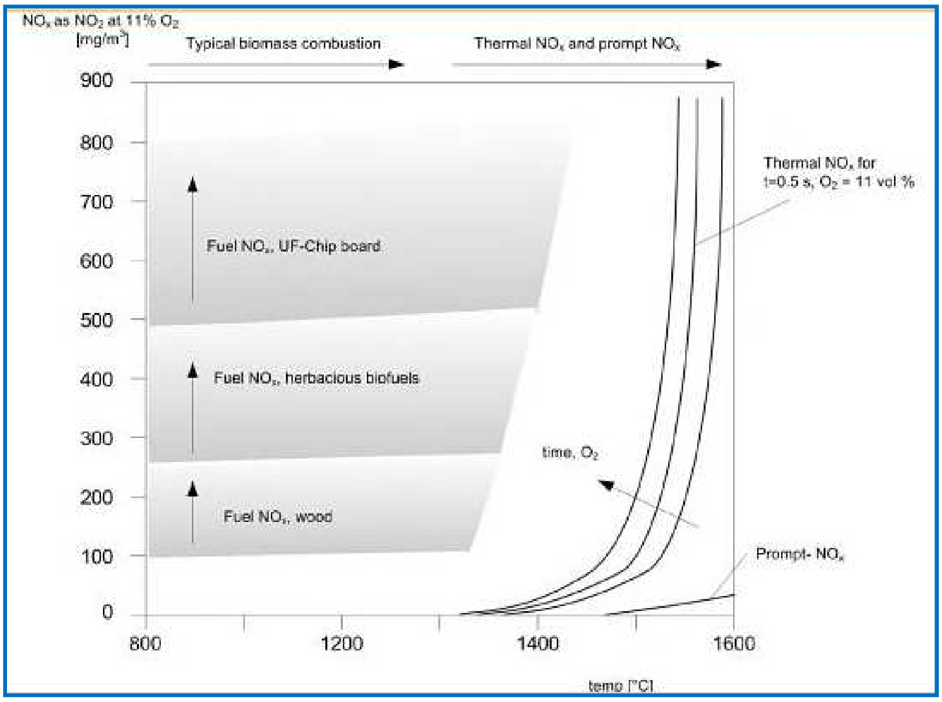

Figure 12: NOx formation mechanisms as a function of the temperature. ***SOURCE: [Ref.63]***

Abatement and reduction techniques

The most typical technique for NOx reduction is the optimisation of the combustion conditions to reduce nitrogen oxides formation. The parameters that specially affect NOx production during a combustion process are the stoichiometric ratio (fuel-air) and the temperature. However, low temperatures and low air flow can lead to incomplete combustion. Therefore, in order to control these parameters, stage combustion is widely used as a method to reduce NOx emissions.

Both the fuel and the air can be fed in stages, creating different combustion zones to achieve a complete combustion minimising nitrogen oxides formation. Figure 13 shows an example of a three-stage combustion process, also called reburning combustion, where both the fuel and the air are introduced in stages:

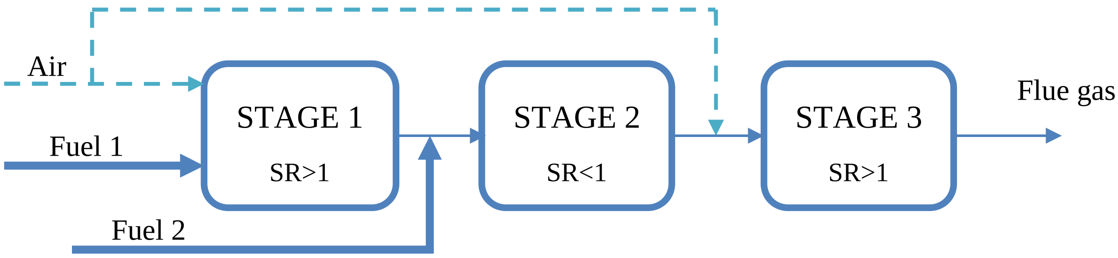

Figure 13: Three- stage combustion process.

In this process the combustion is performed in three stages:

Primary combustion zone: In the first stage, the majority of the fuel is injected and burned with little air excess (Stoichiometric Ratio >1), achieving high combustion efficiency but generating some unburnt products.

Reburn zone: The second stage reproduces a reduction atmosphere with only fuel introduction where the hydrocarbons react with the NO generated in the first step and converts it to N_2. Since volatile content in the wood is high, it performs well as secondary fuel (when burning coal, natural gas is used as secondary fuel because coal does not have the needed properties).

Burnout zone: Finally, overfire air is fed in the third step to eliminate the unburnt compounds generated in the previous stages

2.3. CO

Description and health impacts

Carbon monoxide is a colourless, odourless and tasteless gas produced by incomplete combustion and that quickly oxidises to carbon dioxide in the atmosphere. It can be toxic if inhaled for human beings and animals and it can cause even death in high concentrations, although it is naturally produced in low quantity by the body. “Carbon monoxide poisoning is the most common type of fatal air poisoning in many countries.” (Omaye, 2002, [Ref.45])

In low concentrations it can cause headache, dizziness, fatigue, vomiting, nausea, weakness and neurological diseases such as disorientation, seizures and visual disturbance.

This pollutant is emitted as a result of an incomplete combustion of the fuel. The combustion of carbon follows two steps: the first one causes the oxidation of the carbon to CO and in the second step this compound is oxidised to CO_2, releasing in this last process the majority of the energy contained in the fuel.

To reduce CO emissions, furnaces are designed to minimise incomplete combustion. However, some aspects and burning characteristics can lead to it in spite of a good design. An example of the latter would be having little excess air which is a desired condition to reduce NOx formation and to improve the efficiency of the process. Also, low temperatures, that can be achieved if the moisture content in the fuel is big, and a poor contact between the fuel and the air are other situations that may lead to greater CO emissions.

Abatement and reduction techniques

The control of CO emissions is usually based on a good burner design, where the combustion is fulfilled completely, reducing the formation of unburnt compounds. Favorable conditions for CO abatement are high temperature and good air excess. However, this does not comply with the needed NOx reduction, as NOx formation is favoured in these conditions. Therefore, performing a three-stage combustion helps reducing NOx (in the secondary stage) and unburnt compounds (in the primary and third stage).

3. BIOMASS BOILER EMISSIONS AND REGULATION

3.1. Reasoning

The scope of this review of the European regulation about emissions is to make a comparison among some countries in the European Union in their directives and standards related to emissions and contaminant limit values. This analysis will allow us to have a better understanding of the differences existing in biomass installations around Europe, especially in the chimney heights.

In the next section of this thesis a review of the models and methods for chimney height calculations in some European countries will be carried out, with the purpose of running some sensitivity analysis and comparing them, which will help improving the actual D1 model widely used in the UK. However, the differences among the boiler plants in these countries rely, not only on the calculation procedures, but also on the emission limits required in the different directives and legislation.

Therefore, it is essential to analyse these emission limits in the studied countries, in order to highlight the big differences between values.

In addition to this analysis of the European regulation on biomass boiler emissions, and taking into consideration the relevance of the United States practice in this area, this section includes a small review of the US regulation on biomass emissions, as an extra for comparison with the EU regulation.

3.2. Emission limits and regulation in the EU

European Union

The European Community has developed the directives 1999/30/EC (relating to limit values for sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead in ambient air) and 2008/50/EC (on ambient air quality and cleaner air for Europe). These directives include the limit values of some contaminants in the atmosphere in order to protect human health. These values for NOx, PM, CO and SO_2 are shown in the table below. In a first phase starting in January 2005 the limit value for PM in annual mean concentration was 40 $\mu g/m^3$, but this value has been reduced to 20 $\mu g/m^3$ from 1st January 2010.

Table 3: Pollutant limit values for the protection of human health established by the EN.

Pollutant	**Averaging period**		
	8 hours	24 hours	1 year
SO_2	-	0.125 mg/m^3	*0.025* [1)]
NOx	-	*0.2* [1)]	0.04 mg/m^3
PM	-	0.05 mg/m^3	0.02 mg/m^3
CO	10 mg/m^3	*5.7 mg/m^3* [1)]	*1.14 mg/m^3* [1)]

[1)] For the calculation procedures the annual limit values will be used for all the calculation procedures, except for the Spanish model, which specifies that 24-hourly values should be used.

For some of the pollutants, there is no specification of these values for both averaging periods. Therefore, the US EPA multiplying factors to convert 1-hour concentration estimates to other averaging periods has been used. This table is included in the Appendix as Table A2.

Currently the EU emission standards for biomass boilers do not include emission limits for NOx and PM as PM2.5 and PM10. Therefore, there is a need of developing more adequate standardised tools to assure air quality in a biomass boiler perspective.

For this purpose, the European Committee of Standardisation (CEN) has recently introduced the EN 303-5 Standard, firstly developed by Austrian experts as ÖNORM EN 303-5, for emissions from heating boilers up to 300 kW. The limit emission values (related to 10% O_2) set in this standard for biofuelled boilers are summarised in the table below.

For boilers greater than 300kW local regulations may be applied and therefore these boilers will require a consultation with the Local Authority to agree emission levels.

Table 4: Emission limit values for heating boilers up to 300 kW.

Nominal output (kW)	CO (mg/m^3 10% O_2)			OGC (mg/m^3 10% O_2)			PM (mg/m^3 10% O_2)		
	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3
< 50	15000	5000	3000	1750	200	100	200	180	150
50-150	12500	4500	2500	1250	150	80	200	180	150
150-300	12500	2000	1200	1250	150	80	200	180	150

Class 1: Boiler efficiency 53-62%
Class 2: Boiler efficiency 63-72%
Class 3: Boiler efficiency 73-82 %

However, national requirements in several EU states differ from this Standard in terms of measurement protocols and permitted emissions.

UK

There is no directive in the UK that sets the emission limits for small-medium scale wood-fired boilers (up to 300 kW). Solid fuel boilers with a thermal input up to 20 MW are usually regulated by the appropriate local authority under the Clean Air Act. Larger boilers fall under the Integrated Pollution Prevention and Control and are regulated by the Environment Agency (for boilers >50MW) and the local authority (for boilers 20-50 MW) or, in the case of Scotland, by the Scottish Environment Protection Agency for all boilers >20MW. [Ref.20]

The Clean Air Act was introduced in 1970 to control air pollution arising due to the widespread use of coal in those years. This document includes the declaration of Smoke Control Areas, where burning appliances need to be authorised, and emission limits for exempted appliances (smaller than 44 kW), included in BS PD 6434, and emission limits for grit and dust for burners greater than 240 kW output. For appliances within the range between these values, assessment of emissions is recommended to be done by interpolation between both documents.

Sweden

As it can be read in the Swedish Environmental Protection Agency (SEPA) Webpage, “In contrast to much other national legislation, Emission Limit Values (ELVs) are generally not specified in the Swedish environmental legislation.” In Sweden, the emission limits are specified for each individual installation and they are based on the recommendations of Best Available Techniques (BAT). Therefore, there are differences in the conditions of similar plants as the ELVs vary with the BAT updates and the local environment where the plant in installed.

These permits and the ELVs are continually updated when changes in operation occur and even when there is no change in the plant the SEPA or the regional supervisory authority can review the permit conditions.

More specifically for wood fired boilers, there is a method developed by the Swedish National Testing and Research Institute for testing this type of boilers. The method describes the conditions for the testing (quantity of burned wood, moisture content of the fuel, time of measurements, etc). However, in Sweden, boiler testing procedures are usually performed following the EN 303-5 guideline.

For small scale combustion systems up to 300 kW there are emission threshold values for OGC (Organic Gaseous Carbon) (150 mg/Nm3), but not for other pollutants. There are no ELVs specified for NOx for this type of boilers as general emission limit values, included in NFS 2010:2 [Ref.57] are directed to large installations (>50MW). In practice, the ELVs are set individually by legal authorities and economic incentives are used to reduce these emissions by paying or getting paid dependent on its annual emissions level (if the plant generates more than 25 GWh/year, then the national law (1990:613) is applied).

Similarly, general requirements for particulate emissions are only valid for large combustion plants (NFS 2010:2). For smaller power plants (from 0.5 to 10 MW), the EPA has developed the AR 87:2 which includes general guidelines and also a methodology for chimney height calculation (that have been used for stack height estimation in this report).

The SO_2 emissions are controlled by the National Ordinance (1998:946) which specifies not only the ELVs but also limits in the fuel content for this pollutant. For large combustion installations (with a thermal input greater than 50 MW) the SO_2

emissions are regulated by the EPA (NFS 2002:26) according to the EC directive 2001/80/EG9.

Germany

The DIN 4702 Standard is used for testing wood-fired boilers in Germany. It is very similar to the EN 303-5 Standard. The following tables show the pollutant emission limits for wood fired plants in Germany, for different fuel types and boiler sizes:

Table 5: Emission limit values for wood and straw for small, medium and large scale combustion in Germany.

Heat output	Ref O2	NOx (mg/m^3)	SO_2 (mg/m^3)	PM (mg/m^3)	CO (mg/m^3)
<50 kW	13%	-	-	150	4000
50-150 kW	13%	-	-	150	2000
150-500 kW	13%	-	-	150	1000
500 kW-1 MW	13%	-	-	150	500
1 MW-5 MW	11%	500	400	150	250
5 MW-50 MW	11%	500	400	50	250

Adapted from [Ref.31 & 47]

The TA Luft [Ref. 58] also includes some tables to specify emission values for the protection of human health:

Table 6: Emission values for the protection of human health set by the TA Luft

	Concentration (mg/m^3)	Averaging period	Permissible Annual Frequency of Exceeded Values
NOx	40	1 year	-
	200	1 hour	18
SO_2	50	1 year	-
	125	24 hours	3
	350	1 hour	24
PM	40	1 year	-
	50	24 hours	35

Source: TA Luft

In March 2010 the German Federal Environmental Agency introduces a new ordinance for small combustion plants in Germany, directed primarily to domestic heating furnaces. This Ordinances sets emission limit values for PM and CO for different boiler sizes and fuel types. The following table shows these limit values for clean wood [Ref. 24]:

Table 7: Emission limit values set in the Ordinance for small combustion plants introduced in March 2010 in Germany.

	Nominal output	PM (mg/m^3)	CO (mg/m^3)
Plants built from 22nd March 2010	4-500 kW	100	1000
	>500 kW	100	500
Plants built from 31st December 2014	>4 kW	20	400

As it can be seen, these values are slightly lower than those presented in Table 5 which shows that limitation for biomass emission are becoming stricter.

Denmark

The Danish Guidelines for Air Emissions Regulation establishes some emission limits for combustion plants. For every pollutant it recommends limit values for mass flows (g/h), emissions (mg/Nm^3) and C-values, which means "the total maximum approved contribution from an installation to the concentration of a pollutant in the air at ground level". This last parameter must be respected everywhere outside the installation, regardless the emission rate or the location conditions.

The following table summarises these recommended parameters for the pollutants involved in clean wood fired boilers:

Table 8: Recommended values for clean wood fired boilers in Denmark.

	Mass flow limit (g/h)	Emission limit (mg/Nm3)		C-value (mg/m^3)
NOx	5000	400		0.125
SO2	5000	400		0.25
	(kg/h)	New installation	Existing installation	
Dry dust	≤0.5	300	300	0.08
	0.5-5	50	75	
	>5	10	20-40	

In addition, this document sets emission limits specifically for wood fired systems:

Table 9: Emission limits for wood fired boilers in Denmark set in the Danish Guidelines for Air Emission Regulation.

	Emission limit (mg/Nm^3) (dry flue gas 10% ref O_2)		
	NOx	Dust	CO
120 kW- 1 MW	-	300	500
1 MW-50 MW	300	40 [1]	625

[1] Dependent on the flue gas cleaning methodology. For example, if condensing equipment is used, the emission limit value can be decreased to 100 mg/Nm^3 dry flue gas at 10% O_2.

Austria

Wood fuelled boilers are tested in Austria according to the European Standard EN 303-5, which was firstly developed in this country with the name ÖNORM EN 303-5. However, there are in Austria some regulations that differ from this European Standard to improve efficiency and emissions control, as they are not included in any European directive. These deviations are summarised in the table below:

Table 10: Emission limits for biomass boilers up to 300 kW in Austria.

	Emission limits (mg/MJ)			
	NOx	PM	CO	OGC
Manually fed	150	60	1100	80
Automatically fed	150	60	500 750 (30% part output)	40

Spain

In Spain, there is not a national regulation that sets specific emission threshold values for wood fired small and medium scale combustion plants. Related to this, there is a Royal Decree 430/2004 which establishes the new regulations for emissions from large combustion biomass fired plants (greater than 50 MW). The following table summarises the limit values for NOx, SO_2 and PM for biomass combustion plants >50MW:

Table 11: Emission limits for large scale combustion plants in Spain set by the RD 430/2004.

	SO_2	NOx	PM
50-100 MW	200	400	50
100-300 MW	200	300	30
>300 MW	200	200	30

The technical guide for heating biomass boilers installation in buildings, developed by the Ministry of Industry, tourism and commerce specifies that the products from the combustion of these installations must comply with the environmental requirements set by the national, regional or local authorities to limit the emissions. It also recommends the UNE EN 303-5 Standard for emission limits specification.

3.3. Emission limits and regulation in the US

The main difference between the EU and the US regulation on biomass combustion is how the systems are regulated. While the European standards specify different emission limits for different feeding methods and heat outputs, the US regulation regulates by boiler type, fuels and heat output. Also, EU standards on emission limits are more stringent than those regulating the US biomass practice. [Ref.26]

In the United States, there are not federal or state regulations directed to small-medium scale biomass installations, which leads to a lack of incentive for manufacturers to apply the best technologies or reduce emissions. Moreover, European residential and industrial, commercial and institutional (ICI) biomass boilers usually have a better emissions performance than US devices due to the European design characteristics. [Ref.26]

The federal New Source Performance Standards (NSPS) regulation applies to indoor wood stoves and large industrial boilers. Outdoor wood fired boilers and low mass furnaces can be labelled by the EPA's voluntary labelling program. Table A3, included in the Appendix and extracted from Handley, R. & Associates and NESCAUM, 2009 [Ref.26], makes a summary of the federal and Northeast State regulations for biomass boilers.

4. CHIMNEY HEIGHT CALCULATION

4.1. Introduction

Every burning technology is associated with gaseous emissions with some pollutant concentration, although the underlying effects are dependent on each scenario (fuel type, boiler output, abatement methods, etc.).

For this reason, there is always a need of an effective dispersion of the exhaust gas, which will dilute the contaminants before they reach ground level, with the purpose of reducing their harmful effects in sensitive receptors in the surrounding environment. The EU Waste Incineration Directive, Article 5 quotes: "Incineration and co-incineration plants shall be designed, equipped built and operated in such a way as to prevent emissions into the air giving rise to significant ground-level air pollution, in particular exhaust gases shall be discharged in a controlled fashion and in conformity with relevant Community air quality standards by means of a stack the height of which in calculated in such a way as to safeguard human health and the environment". [Ref.17]. Therefore, a good design of the stack that helps achieving this purpose is essential when developing a fuel burning system.

However, there is not a common European methodology for air quality modelling and chimney height calculation; hence, national standards and recommendations are used for this purpose. There is nowadays a wide number of calculation models that differ in every EU state. Most accurate are those air dispersion models based on short time meteorological data presented always in the shape of complex computer programs. These models are usually purchased by big companies or used by consultancy companies in response to specific plants, and, in general, they are used for big furnaces with substantial air emissions.

However, emissions from smaller plants also need to be controlled, especially in the case of biomass boilers, due to their increasing development. Therefore, this section will look at different stack height calculation methodologies for wood fuelled medium boilers in some European Countries.

Due to the inaccessibility to complex software, the calculation is based on simple models included in the existing regulation and standards for each state.

In addition to the methodologies review, some case studies will be analysed using the different models, in order to be able to make a proper comparison and have a better understanding of the similarities and differences between methods. Moreover, some sensitivity analysis will be carried out for each model, with the purpose of identifying the most relevant aspects affecting the chimney height in every calculation method.

For this purpose, all the methods have been developed as an excel document, in order to simplify the calculation for different case studies and to determine the most influencing parameters by means of the sensitivity analysis.

This section also includes a subsection with the title “Selection of the case studies” where the reasoning for the case studies selection is explained.

4.2. Selection of the case studies

For the case study selection some different boiler types, wood fuels and power capacities have been analysed in order to have a total of four scenarios in representation of all the possibilities. As this project is based on medium boilers, the chimney height calculation has been carried out for four heat output values: 50, 150, 300 and 540 kW, which will allow us to analyse the behaviour of the different models with different boiler size conditions. Taking all this into consideration, the four selected boilers are explained in more detail below.

For the stack height calculation some specific information about the boilers (flue gas temperature, emission values, and flow rate, among other) was needed as input for the models. Therefore, the case study selection was restricted to those boilers whose complete test reports could be accessed.

However, in some of reports there were some parameters needed as inputs in the methods that were not specified. In these cases, their values have been assumed as they do not represent any real case, and they are only used for model comparison.

CHIPPED WOOD HEATING BOILER EVOTHERM HS 50

This is a 50 kW chipped wood fuelled boiler manufactured by Evotherm Heiztechnik Vertriebs GmbH. The test report used to extract the needed data was carried out in 2006 and the measurement equipment and methods used correspond to ÖNORM EN 303-5:1999, ÖNORM EN 304:1992/A1:1998 and EN 267:1999. [Ref. 5]

The nominal heat output measurements were performed after a period of burner operation of three hours at full load. The measurements were carried out over a period of six hours; hence the emission values were averaged over this period, obtaining a single value for CO, CO_2, OGC, dust and NOx. The NOx is declared as NO_2.

The fuel is air dry wood fine chips, according to ÖNORM M 7133:1998 with a water content of 18.4 % and 19.0 %.

The table below shows the main test results at nominal output:

Table 12: Test results for the EVOTHERM HS 50 biomass boiler.

Heat output (kW)	**48.6**	
Flue gas temperature (°C)	117.3	
Recommended stack diameter (mm)	200	
CO_2 (%)	14.4	
Recommended chimney height (m)	9	
	mg/MJ [1)]	mg/m3 [2)]
NOx (as NO_2)	69	141
CO	7	15
Dust	14	28
Organic Carbon	<1	1

1)Emission values in mg/MJ (relating to applied energy), subject to legal requirements in Austria.

2) Emission values in mg/m3 (relating to 10 % O2, 1013 mbar, dry flue gas), according to ÖNORM EN 303-5:1999

The boiler has an average volume of 5 m^3. The figure below shows a sectional view of the boiler:

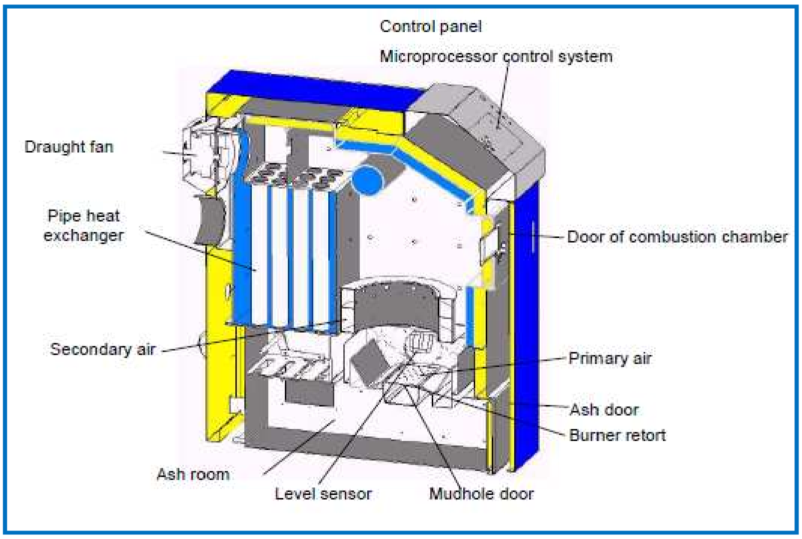

Figure 14: EVOTHERM HS 50 boiler. *SOURCE: EVOTHERM HS 50 test report [Ref.5]*

KWB TDS POWERFIRE 150

This is a KWB boiler fuelled with wood pellets that respond to ÖNORM M 7135 and DIN 51731 with a rated power of 150 kW and a fuel thermal output at rated power of 164kW. The report does not include details about the test measurements and methods. The main results from the boiler test at rated power are specified in the table below: [Ref.33]

Table 13: Test results for the KWB TDS POWERFIRE 150 biomass boiler.

Heat output (kW)	164	
Flue gas temperature (°C)	160	
Recommended stack diameter (mm)	300	
Exhaust gas mass flow (Nm^3/h)	300	
Recommended chimney height (m)	8-10	
	mg/MJ [1)]	mg/m3 [2)]
NOx (as NO_2)	78	116
CO	14	20
Dust	12	18
Organic Carbon	<2	<2

The boiler main components are described in the figure below:

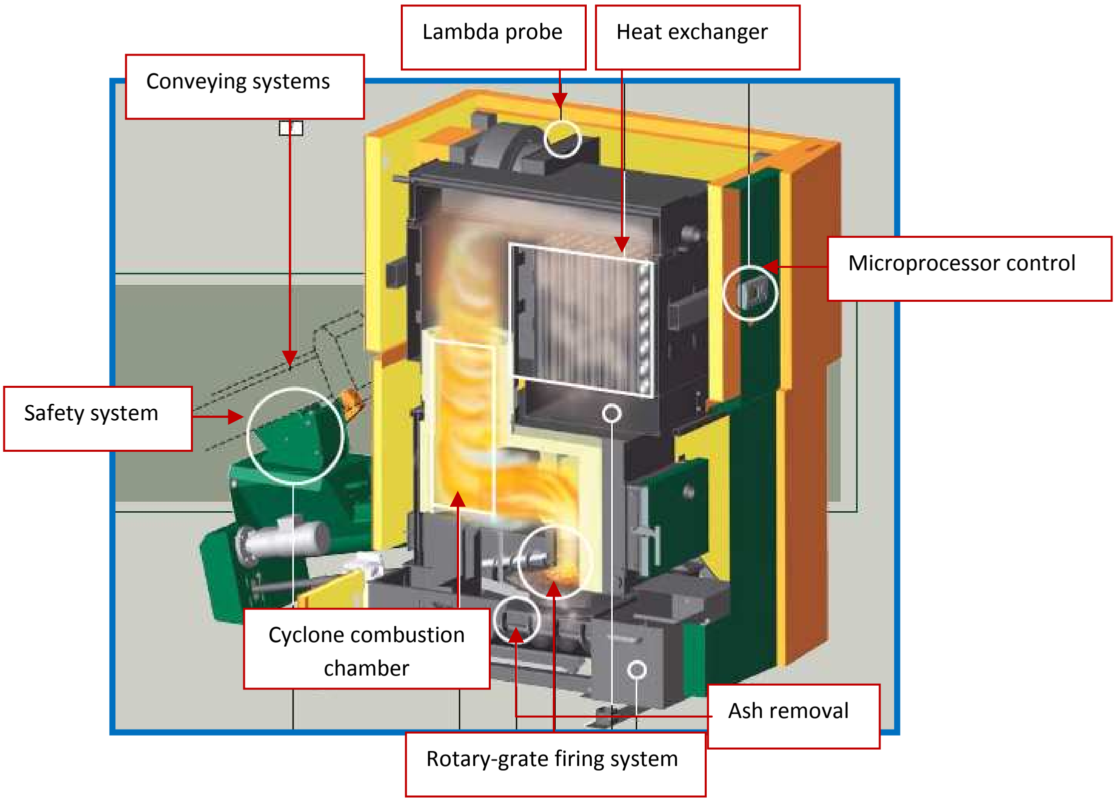

Figure 15:KWB TDS POWERFIRE 150 boiler. ***SOURCE: Boiler test report [Ref.33].***

KWB TDS POWERFIRE 300

This is a heating boiler with a nominal heat output of 300 kW manufactured by KWB Kraft und Wärme aus Biomasse GmbH. The test has been performed in accordance with "ÖNORM EN 303-5, of heating boilers for solid fuels, hand and automatically stocked, nominal heat output up to 300 kW- Terminology, requirements, testing and marking".[Ref. 32]

The average O_2, CO, OGC and NOx contents are determined over the entire test period, which must be at least six hours.

The organic composition of the gas was determined as organically bound carbon (OGC) in dry flue gas.

The sum of nitrogen oxides (NOx), measured as the sum of nitrogen monoxide (NO) and nitrogen dioxide (NO_2), is calculated and declared as nitrogen dioxide (NO_2).

The volume of combustion gas was calculated by means of combustion gas calculation using the DIN 4702 taking into consideration the chemical elementary analysis and the volume of the fuel used during the test.

The velocity of the flue gas was calculated from the volume of combustion gas, on the basis of cross section of the duct, pressure, temperature and moisture content of the flue gas.

The main results for the boiler fuelled with wood pellets are summarised in the table below.

Table 14: Test results for the KWB TDS POWERFIRE 300 biomass boiler.

Nominal heat output (kW)	286	
Flue gas temperature (ºC)	115	
Flue gas velocity (m/s)	1.4	
Dry flue gas mass flow (m^3/h)	393	
Recommended chimney height (m)	13	
	mg/MJ [1)]	mg/m3 [2)]
NOx (as NO_2)	88	130
CO	14	21
Dust	4	5
Organic Carbon	<2	<2

For a better understanding of the emissions profile during the boiler operation, the following graphics show the emission levels for NOx (declared as NO_2), CO, CO_2 and C, related to a dry flue gas, at nominal and minimum heat output.

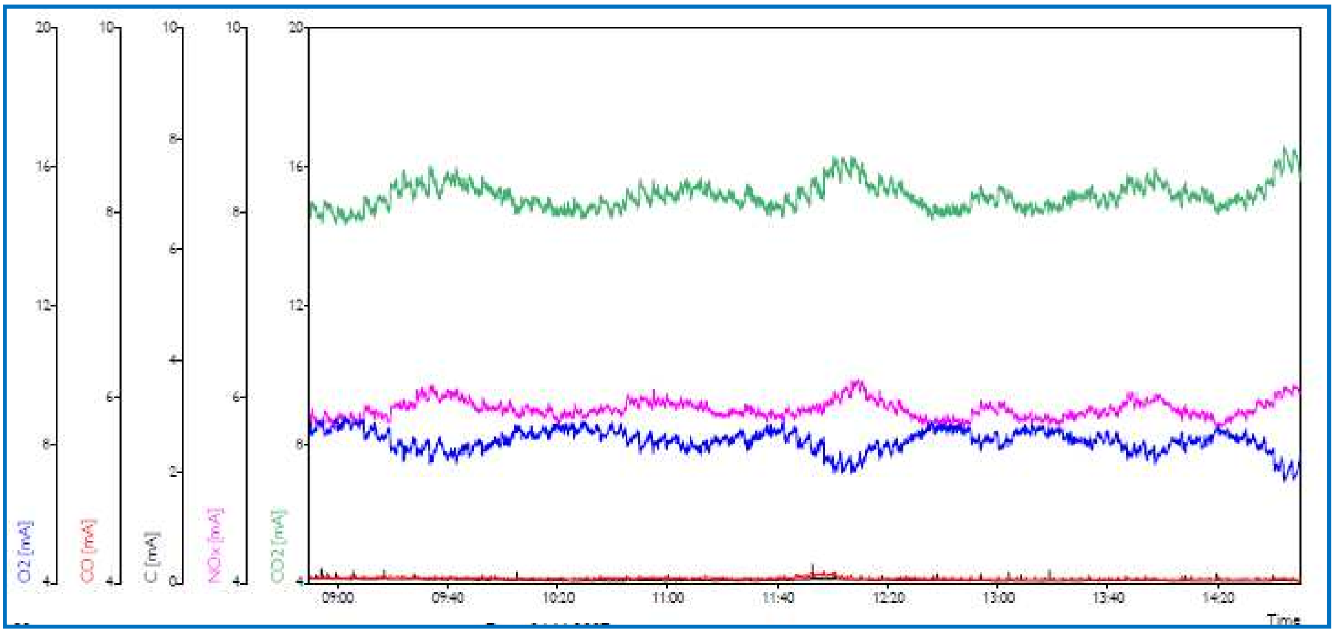

Figure 16: Concentration of air pollutants versus time at nominal heat output. ***SOURCE: [Ref. 32]***

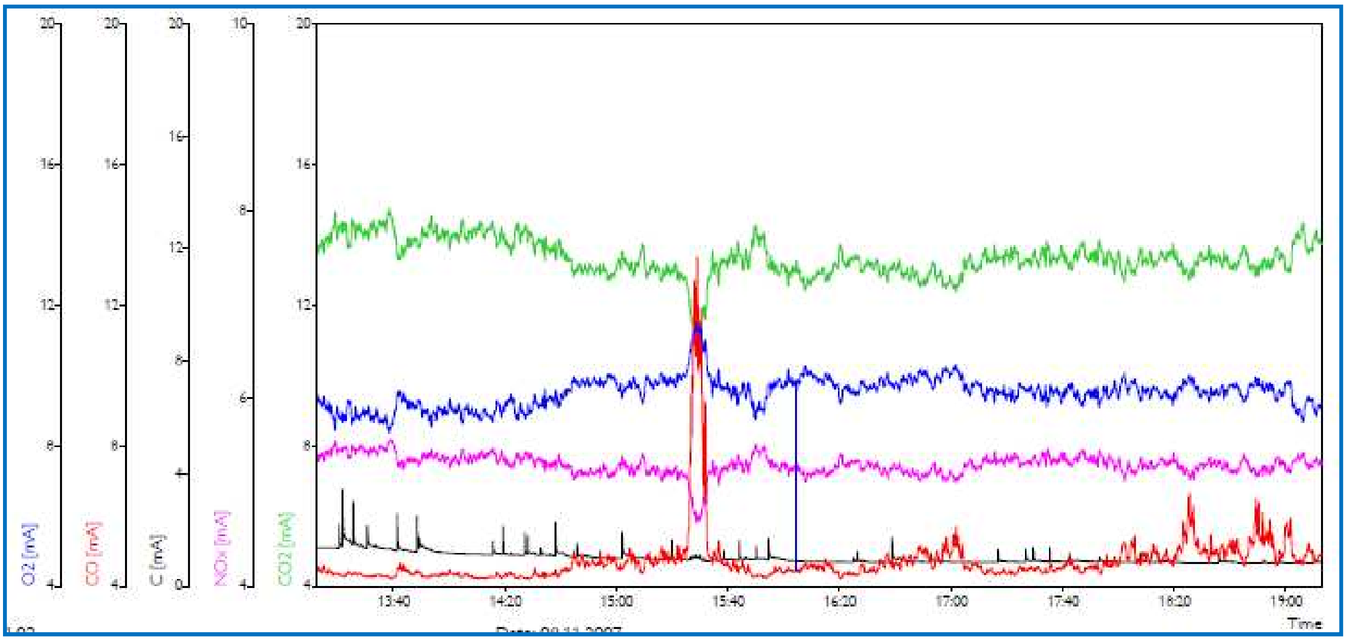

Figure 17: Concentration of air pollutants versus time at minimum heat output. ***SOURCE: [Ref. 32]***

Analysing these two figures it can be seen the difference in the CO emissions between nominal and minimum heat output, being this value higher in the second graphic, as during lower heat output more partial combustion occurs, leading to greater CO emissions.

The figure below represents a sectional view of the KWB Powerfire TDS 300 boiler:

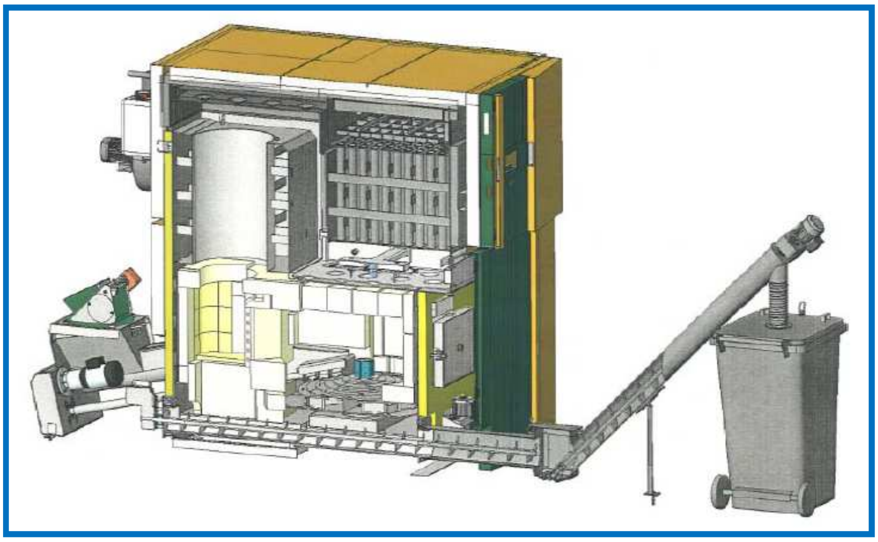

Figure 18: KWB TDS POWERFIRE 300 boiler. ***SOURCE: Boiler test report [Ref. 32]***

PYROT 540

This boiler has been tested according to DIN EN 303-5 by the TÜV SÜD Industrie Service GmbH laboratory. It is a 540 kW boiler manufactured by Köb & Schäfer KG. There is neither a detailed description of the boiler in the report nor an explanation of the measurement techniques. However, the methods used are those in accordance to DIN EN 303-5. [Ref.61]

The table below summarizes the relevant boiler information needed for the chimney height calculation:

Table 15: Test results for the PYROT 540 biomass boiler.

Nominal heat output (kW)	549.3	
Flue gas temperature (ºC)	162.7	
Flue gas velocity (m/s)	4.4	
Stack diameter (mm)	300	
Dry flue gas mass flow (m^3/h)	1008	
	mg/MJ [1)]	mg/m3 [2)]
NOx (as NO_2)	71	140
CO	5	10
Dust	9	18
Organic Carbon	1	2

LOCATION

In this project two different boiler locations are studied: a rural area, with no building influence in the surroundings, and an urban area, where the boiler is surrounded by buildings and hence they must be taking into consideration in the chimney height calculation procedure.

For the urban location selection, first of all, an analysis of the background concentration of the studied pollutants in different UK locations has been done. For this purpose the maps available in the UK and Scottish Air Quality WebPages have been analysed, in order to find some typical background values for NOx, SO_2, PM and CO in urban locations to use in the calculation procedures. This analysis shows that the background concentrations vary significantly between sites, influenced by nearby roads, industries...etc. Therefore, for the urban location, three different values have been selected for background concentrations in order to understand the influence of this in the chimney heights for the different models. These selected values are shown in the following table as annual hourly mean concentration in mg/m^3:

Table 16: Selected background values for chimney height calculation

	LOW VALUE	MEDIUM VALUE	HIGH VALUE
NOx (as NO_2)	0.015 mg/m^3	0.025 mg/m^3	0.035 mg/m^3
PM	0.010 mg/m^3	0.015 mg/m^3	0.025 mg/m^3
SO_2	0.001 mg/m^3	0.003 mg/m^3	0.006 mg/m^3
CO	0.2 mg/m^3	0.4 mg/m^3	0.6 mg/m^3

It must be said that the NOx background concentration exceeded in many cases the limit value set in the directive 2008/50/EC (0.04 mg/m^3) reaching the maximum annual mean value of 0.306 mg/m^3 for the London Marylebone Road monitoring site in 2011.

The PM maximum annual mean concentration corresponds to the same monitoring site, with a value of 0.038 g/m3. Until 2010 the limit value for PM10 in the atmosphere for the protection of human health was 0.04 mg/m^3, but from the 1st of January 2010, this value lowered to 0.02 mg/m^3. Therefore, the measured PM10 concentration in some monitoring sites exceeds this limit.

For the calculation procedures values have been taken that not exceed the limit set by the EC, as the chimney height is influenced by the allowed increase of the pollutant concentration in the air, and if this increase is 0, then it is not possible to install any biomass boiler.

The figures below show the monitoring sites available in urban locations for the Scottish and the UK Air Quality WebPages is shown below:

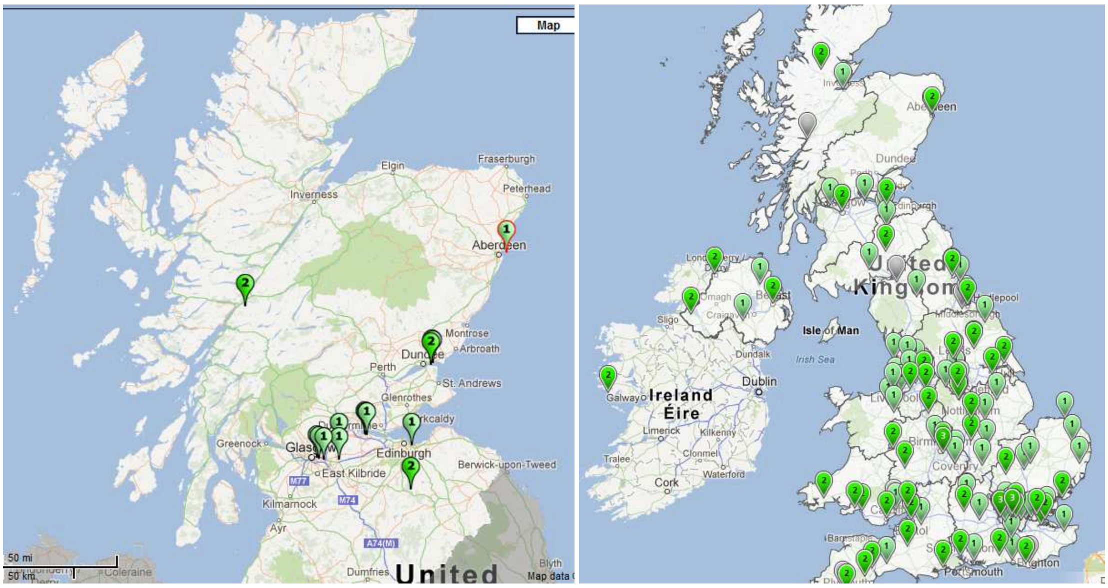

Figure 19: Monitoring sites available in Scotland and the UK for urban locations.

To run the calculations a specific location has to be defined, as most of the methods require building heights and distance to the boiler. Therefore, as a typical urban location, a residential area near a high school in Dundee has been selected. The boiler site and the surrounding area are shown in the Figure below:

Figure 20: Selected boiler location. *SOURCE: Google Earth.*

The boiler has decided to be located next to St John's RC High School, based on the fact that biomass boilers are nowadays being studied as an oil substitution for schools heating. This school has an open green area next to it, where there is space for the boiler plan to be installed.

To simplify the location description, and taking into account that this is not a real case and it is only used for methods evaluation and comparison, some assumptions have been made to define the building heights.

The High School has been considered to be 15-20 m high. Apart from this, the rest of the surrounding buildings are mostly residential houses, whose height has been taken as 6 m. Apart from this, the distances from the buildings to the boiler and the width of the buildings are also needed for the calculation procedures. These have been measured using Google Earth, and the final values are summarised in the table below:

Table 17: Building measures and distance to the boiler.

Building influence	R	Width	Width 2	Height
Boiler building	0	10	10	5
Residential houses (x300)	Vary	15	8	6
High School Build 1	100	61	29	20
High School Build 2	196	50	23	10
High School Build 3	147	70	31	10
High School Build 4	153	28	28	5
High School Build 5	186	70	20	10

The parameter R defines the distance from the building to the boiler.

The selection of the rural location relies on the available information about background concentration of pollutants in those areas, as this data is needed for the calculation procedure. The UK Air Quality Webpage has been used for this purpose.

The selected location is Harwell in South Wales, a rural monitoring site located within the grounds of the Harwell Science Centre. The nearest road is a minor road located approximately 140 metres from the station. The surrounding area is generally open with agricultural fields and the nearest trees are at a distance of 200 - 300 metres from the monitoring station. [Ref.62]

It is located at around 80 km from London which justifies the installation of the monitoring site. However, it has no surrounding buildings, what makes it valid for building influence analysis.

Figure 21: Selected urban location. *SOURCE: Google Maps.*

Table 18: Selected background values for the urban location.

Pollutant	Annual hourly mean
SO_2	0.0018 mg/m^3
NOx (as NO2)	0.012 mg/m^3
PM	0.012 mg/m^3
CO	0.2 mg/m^3

As there is not CO background concentration value for the selected site (this pollutant is only measured in 24 of the 134 monitoring sites) the CO concentration has been taken as 0.2 mg/m3 (London Kensington value)

For the calculation procedure, the following table has been created and included in all the excel documents used to develop the different models. The user is therefore able to select the case and the program runs the calculation for every case study automatically.

District	3	Select one of the two options to define the zone where the boiler is installed
Urban location (LOW)	○1	
Urban location (MEDIUM)	○2	
Urban location (HIGH)	◉3	
Rural location	○4	

		ANNUAL MEAN VALUES				
		NO2	SO2	PM	CO	
	1	0,015	0,001	0,01	0,2	mg/m3
	2	0,025	0,002	0,015	0,4	mg/m3
	3	0,035	0,006	0,018	0,6	mg/m3
	4	0,012	0,0018	0,012	0,2	mg/m3
Guideline concentrations	5	0,04	0,025	0,02	1,14	mg/m3

Figure 22: Screen shot from the Excel documents that reproduce the chimney height calculation methods.

To study the building influence in the chimney height calculation, a similar table has been developed, with small differences for every model, relying on the needed inputs for the calculation. These tables are included in the following section in each method description.

SITE CONDITIONS

For the meteorological data specification, Glasgow information has been used. This city has been chosen to simplify the case study specification, as there is much meteorological information about Glasgow of easy access online. This data is needed for the Spanish method and the values used are summarised in the table below:

Table 19: Glasgow meteorological parameters

	GLASGOW
Average temperature	8.9
Minimum temperature (feb 2012)	-7
Maximum temperature (may 2012)	27
Average temperature in the warmest months (jul, aug)	19
Average temperature in the coldest months (jan, feb)	1
Average relative humidity (jun, jul, aug, sept)	54.4%

4.3. Methodologies and models

UK

<u>D1 calculation model</u>

Before the 90's, the analysis related to flue heights in combustion plants was usually carried out following the steps described in the 1956 Memorandum on Chimney Heights. However, this document is only directed to control sulphur and nitrogen dioxide, as these were the concerning pollutants of the conventional combustion technologies. However, these plants have suffered a wide range of changes during the past years, from the burning technology to the fuels used, and these changes have affected the discharge composition. Therefore, The Memorandum was adapted to this new situation in 1993, and the Technical Guidance Note D1 Guidelines on Discharge Stack Heights for Pollution Emissions [Ref.19] was created. This updated document included a bigger number of pollutants and discharge conditions, in order to be able to reproduce the new combustion systems.

These guidelines have been used as the UK chimney height calculation method for the selected case studies. The steps followed to obtain the final value for the chimney height are summarized below:

Calculation of the Pollution Index

This value is obtained for all the emitted pollutants with the purpose of identifying the most significant emissions. Once they are identified, the minimum chimney height will be based on these pollutants, understood as the worst case scenario. The PI is calculated taking into consideration, not only the quantity of pollutant emitted, but also the background concentration in the case study area, and the effects of this contaminant in the human health, which is represented by the limit value permitted to protect human health in the directives and legislation.

The first step is, therefore, to determine the guideline concentrations. The D1 Technical Guidance Note sets out some commonly used values. However, for this and all the methods, the limit values defined by the European legislation will be used, as it has been understood to be a result of an agreement between the studied countries, and as the EU keeps growing in union and knowledge, the legislation is likely to be similar in all the countries in the near future.

For the selected case studies, the only concerning pollutants are NOx, PM and CO, as SO_2 emissions have been taken as null and other contaminants such as metals and organic compounds are not likely to be emitted from clean wood (they would only be present if the wood was recycled).

The PI is usually divided in groups of similarly affecting pollutants (acid gases, organic...) but in this specific case the emissions don't correspond in the same group, hence their PI can be calculated separately and then added together to find the combined value of PI, following the equation:

$$PI_i = \frac{D}{G - B} \quad (m^3/s)$$

Being:

D: Discharge rate of the pollutant in mg/s

G: The limit concentration value of the pollutant set out in the guidelines in mg/m^3

B: The background concentration of the contaminant the case study area in mg/m^3

Then, the final PI value is: $PI_{combined} = P_{NOx} + P_{CO} + P_{PM}$.

The valid range for this parameter is: 50< PIcombined <10^7

Calculation of the uncorrected stack height

Ub: Uncorrected discharge stack height for buoyancy.

For simplicity, in most cases, the heat release gives the value for the buoyancy. This is calculated by:

$$Q = V \cdot \frac{1 - (^{Ta}/_{Tf})}{2.9} \quad (MW)$$

Being:

V: Total volume flow rate of discharged flue (in m^3/s)

Ta: Ambient temperature in site (in K)

Tf: Flue temperature (in K)

If Q<0.03 MW, Ub is not calculated and, according to the D1 Technical Guidance Note, increasing the heat release should be considered to reduce the density of the exhaust gases.

If 0.03<Q<100 MW, Ub is calculated following:

$$Ub = 10^{a} \cdot PI^{b} \quad (m)$$

If Q<1, $a = -1.11 - 0.19 log_{10}Q$; $b = 0.49 - 0.005 log_{10}Q$

If Q>1, $a = -0.84 - 0.1 \exp{(Q^{0.31})}$; $b = 0.46 + 0.0011 \exp{(Q^{0.32})}$

The valid range for Ub is 1m<Ub<200m

Um: Uncorrected discharge stack height for momentum

$log_{10}Um = x + [(y \cdot log_{10}PI) + z]^{0.5}$, where 1<Um<200 and

$x = -3.7 + (log_{10}M)^{0.9}$

$y = 5.9 - 0.624 log_{10}M$

$z = 4.24 - 9.7 log_{10}M + 1.47(log_{10}M)^{2} - 0.07(log_{10}M)^{3}$

$M = \frac{Ta}{Tf} \cdot V \cdot v \quad (m^{4}/s^{2})$; Valid range: $1<M<2 \cdot 10^{4}$

Being:

v: Flue gas discharge velocity (m/s)

The final value of U is the minimum of Ub and Um, if Ub has been calculated (hence, if Q≥0.03 MW). If there is no calculation of Ub, then U=Um.

Calculation of final discharge stack height

To obtain this final value the buildings surrounding the boiler plant are taken into consideration, so that the pollutants have no effect on them. In order to simplify this procedure, the developed D1 model includes the table shown below, which has been filled to meet the specifications of all the case studies.

Building influence	R	Width	Width 2	Height	Height (considering distance)	K	T	
Residential houses (x300)	135	15	8	6	6	6	15	x300 houses
High School Build 1	100	61	29	20	20	20	50	
High School Build 2	196	50	23	10	0	0	0	
High School Build 3	147	70	31	10	10	10	25	
High School Build 4	153	28	28	5	5	5	12,5	
High School Build 5	186	70	20	10	0	0	0	
					Hmax		Tmax	
					20		50	

Figure 23: Required building information for the UK calculation for the case study: 540 kW boiler, urban location, high background concentration.

It contains information of the surrounding buildings which are located not further than 5 times the value of Um from the chimney. K is the lowest from width and height, and $T = H + 1.5 \cdot K$, being H the height of the building.

Then, the value of Hmax (the maximum height of all buildings) and Tmax (the maximum value of T of all buildings) is obtained. (View Figure 23)

If U>Tmax, then C=Tmax

If U<Tmax, then:

$$C = Hmax + \left(1 - {}^{Hmax}/_{Tmax}\right) \cdot \left[U + \left[(Tmax - U) \cdot \left(1 - A^{-U/Hmax}\right)\right]\right]$$

Being,

C: The calculated chimney height, in m.

U: As defined before, it is the minimum of Um and Ub when Q≥0.03MW, and Um if Q<0.03MW.

A: If Q<0.03MW (or in other words, if there is no value of Ub), then A=1

If Ub>Um, then A=1

In other cases, A=Um/Ub

Therefore, A is always ≥1.

Spain

The Spanish methodology for determining chimney heights is defined in the Ministerial Order of 18th October 1976 [Ref.48], about prevention and correction of the industrial pollution of the atmosphere. As it is specified in this document: "[...] the present disposition establishes [...] the instructions for the chimney height calculation to achieve the most adequate dispersion of pollutants with the purpose of not getting beyond the required air quality conditions.

This procedure is included in the Appendix II of this Order and it is applicable in general for combustion installations with a global power output lower than 100 MW, and for chimneys that emit a maximum of 720 kg/h of any gas or 100 kg/h of particulate matter.

In addition to this, the formulae are applicable if the fumes have a minimum vertical convective impulse that validates the following equation:

$$\Delta T > 188 \cdot \frac{V^2}{H^2}\sqrt{S}$$

Being:

ΔT: The difference between the flue gas temperature in the chimney mouth and the average temperature of the maximum of the warmest moth in the chimney location.

V: Flue gas velocity, in m/s.

H: The calculated chimney height, in m.

S: The minimum interior section of the chimney, in m^2.

The chimney height calculation procedure is detailed below by steps:

Determination of the parameter A

This parameter represents the climatologic conditions of the place where the installation is located and it is equal to:

$$A = 70 \cdot I_0$$

And:

$$I_0 = \frac{\Delta T + 2\delta t}{Tm} + \frac{80}{h}$$

Being:

ΔT: Maximum temperature difference in the place, which means, the difference between the existing maximum and minimum temperature.

δt: Difference between the average temperature of the warmest month and the average temperature of the coldest month.

Tm: Annual average temperature, in ºC

h: Average relative humidity of the months June, July, August and September, in %

This formula is valid when Tm>10ºC. If that is not the case, then Tm=10 is used. In the selected case studies the average temperature is lower than 10 ºC so Tm=10.

Determination of the maximum admissible pollutant concentration C_M

This parameter represents the value of pollutant concentration that cannot be exceeded and is calculated by the difference between the limit established to protect human health and the already existing pollutant concentration in the place, in mg/Nm^3 and 24-hourly measured.

As it is explained in Section 3.2, the 24-hour values are obtained by the multiplication of the annual mean values by the factors established in the US EPA (Appendix, Table A4).

This parameter is obtained for all the pollutants involved and the chimney height is calculated for all of them. Then, the highest value is selected.

Chimney height calculation

Finally, the chimney height is calculated following:

$$H = \sqrt{\frac{A \cdot Q \cdot F}{C_M}} \cdot \sqrt[3]{\frac{n}{v \cdot \Delta T}}$$

Being:

H: The calculated chimney height, in m.

A: As defined before, the parameter that represents the climatologic conditions.

C_M: As defined before, maximum admissible pollutant concentration, in mg/Nm^3.

Q: Maximum pollutant flow rate, in kg/h.

F: Coefficient related to the sedimentation velocity of the pollutants in the atmosphere. For gaseous contaminants F=1 and in the case of particulate matter and other heavy impurities, F=2.

n: number of chimneys, located in a horizontal distance lower than $2 \cdot H$ from the studied chimney.

v: Flue gas flow rate, in m^3/h.

ΔT: Difference between the flue gas temperature in the chimney mouth and the average temperature of the maximum of the warmest month in the chimney location.

Sweden

In Sweden, there is not a specific regulation for chimney heights calculation and air emissions, but some minimum requirements are established as guidelines by the Swedish Environmental Protection Agency (SEPA), especially for small sized furnaces. However, operators can also direct to consultant engineering companies to calculate the impact on air quality in the surroundings and chimney heights.

These guidelines were created in 1970 and at first they only included sulphur dioxide emissions from oil. Years later these guidelines were updated based on reports that the Sweden's Meteorological and Hydrological Institute (SHMI) developed for the SEPA.

These new guidelines included a chimney height calculation considering also the emissions of nitrogen oxides. Some simplifications were required in the calculation procedure which limits it application, avoiding its use in complex situations, where further particular study is recommended, such as:

- Plants located in particularly rough terrain
- Plants with significant emissions through multiple stacks
- For Href higher than 60 m.
- Plants located in urban areas where the NO_2 ground concentration is close to being exceeded

However, a highly simplified calculation method, described in the General Guidelines 87:2 [Ref.36], is usually accepted for smaller combustion plants (0.5-10 MW), with the more complex guidelines used when emissions differ from the conditions specified in the simplified method.

These simplified guidelines were developed in 1987 by the SEPA and there has been no update since then. Therefore, the SEPA informs in their webpage of some recommendations that differ from the published guidelines:

First of all, the guidelines recommend dust emission levels in urban areas to be lower than 100 mg/Nm^3 and lower than 350 mg/Nm^3 in rural areas. However, given the current knowledge about particles and health effects, they specify that the limit value should be 100 mg/Nm^3 in rural areas, and even lower in urban areas.

The guidelines establish a reference height according to the boiler power output. Then, this height is implemented to consider surrounding building influence.

Table 20: Reference height for different boiler outputs

BOILER OUTPUT	Href (m)
0,5-2,5 MW	10
2,5-5 MW	15
5-10 MW	20

The excel document developed to define the Swedish method includes therefore a table to describe the surrounding buildings, as it can be seen below:

Building influence	R	Width	Width 2	Height	Height (R<150m)	htb	hi
Residential houses (x300)	135	15	8	6	20		0
High School Build 1	100	61	29	20	10		0
High School Build 2	196	50	23	10	0	20	0
High School Build 3	147	70	31	10	5		0
High School Build 4	153	28	28	5	0		0
High School Build 5	186	70	20	10	0		0
						h	0
						*max height within 2*Href*	

Figure 24: Required building information for the Swedish calculation

The value R shows the distance of the buildings to the boiler. For equal height, the ones located closer to the boiler have greater influence so only the first line of residential houses has been included, although there are more similar buildings further away. The htb represents the height of the highest building or terrain point within distance 2-20Href, or 20-150 m, if the boiler is up to 1MW.

Then ΔHtb is calculated by:

$$\Delta Htb = htb - 0.3Href$$

The parameter ΔHbd is calculated to consider negative pressure conditions in the leeward side of the chimney. If the tallest building within 2·Href is lower than 0.4·(Href+ΔHtb), then ΔHbd=0. If not, the following graphic is used.

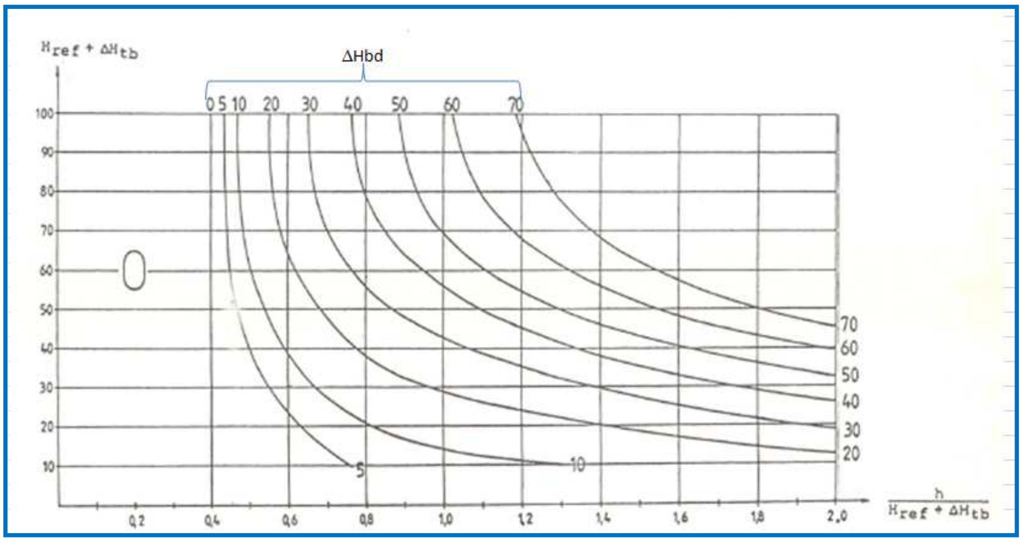

Figure 25: Diagram to calculate ΔHbd

Being h the maximum building height within 2·Href.

Then, the final stack height is:

$$H = Href + \Delta Htb + \Delta Hbd$$

Austria

The Austrian Standard ÖNORM M 9440 [Ref.49] includes some diagrams to estimate chimney heights for cold sources, with an exhaust gas temperature below 50 ºC, and hot sources, which correspond to all the case studies in this project.

The graphic for this last situation is shown below.

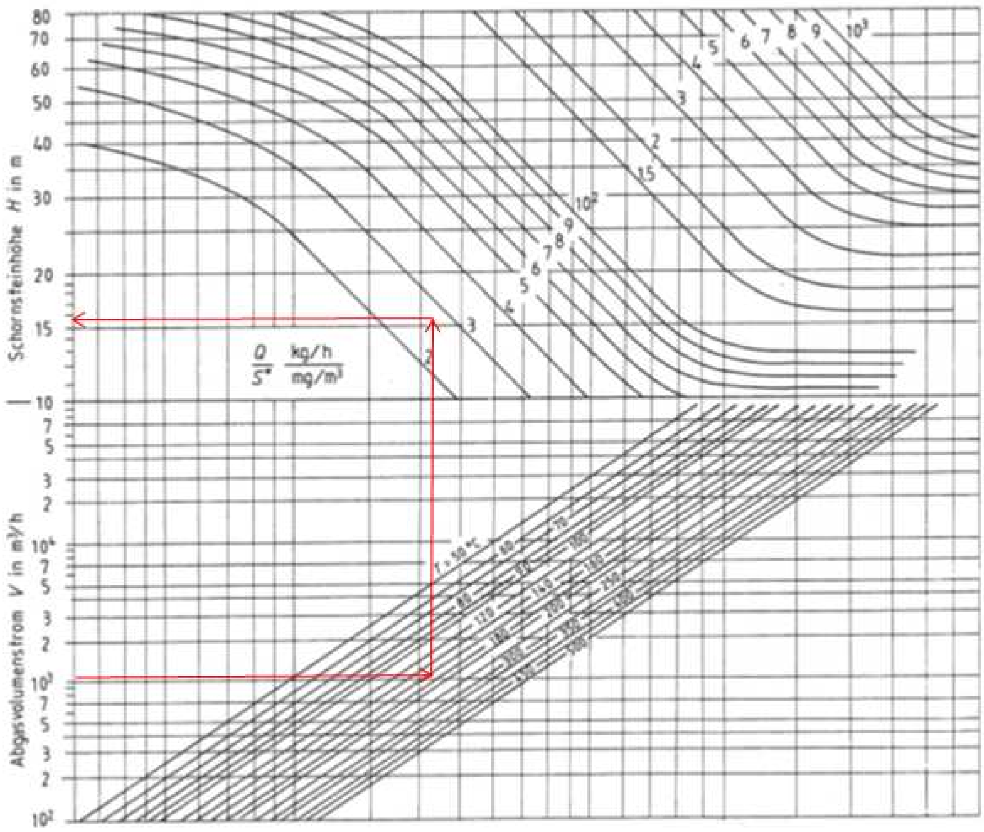

Figure 26: Diagram for chimney height calculation included in the Austrian regulation ÖNORM

Being:

Q: Pollutant flow rate, in kg/h (the maximum value of all the involved pollutants)

S: Allowed increase of pollutant concentration, calculated by making the difference between the pollutant limit established by the guidelines to protect human health and the already existing pollutant concentration in the place

V: Exhaust flue flow rate, in m^3/h

T: Exhaust flue temperature, in ºC

In order to explain how it is used, the calculation for the case study of the 540 kW boiler in the urban location with high background pollutant concentration is shown in the graphic. In this case the needed input parameters are:

V= 1108 m^3/h

Q/S= 28.1 (kg/h)/(mg/m^3)

T= 163 ºC

In this way, the value of V is spotted and matched with the temperature horizontally. In their point of union, a vertical line is drawn to match the value for Q/S. Horizontally to the left, the value for the chimney height can be read, in this case: H= 16 m.

Surrounding building's influence

To consider the surrounding buildings in the chimney height calculation, the following graphic is recommended in the Standard. This same graphic is included in the German Standard TA Luft for the same purpose.

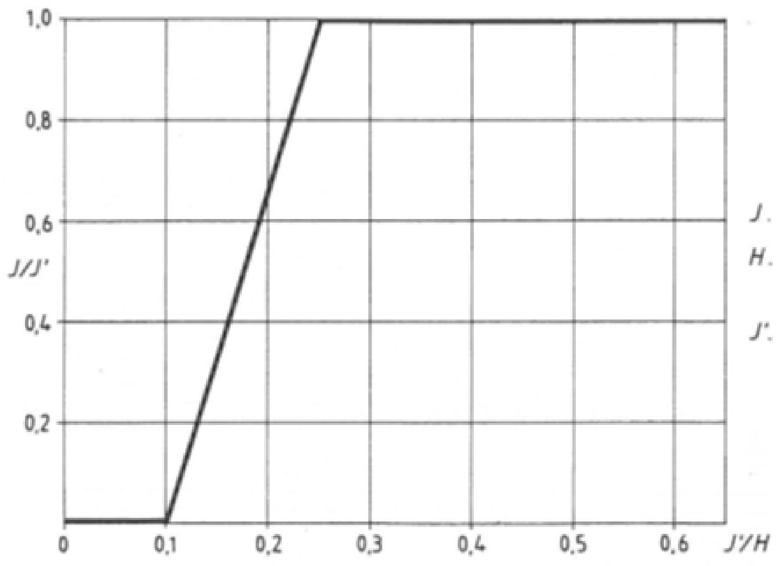

Figure 27: Diagram to include building influence in the Austrian calculation method

This figure is used when the area occupied by the buildings within a radius of 500 m from the chimney (if H<35m), and 15·H (if H>35m) is greater than 5%.

Being:

J': The average height of the surrounding buildings in the selected radius

H: Calculated chimney height

From the diagram, the value for J is obtained and this value is added to the calculated chimney height H, being the final height:

$$H_T = H + J$$

Building influence	R	Width	Width 2	Height	Building Area	
Boiler building	0	10	10	5	100	
Residential houses (x300)	Vary	15	8	6	36000	*x300 houses*
High School Build 1	100	61	29	20	1769	
High School Build 2	196	50	23	10	1150	
High School Build 3	147	70	31	10	2170	
High School Build 4	153	28	28	5	784	
High School Build 5	186	70	20	10	1400	
					43273	

Surrounding A (m2)	a occupied by buildi	% occ	→	J'	J'/H	J/J' (from diagram)	J	Hcorrected (m)
785298	43273	6	If % occ >5	10,2	1,13	1	10,2	19,2

Figure 28: Screen shot of the Excel document that reproduces the Austrian method in calculating the building influence. It corresponds to the 50 kW boiler, urban location case study.

Germany

In Germany, as well as for the rest of the studied EU countries included in this report, there is not a calculation software designed for small and medium sized biomass systems. The TA Luft [Ref.58] contains the requirements for large scale biomass plants and it includes some graphics to estimate chimney height.

This document specifies that: “Waste gases shall be discharged in such a manner that an undisturbed dispersion is made possible by free air stream. As a rule, a discharge through stacks is required, the height of which shall be determined pursuant to 5.5.2 to 5.5.4, notwithstanding better cognition.”

These sections of the document specify that “Stacks shall have a minimum height of 10 m above ground level” and they include the nomograms to estimate chimney height:

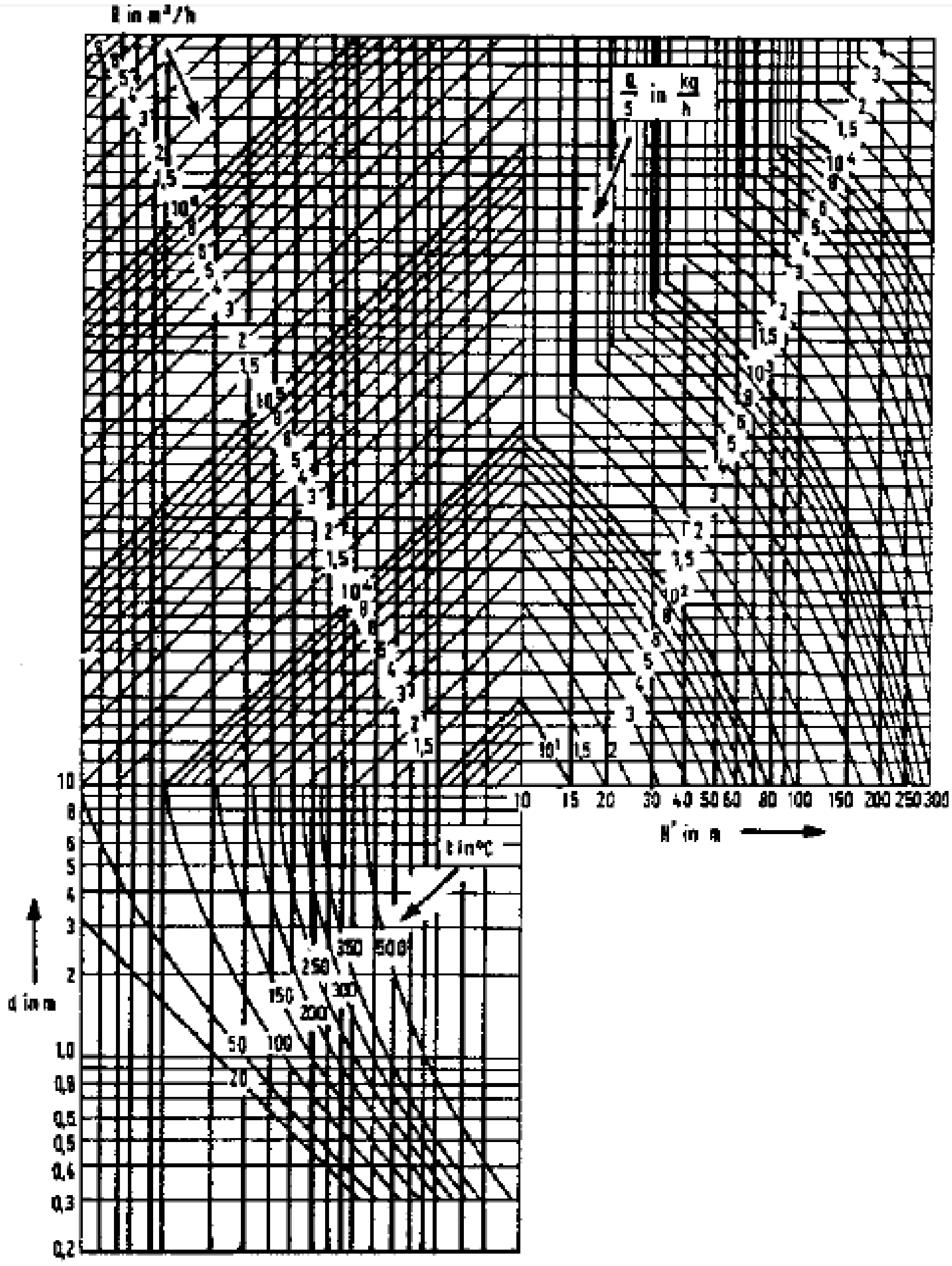

Figure 29: Diagram for calculating chimney height according to the German TA Luft.

Being:

R: Dry volume flow of the waste gas in m^3/h

H' Chimney height taken from the nomogram

d: Inside diameter of the stack, in m.

T: Temperature of the waste gas at the stack mouth, in ºC

Q Emission mass flow of the emitted air pollutant, in kg/h

S: Stack height determination factor; as a rule, S shall be defined by the values specified in the Table A4, included in the Appendix of this thesis.

For the utilization of this diagram, firstly the value of the stack diameter (d) is spotted and matched by a horizontal line with the flue temperature (t); then, a vertical line joins this point with R. From here, horizontally to the right, a line is drawn until it matches the value of Q/S, and vertically down to read the value of the height given by the diagram.

In order to consider surrounding buildings influence, the same method as the one included in the Austrian Standard is used. (View Figure 27).

Although the first nomogram in the TA Luft and the first graphic in the ÖNORM M 9440 for chimney height estimation have very similar inputs, they differ because the German method includes stack diameter as an input for the calculation instead of the flue gas temperature.

However, this nomogram is only applicable for large biomass systems. Hence, this graphic is not applicable for the boiler sizes studied in this report as the inputs are out of the diagrams.

However, a software called P&K 3781 helps doing the mathematical operations involved and it has been used in this report to estimate the stack heights for the case studies. Although the TA Luft, and therefore the P&K program, is directed to bigger boilers, the program does work with the cases' inputs. The results obtained with this software are explained in the following section of this thesis, where its applicability on small-medium scale installation is discussed.

The image below is a screen shot of the program, whose demo version can be downloaded from their website.

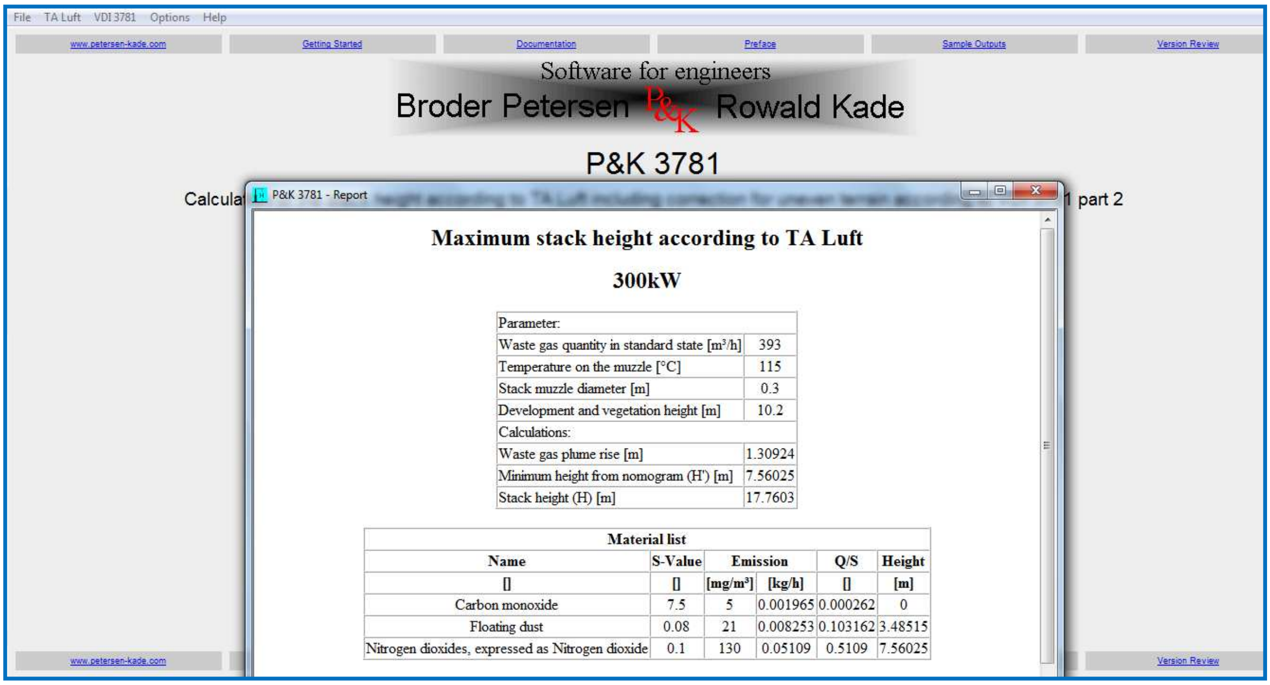

Figure 30: Screen-shot of the P&K software.

The P&K software also includes some mathematical procedure to consider uneven terrain following the VDI Guideline 3781 Part 2. However, this consideration has not been included in the case studies for simplification.

Other calculation methods

In all of these and other EU countries the usual procedure for chimney height calculation, especially for large scale combustion installations, is using modern models based on a time series of short time meteorological data that model the air dispersion of the pollutants for each specific case.

For example, in Denmark, the OML model [Ref.25] is widely used for this purpose and it is the calculation method recommended by the National Environmental Research Institute. Calculations using this model can be performed by the applicants themselves or by consultant professionals. This software is available from the NERI Webpage and can be purchased online.

For Germany, the AUSTAL 2000 is a PC-model used for air dispersion modelling and chimney height calculation and similarly, for the UK and Sweden, ADMS and Dispersion 2.1 are used, respectively. [Ref.9]

All these are modern and complex software that require expertise and knowledge and designers can buy consultancy help for their utilisation. Therefore, due to their complexity and for the economic implications, these PC-models have not been used in this report, and the methods analysis and comparison have been based on simple methods included in each country's regulation and guidelines.

4.4. Chimney height calculation- Results and Sensitivity analysis

UK

This method calculates the chimney height for different pollutant types, dividing the pollutants in two groups: acidic and other contaminants. For the selected case studies, the chimney height relies essentially in the second group, as clean wood combustion hardly has SO_2 or other acidic emissions.

The chimney height is calculated from the global Pollution Index, which in this case reflects the maximum Index of all the pollutants involved that belong to the second group. In all the studied cases this value is greater for NOx, followed by PM and it has its lower value for CO emissions. Therefore, in all the cases, the chimney height relies on the NOx emissions.

The chimney heights obtained with this method for all the case studies are shown in the graphic below:

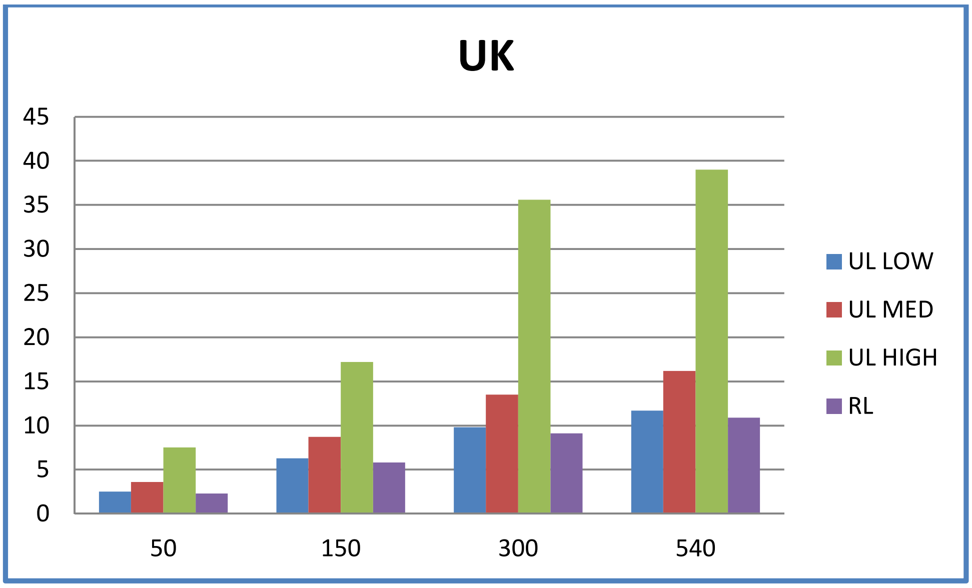

Figure 31: Chimney height calculation results for the created case studies following the UK methodology.

As it can be seen in the graphic, there is a similar shape for all the boiler types, with greater height values for the urban location with higher background pollution, and with the lowest heights corresponding to the rural location.

For the chipped wood heating boiler Evotherm 50 kW, the method gives heights from 2.3 to 7.5 m, within the range of selected background values. For the KWB TDS Powerfire 150 kW, the calculated heights are higher, from 5.8 to 17.2 m. For the two last boiler types, of 300 and 540 kW, the obtained chimney height range is 9.1-35.6 m and 10.9-39 m, respectively.

It can be noticed that for the urban location with higher background pollution with the 300 and 540 kW boilers, the chimney height increases significantly. This is explained because in these two cases the method considers the surrounding buildings, giving heights of 35.6 and 39 m respectively.

In this method, the influence of the emissions in the surrounding building is only considered in a radius of 5·Um. For the selected case studies, the nearest building from the boiler is located at 100 m, and this value stands within a distance of 5·Um only for these two cases, as Um has its highest values. Um increases with the Pollution Index, and this Index is higher when the NOx emissions are greater (PI_{NOx}= 7800 and 5034 m^3/s for the 540 and 300 kW boiler in the highest background pollution conditions, whilst is lower than 2600 m^3/s for the rest of the cases).

A very influencing parameter in this method is the released heat, represented as Q (MW), which in turn relies on the discharge flow rate v (m^3/s). If Q<0.03 MW, then Um is selected as U value, but if Q>0.03 MW, then the minimum from Um and Ub is chosen. In all the studied cases, Ub is lower than Um. Therefore, when Q>0.03 MW, the method gives lower chimney heights.

As an example, for the 540 kW boiler and the urban location-high pollution conditions the discharge flow rate (v) is 0.28 m^3/s, which gives a Q of 0.029 MW and a chimney height of 39 m. However, for this same case, with a flow rate of 0.3 m^3/s, it gives a heat release of 0.031 MW, and a chimney height of 29.5 m, which results in a decrease of 24%.

The flow rate has also a significant influence when Q<0.03 MW as it influences the momentum and this last parameter defines Um. If the flow rate increases, then the discharge velocity and the momentum increases, and the uncorrected discharge stack height for momentum (Um) decreases, giving lower values for the chimney height.

Therefore, this method relies significantly in two parameters: the pollutant emissions, which define the Pollution Index, and the discharge flow rate, which influences the momentum and the heat release. The following figure represents a simplified representation of the relationship between these parameters.

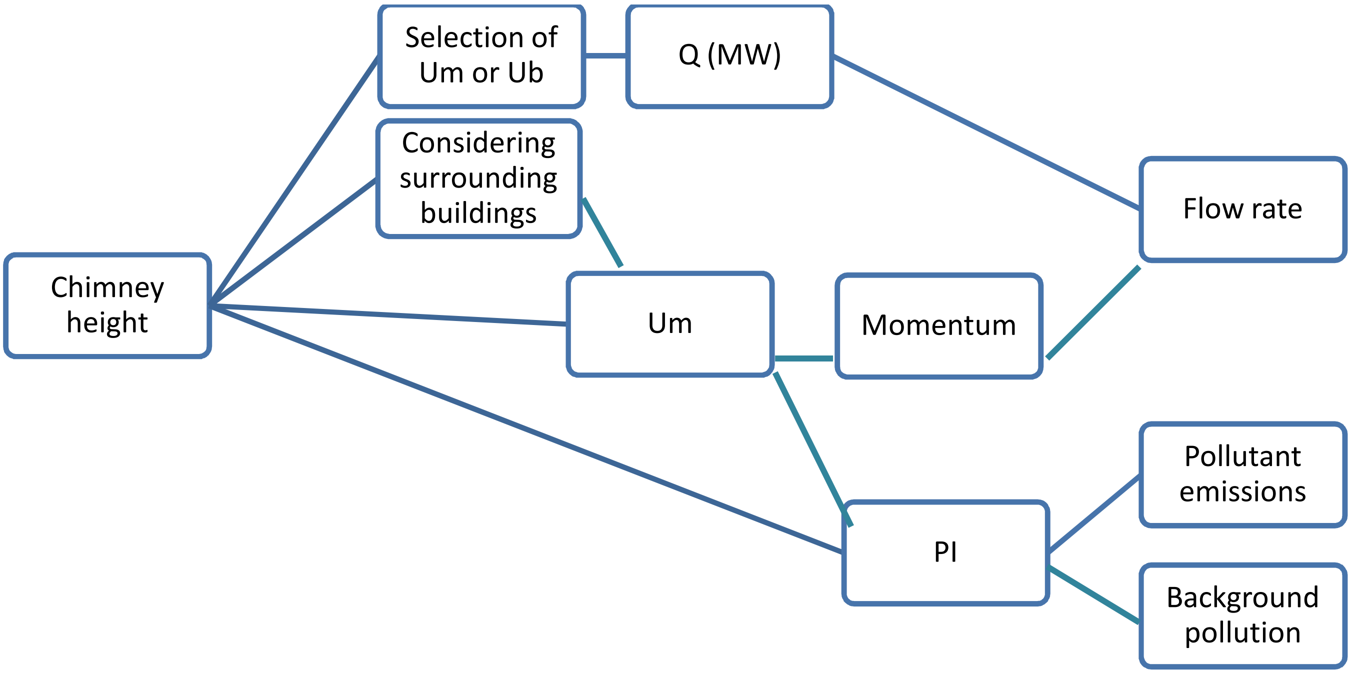

Figure 32: Diagram showing the relationship of the parameters influencing chimney height for the UK calculation procedure.

Spain

The Spanish model, defined in the Ministerial Order of 18th October 1976, is the most different of all the studied methodologies. It considers the meteorological data of the plant location and it does not include any height increase to take into account the effects of the pollutants on the surrounding buildings.

The chimney height results obtained by this method are shown in the figure below:

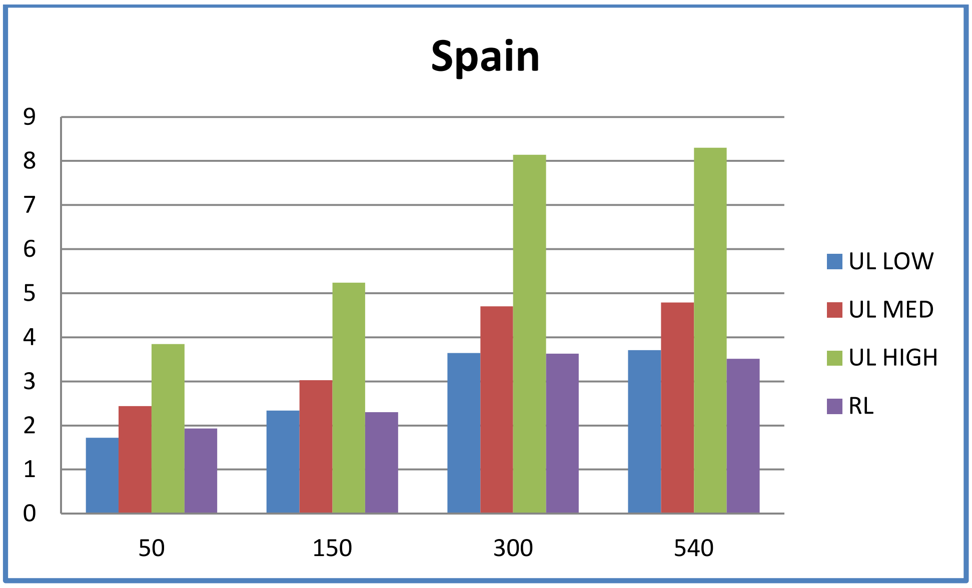

Figure 33: Chimney height calculation results for the created case studies following the Spanish methodology.

It can be seen that it gives low values compared to other European Standards. The explanation for this can be that it does not include surrounding buildings in the calculation procedure. Same to other cases, the highest values correspond to the 300 and 540 kW boiler in the urban location with the most severe background pollution conditions, with values of 8.1 and 8.3 m respectively.

For some of the cases, it is the particulate matter and not the NOx that defines the chimney height. This does not happen in the other calculation procedures because in all cases the NOx emission rate is greater than the PM emission. However, this method takes into consideration the sedimentation properties of the pollutants, which makes PM a more affecting contaminant for some of the case studies. However, the chimney heights calculated from the PM and the NOx are very similar in all of the scenarios.

The chimney heights values vary approximately from 2 to 8 m. The lowest value (1.72 m) corresponds to the smallest boiler in the urban location with the lowest background pollution. It may seem rare that this value is higher for the rural location, but if the background pollution conditions are revised (Section 4.2), it can be noticed that the background PM concentration is higher in the rural location (RL) than in the urban with the lowest pollution (UL-LOW).

It is important to say that the condition for the application of this method: $\Delta T > 188 \cdot \frac{V^2}{H^2}\sqrt{S}$, is complied in all the case studies. However, if this was not the case, changes in the stack diameter can vary the second part of the equation, making the condition valid, so the chimney section can be improved for the method to be applicable.

The following diagram represents the most influencing parameters in the chimney height calculation:

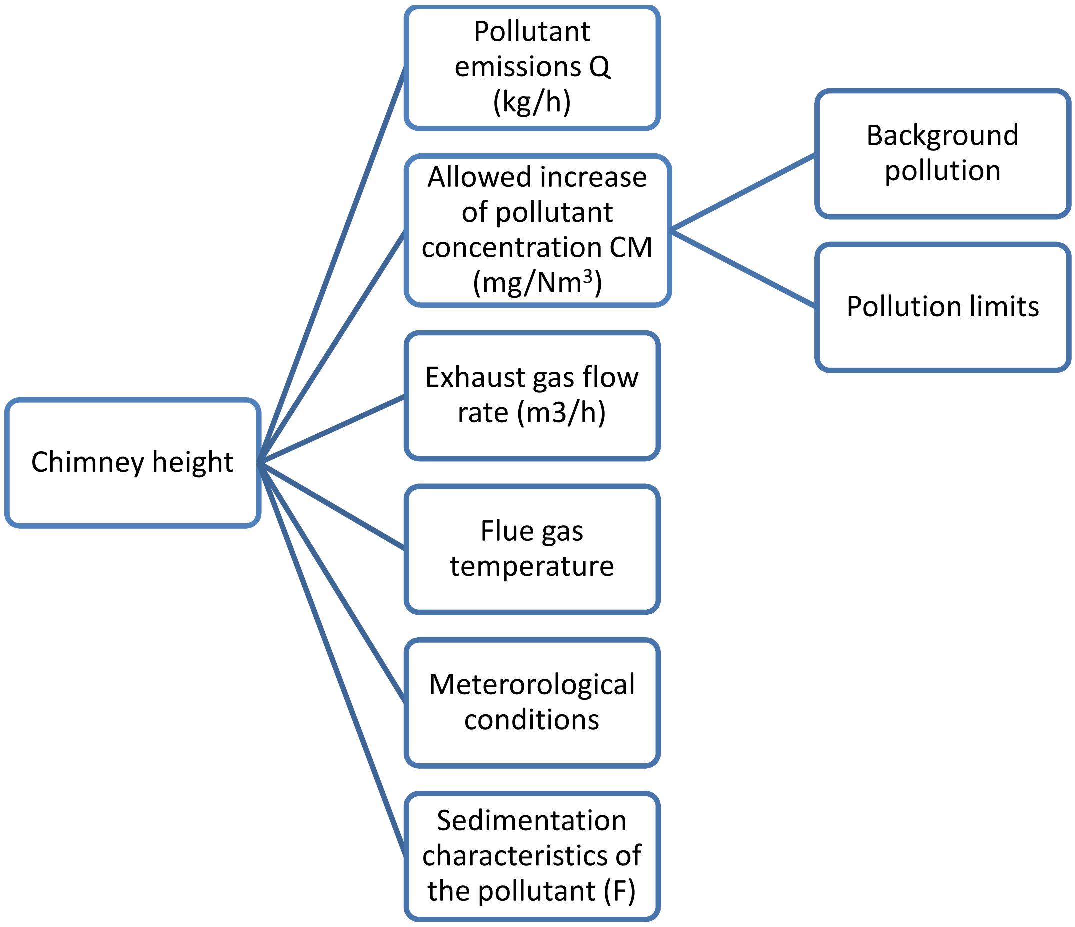

Figure 34: Diagram showing the relationship of the parameters influencing chimney height for the Spanish calculation procedure.

Sweden

The Swedish calculation procedure for boilers smaller than 10 MW makes no difference between boiler sizes from 0.5 to 2.5 MW, recommending a chimney height of 10 m for this size range. Therefore, it can be concluded that, similar to Austria, Sweden has no specific defined procedure for small-medium boilers.

The model includes some calculation to consider the effect of the emitted pollutants on the surrounding buildings that increases the recommended chimney height. Hence, this method gives the same value for all the boiler sizes in the urban location (independent from the background pollution concentration). It gives two values: one for the specified urban location which considers surrounding buildings, and one for the rural location, with no building influence:

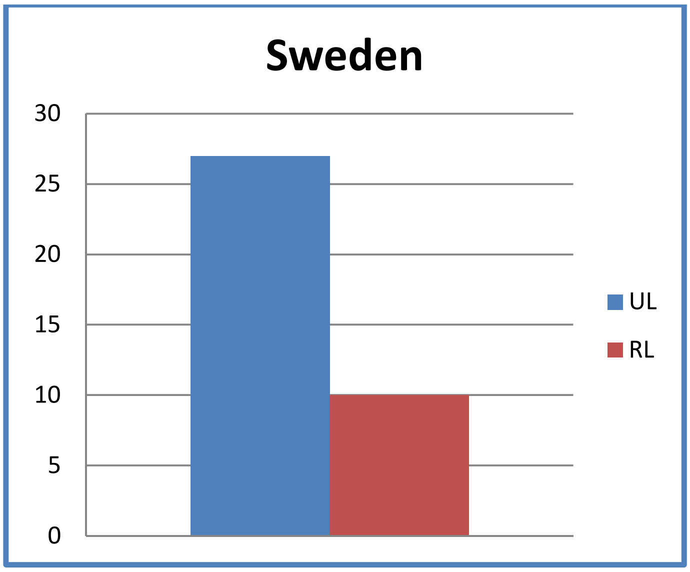

Figure 35: Chimney height calculation results for the created case studies following the Swedish methodology.

The following diagram represents the parameters that influence chimney heights according to the Swedish Standard:

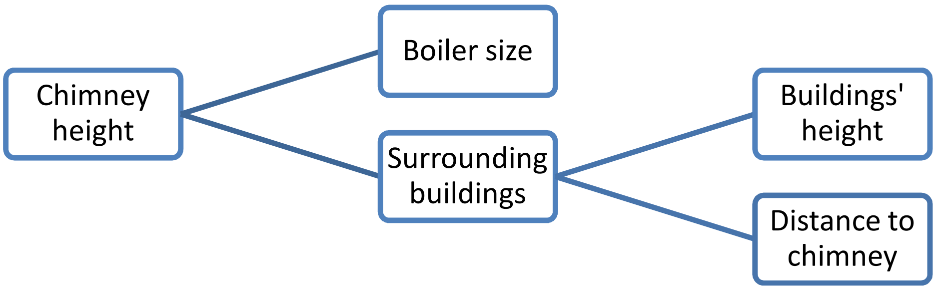

Figure 36: Diagram showing the relationship of the parameters influencing chimney height for the Swedish calculation procedure.

Austria

The method described in the ÖNORM M 9440 Standard is based on the pollutant emissions rate, the allowed increase of ambient pollutant concentration and the flue gas temperature. These parameters are the needed inputs for the graphic that gives the recommended chimney height. However, this graphic is not applicable for many of the studied cases, as the pollutants flow rate is too low. The minimum value represented in the diagram for Q/S (View Section 4.3: Austria) is 20 (kg/h)/(mg/m^3) and in most of the cases this value is lower, so it can be concluded that the method is not applicable for low emission rates and it is basically directed to bigger boilers.

Therefore, for the cases where the first graphic is not applicable, the recommended chimney heights included in the boilers test reports have been used. Then, this height is increased to include surrounding buildings' influence. These recommended chimney heights are specified in the Section 4.2, where the boiler test results are explained.

However, the method is applicable for two cases: the 300 kW and the 540 kW boilers in the urban location with the highest background pollution conditions, as the value for Q/S is close to or higher than 20 (kg/h)/(mg/m^3). For these cases, the NOx is the most influencing pollutant and it is what defines the chimney height.

The results obtained from this model are illustrated in the figure below:

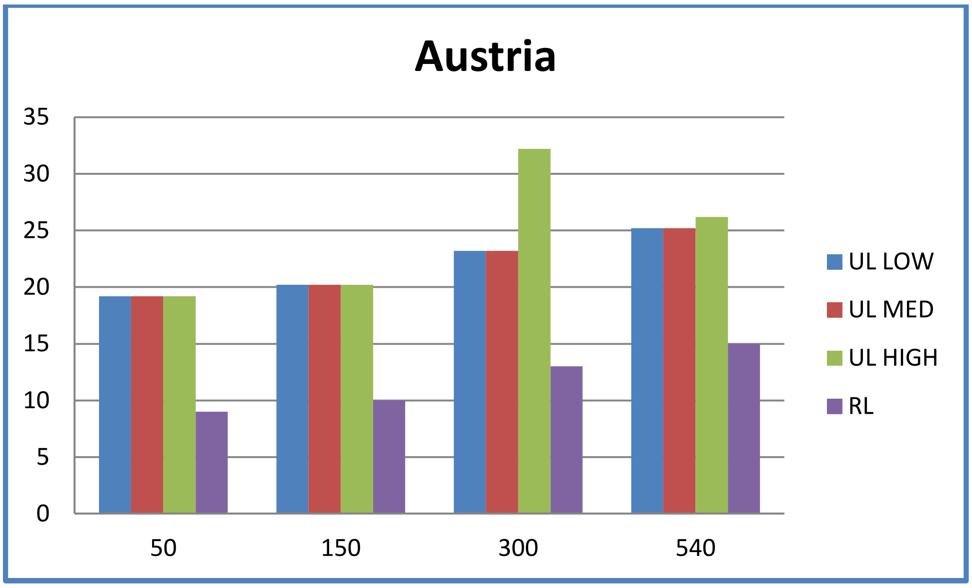

Figure 37: Chimney height calculation results for the created case studies following the Austrian methodology.

It can be seen that for each boiler size the method gives the same results for the urban locations, except for those cases where the diagram is applicable. This is explained because the influence of the surrounding buildings is the same in all the urban cases (as the boiler location does not vary) and the recommended chimney height is the same independent from the background pollution.

The purple columns represent the chimney heights recommended in the test reports for each boiler size, as there is not building influence, and therefore, no height increase. The rest of the columns (except for the green ones in the 300 kW and the 540 kW boilers) are the result of the addition of these recommended heights plus the increase due to buildings' influence.

The highest columns represent the two case studies where the first diagram of the method is applicable. It is higher for the 300 kW boiler because the flue gas flow rate v (m^3/h) in this case is a 61% lower than the flow rate for the 540 kW boiler, generating a lower momentum which justifies that the chimney height needs to be greater not to affect human health.

The highest height given by this method corresponds therefore to the 300 kW boiler in the urban location with higher background pollution, with a value of 32 m.

When both graphics described in the method are applicable, the most influencing parameters are those included in the diagram below:

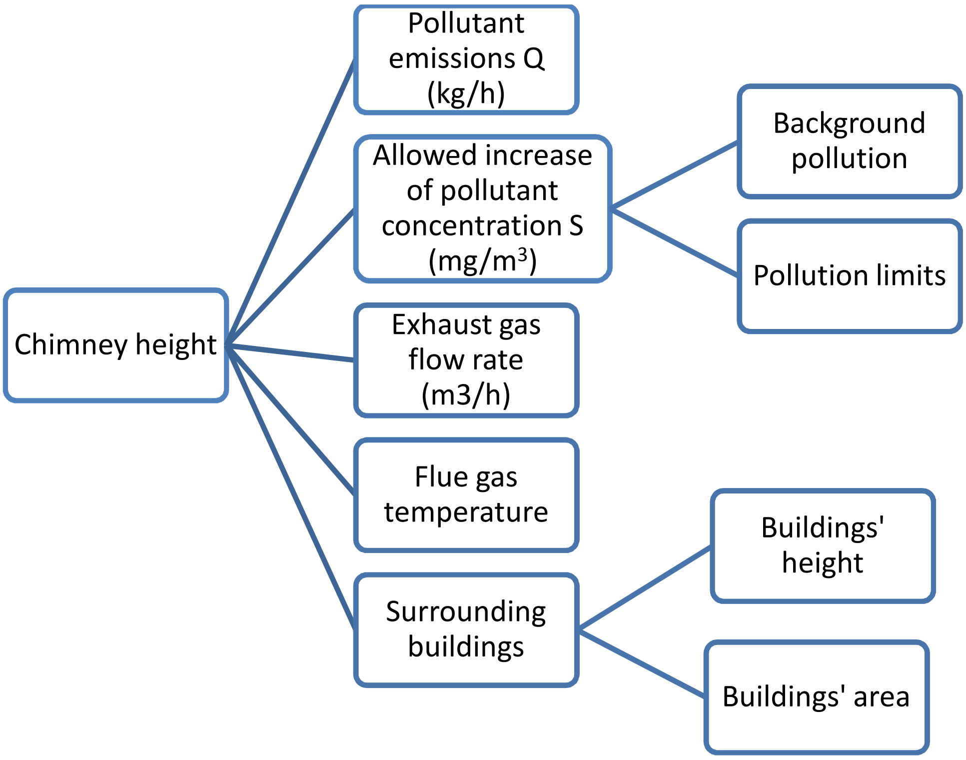

Figure 38: Diagram showing the relationship of the parameters influencing chimney height for the Austrian calculation procedure.

Germany

To calculate the chimney height for the selected case studies the software P&K 3781 has been used. This is a simple program based on the TA Luft and it does not include any input options to define background concentration or pollution limits. Therefore, the case studies for this calculation procedure are reduced to eight, two for every boiler size: rural location (no surrounding buildings' influence) and urban location.

The following graphic shows the results obtained with this software:

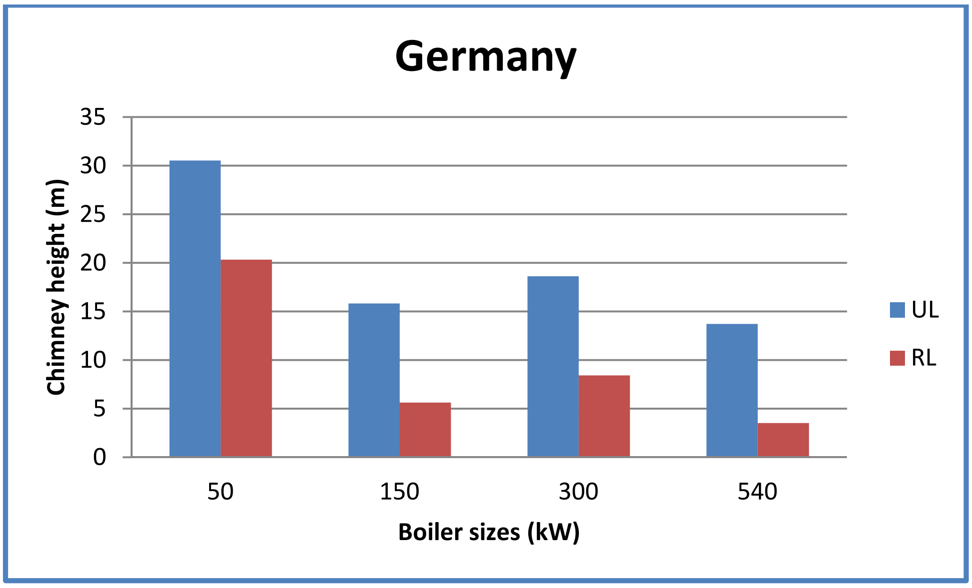

Figure 39: Chimney height calculation results for the created case studies following the German methodology.

It can be seen that, comparing to the results obtained by the other methodologies, these results have a very different appearance. The program gives the highest values for the 50kW and the lowest values for the 540 kW.

This is explained due to the very low value of the exhaust gas flow rate for the first scenario. This affects the momentum and the plume rise, and increases the chimney height.

The flow rate has such a great relevance in this software because the pollutant emissions are not significant in comparison, knowing that this software is directed to large scale biomass boilers. Therefore, it gives higher chimney heights for the cases where the flow rate, and therefore the plume rise, is lower.

In order to have a representation of the influence of this parameter on the height calculation, the flow rate has been changed for the 540kW urban location scenario to create the following figure:

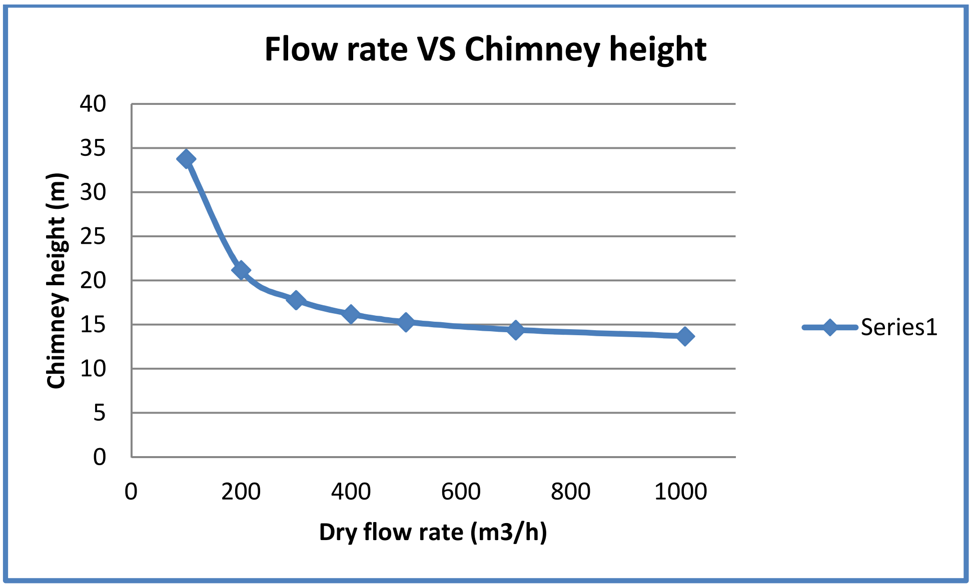

Figure 40: Relationship between the flow rate and the chimney height, according to the results obtained following the German method.

This figure shows how the flow rate affects the chimney height, especially when the value of the flow rate is very low, as the plume is rise is negligible and the height needs to be greater to ensure a good dispersion of the pollutants.

The flow rate had a similar effect in the Austrian method, which gave a greater value of the chimney height for the 300 kW boiler than for the 540 kW boiler because the flow rate was lower for the first scenario. (View Figure 37).

The most influencing parameters taken into consideration in this software are summarised in the diagram below:

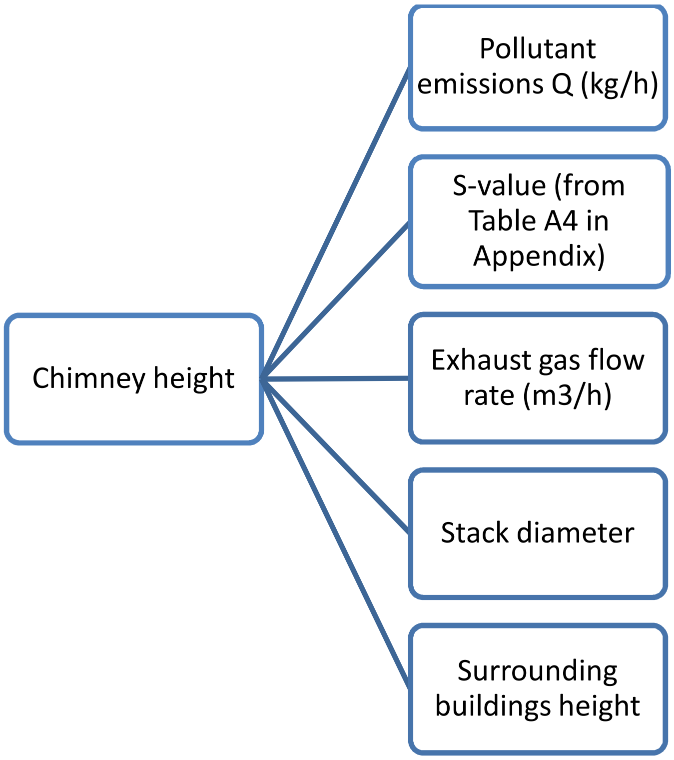

Figure 41: Diagram showing the relationship of the parameters influencing chimney height for the German calculation procedure (P&K software)

As a summary of the results, the following graphic shows the chimney heights calculated for all methods. It is useful to represent the big differences existing among the studied methodologies, which justifies the recommendation of developing a common European simple methodology for small-medium scale biomass boilers:

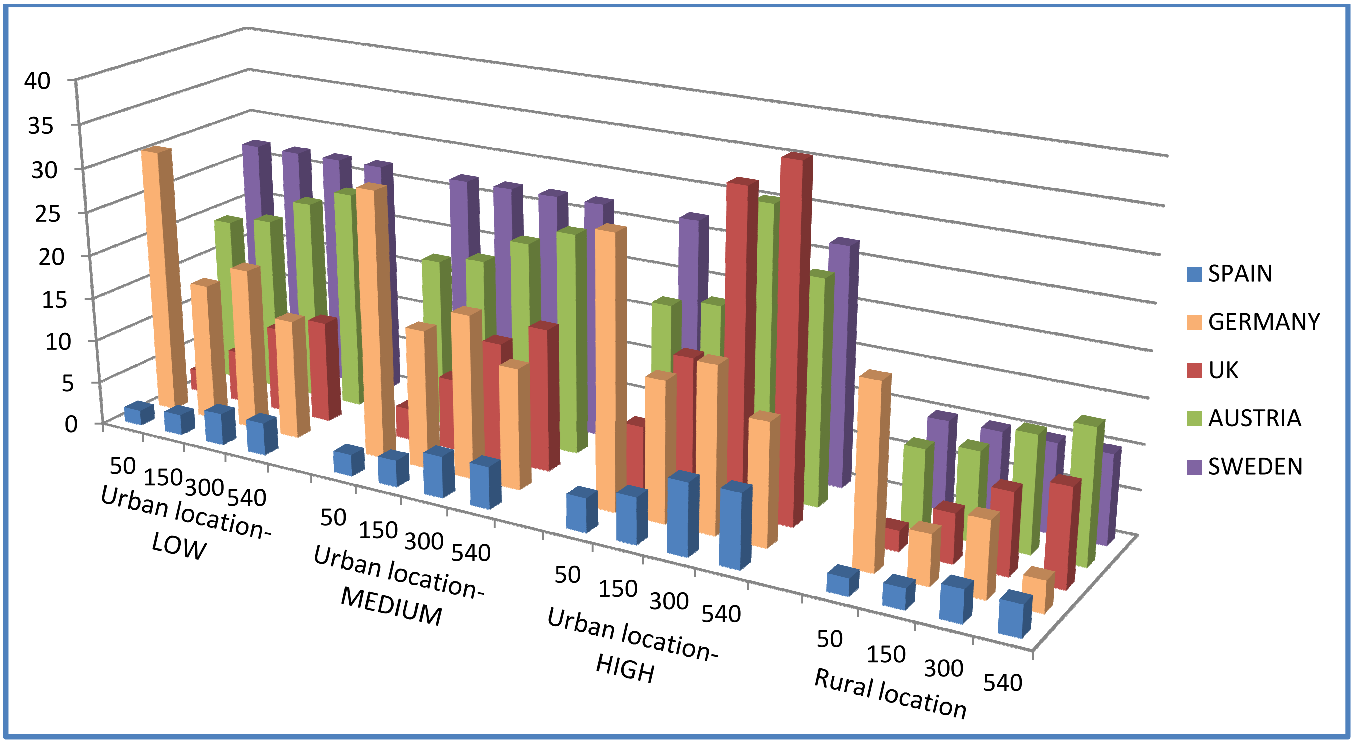

Figure 42: Chimney heights obtained by the different European methodologies.

5. CONCLUSIONS

5.1. Summary

The aim of this project was to understand the differences existing among the European Countries for chimney height determination in small-medium scale biomass boiler installations. First of all, a review and identification of the main regulation related to biomass emissions and chimney height has been carried out. This analysis has clarified a number of issues:

At first, that although the European Committee of Standardisation has published the EN 303-5 Standard directed to heating boilers up to 300 kW, the national regulations in force in the countries reviewed in this thesis are still directed to large scale combustion plants, and there is lack of emission limit specification for small-medium scale installations. In some of this national regulation, there are emission limit values for this plant sizes but not for all the relevant pollutants. There is usually no limit specification for NOx, although this has been the most influencing pollutant for chimney height calculation in the methodologies studied in this project. In most of the national regulation that include limitation for small-medium biomass systems, only PM and in some cases OFC and CO are specified. And in these cases, the values for the different countries vary significantly. Therefore, there is a need of a European agreement in terms of biomass emission limits legislation as it was intended with the EN 303-5 Standard.

From this regulation review it can be noticed that Germany, with its last Ordinance for small combustion plants, offers the most strict limit values for PM and CO.

Secondly, a number of case studies were created in order to perform a series of calculations following the different European methodologies to identify the most influencing parameters in chimney height determination in each country and the main differences among the procedures. Some conclusion can be taken from the results obtained from these calculations:

First of all, that most of the procedures are primarily directed to large scale plants, similarly to what was concluded from the emission limits legislation review. For example, the Austrian methodology could not be applied for the smaller cases and a reference value for chimney height had to be selected to be able to apply the procedure to include building influence. The same occurred with the process developed in the German TA Luft, which justifies that for the analysis of this country, a software developed by P&K, based on the TA Luft equations, was used. However, the results obtained from this software show a rare pattern compared to the rest of the results, giving higher chimney height for the smaller boilers. This is explained in more detail in the corresponding section but as a summary, this pattern can be the result of that this software is mainly directed to larger boilers and therefore cannot be applied for small applications.

Similarly, the Swedish regulation includes a more extended calculation procedure for larger systems, but it is very simple for small-scale boilers, hence it gives the same chimney height for all the studied boiler sizes.

The UK D1 calculation has an important constraint for its use, as it is only applicable when the flue gas has a velocity higher than 10 m/s. This condition can be achieved by reducing the chimney section but it is not usual for small systems that the gas speed is that high.

From the calculations performed, the lowest values for chimney heights were obtained with the Spanish methodology, giving a height range of 1.7-8.3 m, mainly because this method does not include surrounding building influence. The UK model gives the biggest range of heights with the lowest value being 2.3 m and the greatest 39 m. Form the German method big differences in the results among the case studies are also obtained, with values of chimney height from 3.5 to 30.5 m. The chimney heights calculated by the Austrian methodology vary from 9 to 32.2 m. Finally, the Swedish model only gives two different values: 10 m for the rural location and 27 m for the urban location, with no differences in the results among boiler sizes or background concentrations.

From the sensitivity analysis performed, it can be concluded that in all of the studied methodologies (except for the Swedish model), the chimney height depends on the pollutant emissions and the allowed increase of pollutant concentration, which relies on the background concentration and the emission limits. Therefore, the emissions regulation in force in each country can make a big difference in the final result. For the calculations, the limits established in the EN 303-5 were used; hence the limits were the same for every method. However, if national regulations were used, knowing that the differences in emissions regulation among the studied countries are significant, the results would differ considerably.

Another highly influencing parameter in the calculation procedure is the height, and in some cases the distance to the boiler, of the surrounding buildings, except for the Spanish methodology which does not include surrounding buildings' influence.

The flow rate also influences the results in most of the methodologies, especially in the German, which gives bigger values of chimney height for the smaller boilers because the flow rate, and therefore the plume rise, is lower.

As a main conclusion, there is a need to develop new methodologies for their use in chimney height calculation for small-medium scale applications. There is a wide number of complex software that model air dispersion and therefore, they are able to give an optimum understanding of each plant conditions, and a very reliable value for chimney height. However, this software needs to be purchased and they usually need of good program knowledge, hence they are usually directed to big companies that can acquire the program or the help of a consultancy group.

For small applications, which in many cases refers to domestic use, this software are practically unreachable, hence a development of a simpler methodology that can be used by small-medium scale applicants could be of great help.

5.2. Recommendations

The main recommendations extracted from this project are:

A European agreement of the biomass combustion requirements, especially in terms of emission limits. The development of a European legislation including emission threshold values for all the pollutants involved for different boiler sizes and a standardised compilation of the most efficient abatement technologies for the reduction of these pollutants could be of great help.

The development of a common simple methodology for chimney height calculation, primarily directed to small-medium scale biomass boilers that could be utilised by independent users.

One of the main issues of this project was having access to all the information, due to the great language differences among the European countries. Therefore, a full translation of the most relevant documents is suggested, for the rest of the countries to be able to access other countries' knowledge, as atmospheric and health impact is a common concern and it should be an obligation of all to work together to respond to it.

5.3. Further Study

During the completion of this project, some areas that could be object of further work were identified. First of all, an analysis of the existing air modelling software in each country could be of help to understand better the differences in chimney height calculation among the European countries. However, this needs of a great time of work to be able to know the different programs, and also access to the programs, which in all cases have to be purchased, is needed. However, performing a similar study than the one carried out in this project with these models will give a solid understanding of the European practice in chimney heights determination, especially if studying bigger boiler sizes when these modelling programs are widely used.

It would be also interesting to study other boiler sizes and fuels, which would lead to different emission rates and pollutants, in order to have a good understanding of all the biomass combustion technologies.

Also, a comparison of the methodologies analysed in this project with the modelling software could be useful for the implementation of these simple methods and could be of help in the development of a common simple model directed to small-medium scale biomass systems.

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APPENDIX

Table A1: Concerning pollutants from wood combustion set by the US EPA. *SOURCE: [Ref.6]*

Substance	Surrogate Controls*
Acetaldehyde	C
Alpha-pinene	C
Beta-pinene	C
Carbon monoxide (CO)	C
Formaldehyde	C
Methanol	C
Naphthalene	C
Toluene	C
Total phenols	C
Turpentine	C
PAHs	C/P
2,3,7,8 Tetrachlorodibenzo-p-dioxin (TCDD)	C/P
2,3,7,8-Tetrachlorodibenzo-p-furan	C/P
Hydrogen sulphide	C/S
Nitrogen oxides (NO_x)	N
Beryllium	P
Cadmium and compounds	P
Chromium (II) compounds, as Cr	P
Chromium (III) compounds, Cr	P
Chromium (metal)	P
Chromium (total)	P
Chromium, hexavalent metal and compounds	P
Cobalt as Co metal Dust and fume	P
Cobalt carbonyl as Co	P
Copper, Dusts and mists, as Cu^3	P
Copper, Fume	P
Iron	P
Lead arsenate, as Pb_3 (A_2O_4)	P
Lead chromate, as Cr	P
Lead compounds	P
Magnesium	P
Manganese	P
Molybdenum	P
Nickel and compounds	P
Particulate matter (PM)	P
Phosphorus	P
Selenium	P
Silver	P
Thallium	P
Zinc	P
Arsenic and inorganic arsenic compounds	P/S
Mercury	P/S
Hydrochloric acid	S
Sulphuric acid	S
Sulphur dioxide (SO_2)	S

***Surrogate Controls Index**

C - Carbon monoxide (good combustion practices & control)
P - Particulate matter (cyclones, filters, ESP, …)
S - Sulphur dioxide (acid gases - scrubbers)
N - Nitrogen oxides (nitrogen in fuel and combustion modifications)

Ref. #32: Washington State

Table A2: Multiplying factors to convert 1-hour concentration values to other averaging periods. *SOURCE: US EPA*

Averaging Period	EPA Multiplying Factor for POINT Sources[a]
3 hours	0.9
8 hours	0.7
24 hours	0.4
annual	0.08
[a] "Screening Procedures for Estimating the Air Quality Impact of Stationary Sources, Revised," EPA-454/R-92-019, page 4-16).	

Table A3: Summary of the Federal and Northeast State regulations for biomass boilers in the US. *SOURCE: [Ref.26]*

Device Type	Federal	Northeast States
Fireplace	• Exempt from residential wood heater NSPS • EPA voluntary program under development	• No applicable state regulations
Indoor woodstove	• Subject to residential wood heater NSPS • Standard set in 1988 (CAA requires review of standard every 5 years) • EPA working on review	• No applicable state regulations
Pellet stoves	• Loophole in residential wood heater NSPS exempts most units	• No applicable state regulations
Coal and other residential solid fuel stoves	• No applicable federal regulations	• No applicable state regulations
Indoor wood furnace/boiler	• No applicable federal regulations • May participate in EPA OWHH voluntary program	• No applicable state regulations
Outdoor wood boiler/furnace	• EPA voluntary program	• State emission standards in MA, ME, NH, VT • Pending action in RI, NJ, NY
Other residential solid fuels – coal, grass, corn	• No applicable federal regulations	• No applicable state regulations
Under 10 MMBtu	• No applicable federal NSPS regulations • Area source rule in 2010 will impact all institutional, and industrial boilers for mercury and carbon monoxide emissions	• Limited state regulations, • See Figure 1 for size triggers and emission limits
10-30 MMBtu	• Units burning liquid fuels must comply with federal boiler NSPS • Units burning solid fuels, such as biomass, exempt from federal NSPS	• State regulations vary significantly • See Figure 1 for size triggers and emission limits
>30 MMBtu	• Boiler NSPS • May be subject to industrial boiler MACT	• New Source Review permitting

Table A4: S-values specified by TA-Luft for their use in the chimney calculation procedure.
SOURCE: TA-Luft

Substance	S–Value
Suspended particulate matter	0.08
Lead and its inorganic compounds, indicated as Pb	0.0025
Cadmium and its inorganic compounds, indicated as Cd	0.00013
Mercury and its inorganic compounds, indicated as Hg	0.00013
Chlorine	0.09
Inorganic gaseous chlorine compounds, indicated as hydrogen chlorine	0.1
Fluoride and its inorganic gaseous compounds, indicated as hydrogen fluoride	0.0018
Carbon monoxide	7.5
Sulphur oxides (sulphur dioxide and sulphur trioxide), indicated as sulphur dioxide	0.14
Hydrogen sulphide	0.003
Nitrogen oxides, indicated as nitrogen dioxides	0.1
For substances pursuant to 5.2.2 • Class I • Class II • Class III	 0.005 0.05 0.1
For substances pursuant to 5.2.5 • Total Carbon • Class I • Class II	 0.1 0.05 0.1
For substances pursuant to 5.2.7 • 5.2.7.1.1 Class I • 5.2.7.1.1 Class II • 5.2.7.1.1 Class III	 0.00005 0.0005 0.005

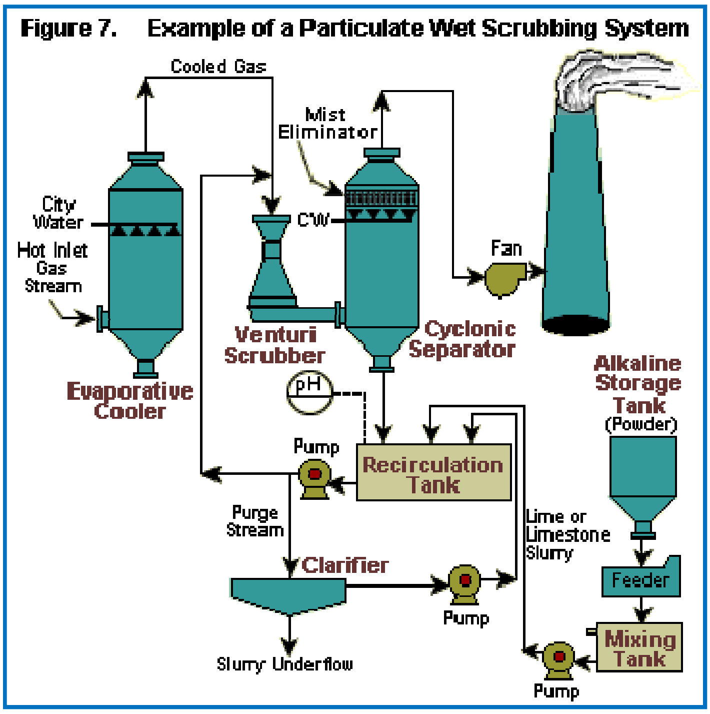

Figure A1: Example of a PM Wet Scrubbing system. *SOURCE: US EPA*