

Nordsyn ecodesign task 2 report

Analysis of technical
measures to reduce
emissions from solid
fuel space heaters



Contents

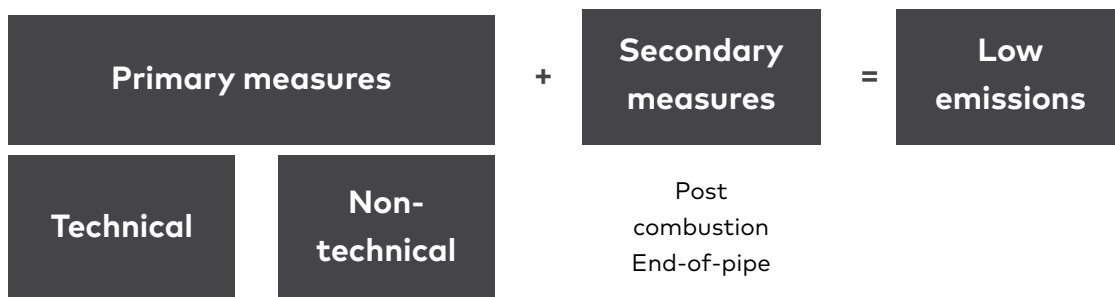
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1. Introduction

According to Cognitive Market Research (CMR, 2025), the small-scale room heater (wood/pellets) market stands strong in the European region, representing a significant share of the global industry. Europe's affinity for traditional, efficient, and environmentally friendly heating solutions has propelled the demand for such appliances. One notable segment within this market comprises high-efficiency wood-burning stoves equipped with advanced features, including automatic combustion control (AAC) and improved safety mechanisms. However, the combustion of biomass in the shape of pellets or logs still produces unwanted by-products that are harmful to the environment and public health. Therefore, designing and operating wood stoves correctly is important to reduce these emissions. Experts opine that both parts are equally important in reducing emissions. To achieve as low emissions as possible, the entire system, including the stove, chimney and additional equipment, should preferably be optimized as one common unit and tested for correct functionality after installation.

For the last two decades, combustion control in wood stoves has advanced significantly, proving the technology's effectiveness. Though it was initially adopted by a few industries, many, mainly the largest companies, have now followed. Due to the development cost, most systems are kept proprietary to each manufacturer, each developing its own system. The main purpose of an automatic combustion control (AAC) system is to adjust the combustion airflows during the different phases of the combustion process. While improving the combustion, additional secondary measures can be added downstream to the combustion chamber to further reduce emissions. Both unburnt gases and particles can be catalytically oxidized, while remaining particles can be removed using electrostatic filters (ESP). There are currently no practical primary or secondary measures to address NO_x emissions from wood stoves.



Several technologies, both primary and secondary measures, can be leveraged to reduce emissions from Solid Fuel Local Space heaters (SFLSH). In this report the focus is on log wood stoves. Primary and secondary measures to reduce harmful emissions and pollutants during combustion from wood stoves involve two distinct approaches. These measures address different stages of the combustion process and encompass a range of strategies to achieve emission reduction. Primary measures (both technical, including ACC, and non-technical) are also referred to as source control measures, while secondary measures are commonly known as post-combustion or end-of-pipe measures. Non-technical primary measures comprise improved user behavior, quick user guides, stricter emission limits, new test standards, user awareness regarding fuel quality being used, maintenance practices, community awareness programs, and so forth.

While primary measures focus on improving wood stove design and combustion efficiency, secondary measures are vital to further reduce harmful emissions. More specifically, primary measures refer to the design and engineering parts of the wood stove that aim to enhance combustion efficiency and prevent the formation of harmful compounds. These measures include improved combustion chambers, increased insulation, and better air control mechanisms for improved mixing of air and combustibles. While primary measures are essential for reducing emissions, they often have limitations in achieving ideal performance under real-world conditions. Secondary measures are additional techniques or technologies that can be employed alongside primary measures to further reduce harmful emissions. These measures primarily focus on post-combustion treatment and emission control; examples include catalytic converters, particulate matter filters, and chimney fans.

However, experts and most scientific literature recommend reducing emissions as much as possible by optimizing the actual combustion process first. Additional devices can still be necessary to convert or remove the problematic compounds after they have been formed, downstream to the combustion chamber. Such secondary emission reduction technologies can be built into the stove (e.g., a catalyst) or retrofitted in the chimney.

Secondary measures are critical in reducing harmful emissions from wood stoves for several reasons:

- **Complementary to primary measures:** Secondary measures work with primary measures to optimize wood stoves' performance. By addressing the limitations of primary measures, secondary measures can ensure a more efficient and cleaner combustion process.
- **Retrofitting existing stoves:** Secondary measures offer the advantage of being applicable to existing wood stoves, allowing homeowners to upgrade their stoves without needing complete replacement, making it a

cost-effective solution in some situations and an esthetic one in other cases (e.g., being able to keep antique stoves if they meet the emission limits after secondary measures have been installed).

- Environmental impact: Wood stoves are a significant source of particulate matter, volatile organic compounds (VOCs), and carbon monoxide emissions. Secondary measures can help reduce remaining harmful pollutants to a certain degree, thus contributing to improved air quality and reduced environmental impact.

Using secondary measures, such as flue gas fans, catalytic converters, particulate matter filters, foamed ceramics, baghouse filters, or scrubbers, emissions of pollutants from wood stoves, such as carbon monoxide, VOCs, and particulate matter, can be significantly reduced. Such measures may provide a more cost-effective solution to homeowners than upgrading an existing stove. Authorities should encourage putting efficient secondary measures into practice to promote cleaner and more sustainable heating practices.

Wood stoves, also known as room heaters or chimney stoves—including cookers, fireplaces/inserts, slow heat release appliances, and tiled stoves—are widely used, popular appliances in Europe for renewable heat supply. The number of firewood room-heating appliances in Europe is currently about 65 million, with annual sales reaching around 2.4 million devices. Assuming an average product price of €2000, the annual sales volume amounts to about €4.8 billion (Reichert and Schmidl, 2023a).

One possible, albeit somewhat extreme, solution to the emissions issues is prohibiting sales and using wood stoves. Some European countries, such as Germany, Switzerland, and Italy, have implemented regional bans on firewood stoves. Paris also attempted to ban open fireplaces without success. However, such bans often face strong opposition from the population. Therefore, finding alternatives that meet the minimal emissions requirements while fulfilling people's basic and emotional needs related to manual firewood combustion would be ideal.

Some local areas in Germany now require the Blauer Engel Ecolabel certification (Blauer Engel, Kaminöfen für Holz, DE-UZ 212), currently one of the strictest certifications worldwide; currently, only five producers have products that are compliant. To achieve the stringent requirements of Blauer Engel, most appliances need to resort to ACC, catalyst, and ESP, making some of them quite expensive.

Since the beginning of 2022, the European Union has enforced general requirements regarding maximum emissions and minimum efficiency performance for stoves. Emission requirements will become even stricter in the coming years. Several manufacturers are exploring measures and technologies to achieve "zero-emissions" or "nearly zero-emissions" soon. Most larger stove producers already

have some form of automation, from simple mechanical ones based on bi-metals, to fully automated solutions that include temperature, oxygen, and door-opening sensors. Some also have automated the ignition process, which can be initiated using a mobile phone.

Improving user behavior is also an important non-technical approach to enhancing the performance of stoves in real-life operation and reducing emissions. Even the most sophisticated ACC-operated stoves can be misused by using the wrong fuel, using fuel with too much moisture, or adding too much firewood.

If the wood stove sector does not significantly lower its appliances emissions within the next few years, a possible consequence might be the ban of wood burning, at least in larger European cities (ABC News, 2023; "Ban on wood stoves? Government has confirmed through its Environment Improvement Plan 2023 that there will not be a ban on wood burning stoves," 2023; Carrington and editor, 2023; Purves, 2023).

Wood could be a winning candidate for space heating if the industry manages to reduce emissions down to accepted levels. In EU, an average household uses more energy on heating than on anything else. In 2023, space and water heating represented 77.6% (60% for space heating alone) of the total final energy consumed by the households (EU, State of the Union, 2025). Assuming the fuel needed to cover this 60% can be supplied sustainably (transport, biodiversity, forest maintenance, etc.), other sources, such as gas and electricity, can be partly phased out or redirected to more profitable uses.

2. Automatic Combustion Control: A Primary Measure

This section first offers some lost history of automated stoves and two-stage combustion for the uninitiated. Even at the turn of the 20th century, people, in general, were concerned about the cost of heating their homes. The most typical stove in those days was the “all-burning” coke stove, which would be filled with coke and then ignited at the top. It would burn all night. Usually, it was the women’s responsibility to keep the stoves in each room burning. Unsurprisingly, Prof. Adolf Watzinger at NTH (Norges Tekniske Høgskole) invented an automated stove in 1927 to ease their work (Digitalarkivet, 1927). People then cared less about emissions and more about the efficiency and ease of operation. The automated stove could burn for more than 24 hours without intervention. Another innovation around the same time was the use of secondary pre-heated combustion air, as in Bjørnovnen from Drammen Ironworks (Lid, 1940), though the stoves were still missing the insulated combustion chamber.

In 2025, Ecodesign suggested that ACC should become mandatory on all new stoves, a suggestion that presumably comes from studying the Blauer Engel (Blauer Engel, 2020) certification. This sent a kind of a shockwave through the stove manufacturing industry.

Automatisk regulering av magasinovner.

En epokegjørende opfindelse.

I vort kolde Norge strækker ikke solvarmen til i stort mere end 4 maaneder. Vi er altsaa henvist til i størstedelen av aaret at stole paa vore ovner, og ethvert forsøk paa at bedre disse og gjøre dem mest mulig fuldkomne, maa hilses med glæde av alle.

Den trækregulator, som nedenfor er beskrevet, vil efter vor mening

spare mindst 20 % i brændsel,

og hvad betyr saa ikke dette nationaløkonomisk? Besparelsen løper op i millioner.

Og vi mener at regulatoren vil **spare 80 % i betjening,**

et resultat som vore husmødre nok vil vite at værdsætte.

Regulatoren har været indgaaende prøvet i det varmetekniske laboratorium ved Den Tekniske Høiskole i Trondhjem. Professor Dr. Watzinger har avgitt en indgaaende rapport om forsøkene, hvorunder saavel koksforbruk som varmeeffekt nøie blev kontrollert.

Professor Dr. Watzinger kom til et i alle dele meget gunstig resultat.

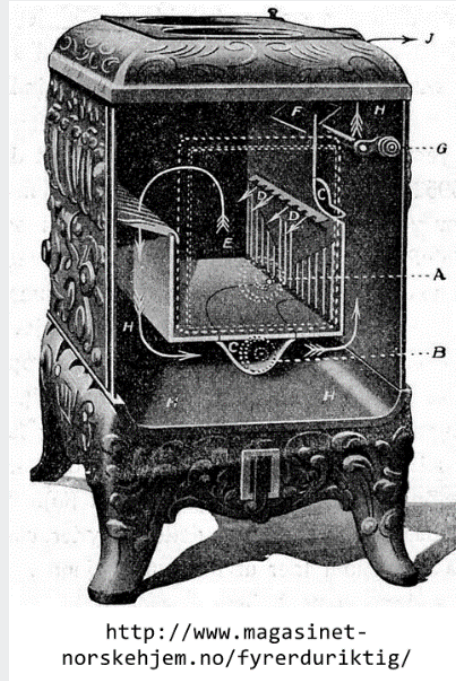
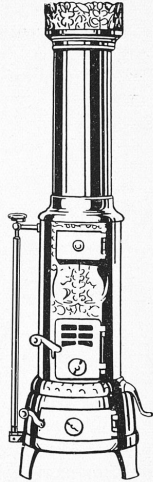


Figure 1: An early automated stove for coke combustion

Figure 2: An early stove with staged combustion

Adolf Wilhelm Josef Watzinger (born 10 June 1879 in Darmstadt in the Grand Duchy of Hesse in the German Empire, died 13 September 1959 in Trondheim, Norway). He was a mechanical engineer, dr.ing. 1909, educated at the college in Darmstadt and at the University of Geneva. He was appointed as a professor of machine learning at the Norwegian Technical University in 1909 as the very first professor at the university.

Description of Technology

In Europe, fully automated stoves have been on the market for some time—for example, RIKA (AU) since 2007 (RIKA Rikatronic, 2025) and HWAM (DK) since 2012 (HWAM, 2025)—and are beginning to gain wider recognition amongst consumers and distributors. The Rikatronic technology (now Rikatronic4 as the latest version) was introduced by RIKA of Austria in 2007; it integrates temperature sensors and electronics to control the air supply and advises when another wood log should be put on the fire through a light visible at the front of the fireplace. This seems to be the most advanced technology for a batch fed or manual wood log burner in terms of automating the reloading and ensuring optimum firebox temperatures for reducing emissions. RIKA controls the primary and secondary air input via flap valves, using the temperature signal from a strategically placed thermocouple to control the amount of air. Recently, RIKA has added the possibility of automated ignition. Ignition through the touch of a button is achieved using a heated resistance and the so-called RIKA eco-lighters. Ignition is performed from below the wood logs. The average electrical power consumption is about 4 Watt in heating operation and approximately 150 Watt during automatic ignition. HWAM, in addition to being a fully automated solution, applies sensors for both temperature and oxygen to control three airflows to distinct parts of the stove. HWAM also has a cheaper mechanical solution based on a bi-metallic coil that acts as a heat-sensitive thermostat. The mechanical solution is delivered as standard, while the fully automated system can be added as an option for an additional cost. Several other manufacturers also apply mechanical combustion control.

At laboratory conditions, ACC shows reduced emissions of particulate matter by 60%–95% and carbon monoxide and organic gaseous carbon by 50%–80% (Mandl, C., 2017; IEA Task 32, 2022, Oregon State University, 2025) by optimizing the combustion air through the different stages of combustion, thus eliminating user-induced errors. The latter being a major reason for high emissions in manually operated stoves. Sensors monitor temperature and flue gas composition. Actuators adjust air supply dynamically during ignition, steady burn, and char burnout phases. Control algorithms optimize combustion conditions in real time, reducing emissions spikes during reload and startup. Primary, secondary, and purge air streams are controlled to match combustion needs. Table 1 lists some differences affecting the efficiency and emissions between manual and automated stoves (SusWoodStoves).

Table 1: The differences between manual BAT and automated stoves, acc. to NS 3058-1/2:1994

Aspect	Manual Combustion, BAT 2024	Automated Combustion Control
Thermal Efficiency	75%–85% (stoves with heat storage cap. have higher eff.)	80%–88%
Particulate Matter (PM)	Very user-dependent, 20–120 mg/m ³	Reduced by 60%–95%
Carbon Monoxide (CO)	Very user dependent, 900–2000 mg/m ³	Reduced by 50%–80%
Organic Gaseous Carbon (OGC)	Very user dependent, 40–400 mg/m ³	Reduced by 12%-55%
Air-Supply Regulation	Manual, often suboptimal	Dynamic, sensor-based, phase-specific
Combustion Phases	Poorly controlled	Optimized for ignition, pyrolysis, burnout
User Influence	High (loading, timing, air settings)	Low (system adapts automatically)
Maintenance of Optimal Burn	Difficult	Consistently maintained
Retrofit Possibility	Not applicable	Some systems can be retrofitted
Environmental Impact	Higher emissions, lower efficiency	Lower emissions, higher efficiency

At SINTEF Energy, we have studied ACC since 2017 (AEOLUS/AEOLUS+), developing such solutions for the Norwegian industry partners through various national projects. During the experiments, either of the two test standards (a method and a procedure)—the European one (NS-EN16510-1:2022, 2022; in progress) or the national test standard (NS 3058-1/2:1994 and NS3059:1994, 1994; discontinued) – were applied. The work involved testing a representative clean-burning cast-iron wood stove operated in either manual (Figure 3 a1, a2) or automatic (Figure 3 b1, b2) air-control mode, both according to the mentioned standards. During the testing, we also adapted both standards towards more real-life operation with natural draft by varying the ignition procedure, wood species (birch, spruce, and pine), amount of fuel, log size, and moisture content.

Applying ACC using an in-house regulation strategy reduced the particulate matter (PM) by 66% when tested according to the Norwegian test method. Using the European test method, automation increased the efficiency by 8% and decreased PM, CO, and organic gaseous compounds (OGC) by 12%, 34%, and 55%, respectively. At low burn rates with birch, automation reduced PM by 4% and CO by 61% for a 1.2 kg fuel load, compared to nominal and high fuel loads with birch. For a 1.8 kg fuel load, automation resulted in even higher reductions in PM, CO, and OGC of 68%, 52%, and 82%, respectively. Automation also substantially decreased CO (70%) emissions when burning briquette presses. End-user operation—such as ignition from a cold stove and the use of fuels with varying properties, as in PMB—caused significant variation in emissions during the ignition period.

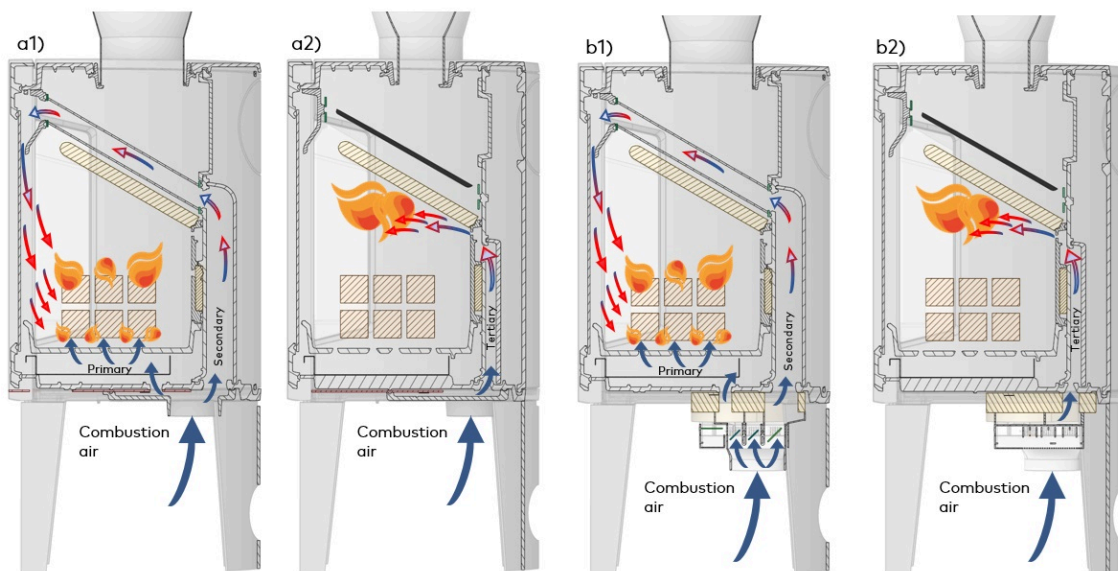


Figure 3: Typical cast-iron clean-burning wood stove used in Scandinavia, manual and automated versions: a1) manual valves, primary and secondary air channels; a2) tertiary air channels; b1) automatic valves, primary and secondary air channels; b2) tertiary air channels.

Consistently good ignition, according to the Norwegian standard, can be achieved by ensuring that the fuel catches fire before the door is closed and/or by reducing the primary/secondary air flows. Compared to correct ignition, bad ignition due to over- or under-firing and dense stacking can produce at least twice as much PM and CO and 3–4 times the OGC. No significant differences in emissions were found when comparing birch, spruce, and pine for wood with equal moisture content. However, burning pine produced higher emissions of total carbon particles—both elemental and organic—at comparable levels to poor ignition.

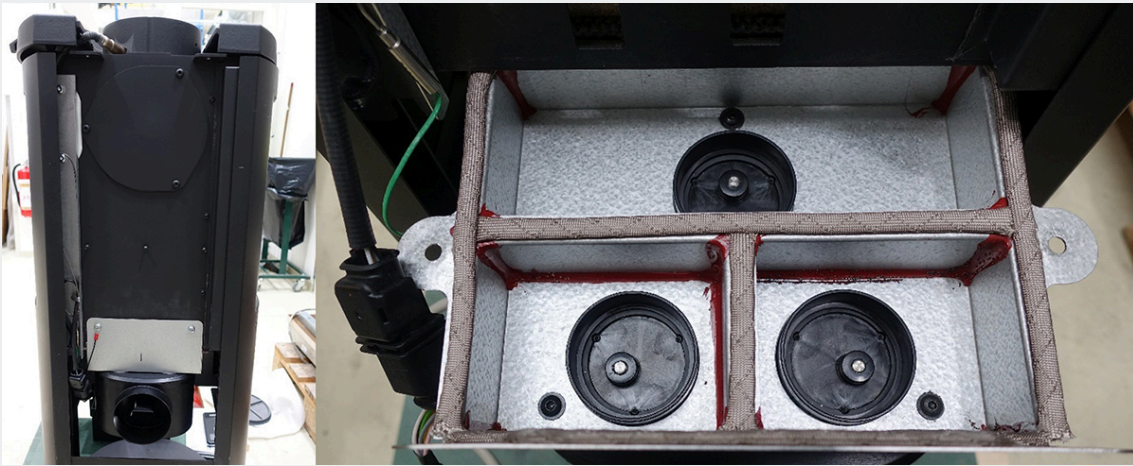


Figure 4: ACC integration by HWAM, three-way air distribution

ACC systems commonly use electronic valve regulation of two or three combustion air inlets and at least one temperature sensor at the stove flue gas outlet for feedback. An example is the HWAM SmartControl. The device shows how the company integrated the air distribution box with the electronics (behind a side-panel; see Figure 4), easily adaptable to most of the company's models. The lambda sonde and the thermocouple are placed at the top at the stove outlet.

ACC systems are specific for each manufacturer with specific integration and specific in-house control strategies, additional temperature sensors, and an additional lambda sensor (O_2 concentration). Lambda sensors are expensive and require constant heating (using much more energy than the remaining components, 10–15 W). Control strategies can vary widely, from sophisticated algorithms that analyze past performance to predict optimal actions, to simpler approaches aimed at achieving desired results in real time. Other strategies are quite simple and may, for example, use just a tuned PID regulation strategy.

ACC is normally designed with multiple heat output settings, normally from low to high, and sometimes controlled by signals from a room thermostat. These conditions should preferably be tested as part of the type testing process to ensure proper operation during actual use. The European Standard EN 16510 allows manufacturers to determine the amount of wood used during testing, which is significantly lower compared to other standards, such as the Norwegian NS 3058 or those used in the US, Canada, Australia, and New Zealand.

Table 4 provides a list of the European manufacturers who can provide ACC solutions, most of which are tightly integrated internally into the stove design. Only a few stove-independent systems have been proposed so far, for example, the one proposed by Timpex (Timpex, 2025). This system is easily adaptable (Figure 5),

though it can regulate only the total amount of combustion air. Emission reductions and efficiency increase have not been specified, though the manufacturer claims a 30% reduction in wood consumption.



Figure 5: Easily adaptable solution from Timpex (CZ)

Financial Considerations

Stoves equipped with ACC cost more upfront than manual models do because they integrate electronic sensors and computer controls for more efficient, precise combustion, but they offer better fuel efficiency and environmental performance, which can lead to lower operating costs over time. Costs vary by manufacturer, but manual stoves have lower initial expenses for simpler design and operation. Manufacturers should be cautious not to overprice their new ACC stove systems to avoid too large a gap between these products and, for example, heat pump solutions. As exchanging old stoves for new ones is the most efficient way to reduce emissions from wood burning, new stoves with ACC must not become too expensive compared to the manual ones to avoid excluding most common people. Otherwise, most consumers might opt for a new manual one or a heat pump.

The cost of ACC solutions varies widely, but a complete system typically ranges €3000^{[1][1]}-€15000^{[2][2]}.

HWAM supplies most of its standard stoves with mechanical regulation using a bi-metal mechanism called Autopilot. The manufacturer offers the option to retrofit with an electronic ACC system called SmartControl. The cost of retrofitting is around €1500.

1. <https://www.pejseringen.dk/hwam-3120c-smartcontrol>
2. <https://www.schiedel.com/downloads/de-DE/Preislisten/preisliste-schiedel-keramik-schornstein-und-ofensysteme-2025.pdf>

3. Electrostatic Precipitator & Catalyst: Secondary Measures

Wood stoves have long been cherished for their ability to provide warmth, comfort, and a cozy atmosphere. However, their contribution to harmful gaseous and particulate emissions has raised concerns about their impact on environment and public health. Implementing secondary measures has emerged as an important strategy in response to these challenges to mitigate emissions from wood stoves. Secondary measures encompass the incorporation of devices designed to capture and reduce emissions after their generation during combustion. Examples include particle filters, electrostatic precipitators, catalysts, scrubbers and so forth. These devices are installed within the stove's exhaust system to trap pollutants before they are released into the atmosphere. The most relevant performance indicator is the pollutant removal efficiency, which can easily be found by measuring pollutant concentrations before and after the device is put in place.

The two main and most mature secondary measures for mitigating wood smoke are electrostatic precipitators and catalytic converters, as described in the following two chapters. German and Swiss producers dominate the production of such devices, as these countries were the most active early adopters of this technology. Other, less established technologies, such as packing technology, electric soot collectors, flue gas scrubber, and additives, are currently being tested.

3.1. Electrostatic Precipitator

Description Of Technology

An electrostatic precipitator (ESP) can be a secondary end-of-pipe measure to reduce emissions from solid fuel combustion, such as wood in wood pellet stoves. Solid particles, that is, ash, soot, and fine organic and mineral particles, can be separated from flue gases with an ESP by charging them electrostatically before the smoke leaves the flue gas pipe.

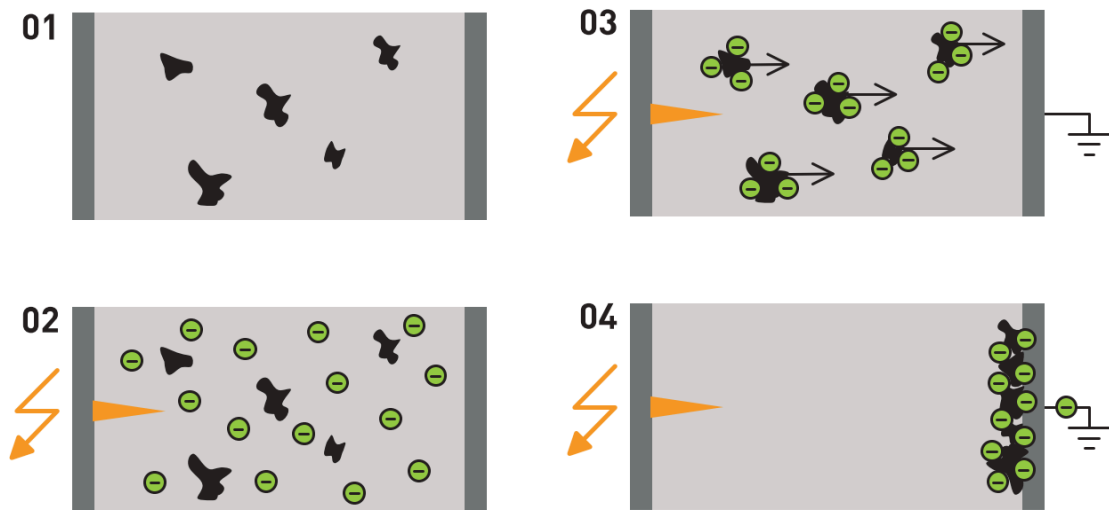


Figure 6: (left) Typical principle of particle separation in wood stove ESPs; example from (OekoSolve, 2023)

An electrode is placed in the flue gas pipe as a metal wire mesh or a rod. A DC voltage of several tens of kilovolts is applied to it with a high voltage generator, releasing free electrons, of which some charge the passing-through particles. The strong electrical field around the electrode pushes the charged particles and remaining free electrons towards the surrounding positively charged metal pipe or wall of the flue gas pipe. Figure 6 illustrates the physical principle of an ESP.

Besides the wet flue gas volume flow and the collecting electrode's effective surface, the particle migration velocity is also essential. The migration velocity depends on the electrical conductivity of particles, flue gas temperature, flue gas composition, particle size, and the effective electric field intensity (Nussbaumer et al., 2009). The ESP design for wood stove applications typically aims at flue gas velocities between 1.0 and 1.8 m/s between the electrodes (Strauss, 2016); this is about 10 times higher than in larger industrial ESPs. For particles smaller than 100 μm , high separation efficiencies are achievable, as illustrated in Figure 6 (right). However, particle sizes between 0.2 μm and 0.5 μm show minimum separation efficiency because the dominating separation mechanism transitions from impact ionization (dominant for particle sizes $> 1 \mu\text{m}$) to Brownian diffusion of ions (dominant for particle sizes $< 0.1 \mu\text{m}$; Nussbaumer et al., 2009). ESPs today are state-of-the-art for large industrial applications. Application of such devices in small-scale appliances, especially stoves, is increasing since emission limit values have become more stringent in recent years. Compared to fabric baghouse filters, an important advantage is the low pressure drops of ESPs that allow unproblematic operations under natural draught conditions. However, temperatures are also important and should generally range between 120°C and 180°C to avoid flue gas condensation. Combustion quality is essential since the separation efficiency of ESPs differs between mineral particles, tar, and soot. Soot and tar can cause

problems, either by sticking on the electrodes (tar) or by re-entrainment of particles into the flue gas flow (Lauber and Nussbaumer, 2010). The application of ESPs in manually operated room-heating appliances faces several challenges: minimising noise from sparking; avoiding contamination such as chimney agglomerations or release of flakes (~5 mm); deciding whether to place ESPs in the chimney system or integrate them in the room-heating appliance; addressing high voltage in a living space; ensuring electrode placement in integrated systems allows for good accessibility and suitable temperature levels during operation; and combining ESPs with secondary technologies such as catalysts for PM emission reduction, focusing on gaseous emission reduction.

ESPs as a retrofit solution have two variants: placed (a) at the mouth of the chimney or (b) directly in the flue gas pipe right after the appliance, as illustrated in Figure 7. The issue of installing an ESP in the flue gas duct can be solved in different ways: either by making an opening in the chimney where the ESP is then placed and fastened with a sealing ring and tension strap or with a T-piece in which the ESP is integrated. Some producers can provide such ESPs (e.g., OekoTube Inside model [OekoSolve, 2023], Kutzner + Weber Airjekt model [Kutzner und Weber, 2023], as shown in Figure 8b).

Cleaning of ESP systems is either automatic, semi-automatic, or manual. In most cases, the cleaning relies on sweeping the chimney at regular intervals and then cleaning the electrode at the same time. Semi-automatic cleaning is mechanical—physically removing the collected particles from the electrodes and then removing them from the device. Fine particles can be removed in several ways: with a built-in brush, a magnetic vibrator attached to springs on the inner wall, or water injected through a nozzle system. The fine particles or slurry in the case of water injection are then collected in a pan, which the user must empty manually. It is uncertain whether the residues should be disposed of as waste or not, mainly due to PAH up-concentration when flue gas and particles pass through the ESP reactor (see page 21). Sometimes, the automatic cleaning must be started manually (Oberberger and Mandl, 2011). Fully automatic cleaning means that no manual operation is necessary to keep the device operating as intended for periods of months or years.

The OekoTube (OekoSolve, 2023) system was developed in Switzerland in 2006 and has constantly improved over the years. The OekoTube-Outside (see Figure 8a) is designed and suitable for all wood stoves with a capacity below 50 kW. It is either mounted on top of the chimney or inserted next to the wood stove with the ESP OekoTube Inside solution. It is suitable for most small-scale room heaters, such as open fireplaces, free-standing wood stoves, coal stoves, and central heating systems fueled with wood logs, shavings, or wood chips. It has been proven and officially tested to have a 70%–95% particle removal efficiency and can be fitted on any chimney. The device is manually cleaned through chimney sweeping. The maximum power consumption is 30 W, with a standby power of less than 1 W, at 230V AC. It can support flue gas temperatures up to 400°C.

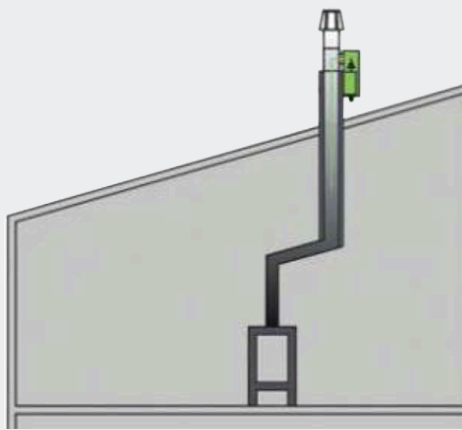


Figure 7a: ESP fitted at the mouth of the chimney

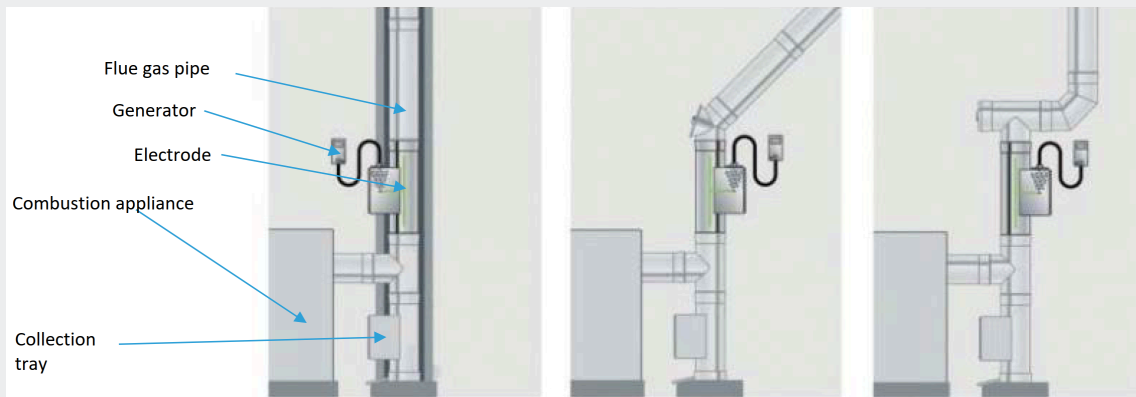


Figure 7b: ESP fitted in the flue gas pipe (three variants)

A Danish producer, Exodraft (Exodraft a/s, 2023), uses electricity to burn off the particles (the nature of emissions being undocumented) collected on a wire mesh at given intervals. In addition, the producer has included a chimney fan at the device outlet to ensure enough draft, enhance all combustion phases, and reduce indoor smoke. This is the only appliance on the market with this self-cleaning solution combined with a chimney fan. Intentionally, the device was supposed to treat diluted flue gas. However, this function has not yet been incorporated. Figure 8c shows the device.

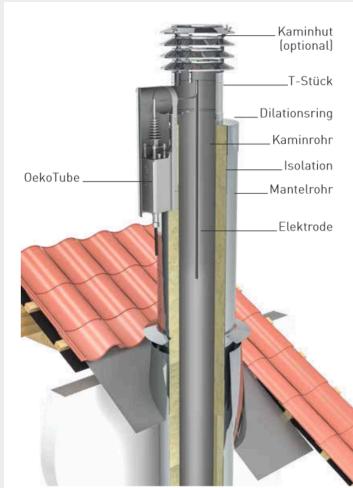


Figure 8a: OekoTube by OekoSolve

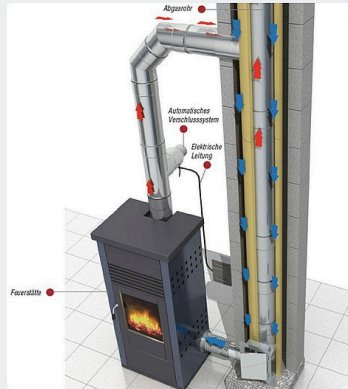


Figure 8b: Kutzner und Weber Airjekt 1 model



Figure 8c: the Exodraft solution

Cheminées Poujoulat (Cheminées Poujoulat, 2023), one of the largest chimney producers in Europe, offers a particle filtration solution based on the OekoTube product, both as a retrofit and as new installations. Figure 9 shows three variations of this solution.

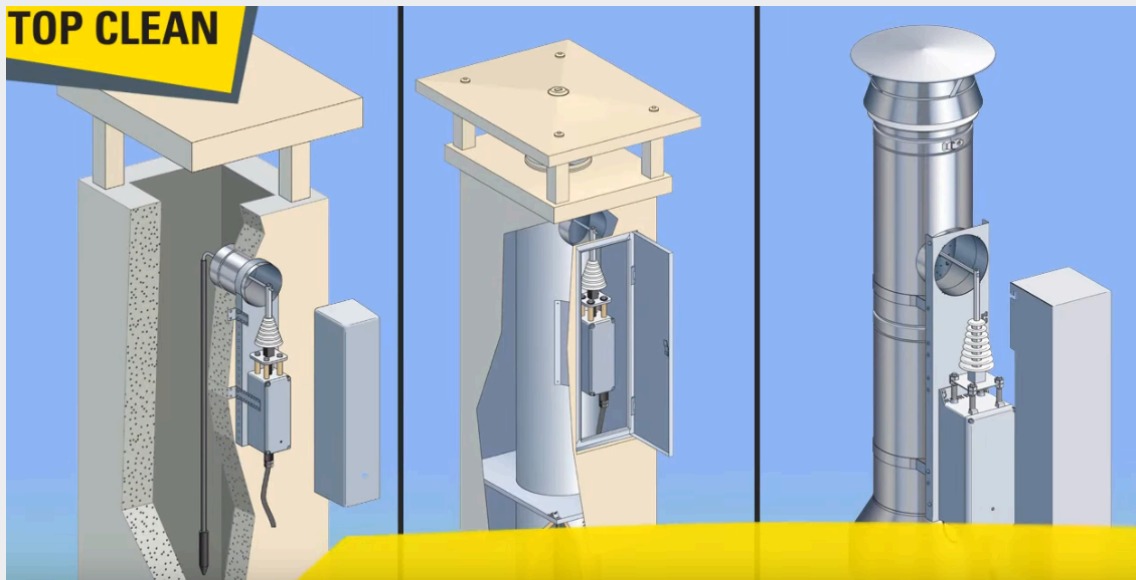


Figure 9: Three variations of the Poujoulat ESP solution

In case of manually cleaned ESP systems, the particles collected on the positive electrode surface must be removed regularly by chimney sweeps. Many modern ESP devices continuously measure the distance between the electrode and chimney wall and pass signals when maintenance is required. The cleaning frequency and maintenance strongly depend on the type of stove, the ash residues from the fuel, the firing behavior, and the firing frequency. This frequency is estimated to be once or twice a year (Oberberger and Mandl, 2011).

ESPs can be applied on all types of domestic wood appliances: fireplaces, stoves, and boilers. However, installing an ESP in flue gases with a lot of lipids is not recommended due to the increased risk of a chimney fire, such as in flue gases from ovens used in restaurants. When the ESP is installed, the transformer creating the high voltage is adjusted according to the features of the appliance and the chimney. If the appliance is replaced later, for instance, by a newer appliance, the transformer has to be adjusted accordingly, and the ESP can continue to operate as before.

For ESPs installed as a retrofit at the chimney outlet, the chimney diameter must have certain dimensions, which will depend on the manufacturer and the desired model. If the diameter is too wide, the removal efficiency will be low. The top of the chimney can be made smaller or narrower if necessary. In addition, ensuring the proper functioning of the ESP has some technical constraints:

- To avoid damage to the ESP, the entering flue gas temperature should not exceed 250°C–400°C, with slight variations between different products.
- The flue gas pipe must include a straight vertical duct of 38–160 cm, depending on the ESP type. This is the length of the ribbon that acts as an electrode and the surface needed to charge all types of fine particles. The longer the remaining pipe after the ESP, the finer the particles deposited on the chimney walls. In addition, collecting fine particles at the bottom of the chimney should also be possible.
- For pellet stoves and pellet boilers, a straight vertical piece of 50 cm chimney is enough because the wood input is controlled and the surface needed to electrostatically charge the particles is smaller.
- Chimneys protruding over 1.5 m above the flat or sloping roofs complicate the installation and maintenance of the system due to the poor accessibility for the installer and the chimney sweep. This concerns most chimneys, and in these cases, the installation will require the use of an aerial work platform. Chimney cleaning can also be done from below.

For ESPs installed in the chimney shortly after the appliance,

- the chimneys must be made of a positively charged material to attract the negatively charged particles. Metal chimneys are suitable for this, but ceramic flue gas channels and masonry chimneys may also work provided they are earthed;
- it must be possible to install the ESP in an easily accessible and visible part of the flue gas chimney, meaning that this configuration can be used only for boilers and stoves where the flue gas chimney is accessible. For difficult to reach flue gas ducts, such as in built-in stoves, using an inspection hatch may be necessary. In addition, there must be a straight vertical duct of at least 50 cm for pellet stoves and pellet boilers; and
- the ESP in the flue gas pipe is only partly suitable for old solid-fuel boilers and stoves due to the possible condensation of tar on the electrode (Obernberger and Mandl, 2011).

The environmental benefit of an ESP is that the particles that can be electrically charged, such as soot and organic and mineral fine particles, can be removed, but it does not affect the flue gases. The reported removal efficiencies vary widely, ranging from 11% to over 90%. This wide range is partly due to dust agglomeration on the walls—later coming loose and being re-emitted—and partly due to the fact that combustion conditions, appliance brands, and duration of the tests often differ. The TU Graz survey (Obernberger and Mandl, 2011) on ESPs for residential biomass combustion in IEA Bioenergy Task 32 member countries reviewed several sources to assess removal efficiencies of ESP devices and provide valuable independent insights on the state-of-the-art of these devices. Table 2 summarises the removal efficiencies of different ESP devices according to various sources, including Greet et al. (2020).

Table 2: Overview of fine particle removal efficiencies of different ESPs

Name of ESP	Installation	Combustion appliance	Average removal efficiency for fine particles	Type and duration of test	Cleaning method	Source information
Residential ESP	Chimney	Old-wood stove Old-wood stove Multi-stoker boiler Modern stove Old stove	54%–61% 85%–99% 80% 69% 55%	Field, 61 days Lab, 250 minutes Lab, duration unknown Field, 4,300 hours Field, 4,300 hours	Manual	TU Graz
Carola-KIT	Flue gas pipe	Modern stove Wood pellet boiler	87% 82%	Lab, duration unknown	Semi-automatic	TU Graz
Zumikron	Flue gas pipe	Wood boiler Modern/old stove	41% 17% 11%	Field, 545 hours	Manual	TU Graz
OekoTube	Chimney	Modern pellet boiler	97%	Lab, 5 hours	Manual	TU Graz
Bosch	Flue gas pipe	Modern pellet boiler	70%	Lab, 860 hours	Semi-automatic	TU Graz
RuFF-Kat	Chimney	Modern wood boiler	>70%	Lab, duration unknown	Semi-automatic	TU Graz
AL-Top Schröder	Flue gas pipe	Modern wood boiler	48%–82%	Lab, duration unknown	Semi-automatic	TU Graz
SF20 – Spanner	Flue gas pipe	Modern/old wood boiler	60% 25% and 80%	Field, 410 hours Field, 2,900 hours	Semi-automatic	TU Graz
Airbox	Above combustion chamber	Wood stove	60%–80%	Lab, duration unknown	Manual	TU Graz
Kamin-Feinstaubkiller	Chimney	Old wood boiler	64%	Lab, 30 hours	Semi-automatic	TU Graz
OekoTube	Flue gas pipe	Modern stove	34%–55%	Lab, duration unknown	Manual	Divi-Divi-VITO
Residential	Chimney	Old stove Modern stove	55% 69%	Field, duration unknown	Manual	(Hartmann et al., 2010)
SF20 Spanner	Flue gas pipe	Pellet boiler	80%	Field, duration unknown	Semi-automatic	(Hartmann et al., 2010)
Exodraft	Chimney	Modern/old stove	70% of total PM mass, 95% reduction in PM number	Lab, several years	Automatic	Exodraft/DTI (Exodraft a/s, 2023)
Airjekt 1 NW 130-250 mm	Flue gas pipe	Modern/old stove	Separation rate possible up to 95%, Filtration efficiency >50 %	Lab, several years	Manual	(Kutzner und Weber, 2023)

From Table 2, the minimum removal efficiency is 11%, and the maximum efficiency is close to 100%, with an average efficiency of approximately 66%, indicating the current immaturity of some solutions. Some of the tested products are prone to be affected by the type of stove, local variations in chimney properties, and fuel quality. During laboratory testing, emissions are usually measured only at the hot burn-out phase (not during ignition or carbon burn-out phases) when the ESP is functional. Moreover, the method for measuring particles may differ. Whether emissions from lab test conform with real-life emissions remains unclear. The actual removal efficiencies in people's homes over a full season are unlikely to be comparable to field test results.

The tested ESPs also seem to achieve lower removal efficiency for older combustion appliances, most probably due to the high concentrations of fine dust in the flue gas entering the device. In old domestic combustion appliances with high PM and unburnt hydrocarbon loads, considerable dirt is collected on the electrodes (as shown in Figure 10) and the electric insulation, which can lead to malfunctions and short circuits if the electrode is not cleaned regularly. Some ESPs installed with older stoves with poor combustion require a by-pass during the combustion start-up phase to avoid soot deposits that may cause short circuits (Oberberger and Mandl, 2011).

The TU Graz survey revealed that laboratory tests often achieved a higher removal efficiency than field tests because, often, ESP malfunctions occur that cannot be resolved quickly, thus reducing the average efficiency.



Figure 10: Electrode clamp of the Zumikron ESP, demounted for cleaning

The malfunctions reported by Hartmann et al. (2010) include the following:

- loss of the airflow around the electrode;
- fuse tripping due to malfunctions and short circuits (especially when the PM load is significant and tars sticks to the electrodes);
- electrode breakage, often caused by improper cleaning of the electrode (e.g., when scratches are made with a steel brush);
- voltage loss at the electrodes;
- chimney draught problems (particularly relevant in problematic situations where there is already a challenge with the chimney draught); and
- infiltration of rainwater.

Soot and ash deposition on a high-voltage electrode may cause spark discharge, which can lead to noise pollution. According to TU Graz and Hartmann, complaints of noise pollution were received during all field tests, both from the users themselves due to the built-in fan and from neighbours due to the spark discharge. According to the manufacturers, spark discharge can be avoided with correct installation and adequate maintenance.

There are no indications that an ESP increases the risk of a chimney fire when used for domestic wood-heating applications. However, it is different in case of flue gases containing a considerable amount of lipids (e.g., restaurant cooking) or with high flue gas temperatures (e.g., pizza ovens).

It is still uncertain whether dust collected in an ESP must be treated as special waste or if it can be disposed of in normal household trash bins. Recent research shows that significant amounts of gaseous PAH is deposited on the particles collected by the ESP (Greet et al., 2020; Wohter et al., 2022). The quantity and composition of the dust depend on the quantity and quality of the dust released during combustion and are also linked to the appliance used and the combustion conditions. Contaminants present in the flue gases (e.g., PAHs) will also be found in the separated dust particles.

In a survey of ESPs available on the Danish market conducted in 2011 by Miljøstyrelsen (Schleicher and Fuglsang, 2011), three different ESPs were tested. The overall evaluation was that none of the technologies had any significant reducing effect on ultrafine particle emission (particles smaller than 0.1µm in diameter) in terms of number. The main difference was in the way these ESPs were tested, compared to the samples in other European studies. In the Danish survey, the dilution tunnel method (Norwegian test standard) was used, as opposed to the hot-filter method (EU test standard). If the flue gas is not diluted before the ESP, the condensables pass as gases and cannot be captured. Experts agree that cooled diluted flue gas from wood stoves contains 2–5 times more PM than hot undiluted flue gas.

The same survey (Schleicher and Fuglsang, 2011) strongly indicated that the ESP technology increases the number of ultrafine particles emitted. The reported reason was that when large particles are removed and the flue gas subsequently cools down after escaping the chimney, the condensables condense in the form of many ultrafine particles instead of condensing on the larger particles and increasing their size.

In 2015–2016, a two-year field-testing campaign (Brunner et al., 2018) evaluated both the inside and the outside versions of the OekoTube ESP. Plant-monitoring data revealed high ESP availabilities (up-time): 81.7% and 80.2% for the chimney-top version and 97.7% for the inside model. The availability of the OekoTube inside was evaluated to be 81.2%. These availabilities were all above the target value of 80%, which has been defined by the manufacturer OekoSolve for this product.

In a more recent study, Vicente et al. (2022), tested the same OekoTube ESP on a traditional wood stove and a modern pellet stove. Only a 29% reduction in particle mass was obtained (measuring total suspended particles in diluted flue gas). The effect of the ESP was, therefore, insufficient for the appliance, an older stove type, to meet the new ecodesign limits. Given these results, the authors recommended that, instead of installing flue gas depollution technologies, traditional older combustion appliances should be replaced by modern appliances. They also mentioned additional challenges regarding cleaning and maintenance of the ESP. The authors recommended that future work should consider the effect of ESPs on the chemical and toxicological properties of the captured particles.

In a review of ESPs for small-scale (<50 kW) domestic boilers, and pellet and wood stoves, Jaworek et al. (2021) concluded that the collection efficiencies for the state-of-the-art lab-constructed and market-available ESPs were too low to comply with the new ecodesign regulations (Ecodesign 1189, 2015) and that further development must be carried out to increase the collection efficiency for $PM_{2.5}$ particles to above 95%. The authors stated that in spite of the many efforts in constructing low-cost and highly efficient ESPs for residential boilers during the last two decades, this technology is still at an emerging level. The available literature (75 peer-reviewed articles from the Scopus database, [Scopus, 2023]) shows that the mass collection efficiency of ESPs for $PM_{2.5}$ particles, operating under real conditions, not in the laboratory, is usually at a level of about 80% or below (also see Table 2). The study concluded that the main challenges related to ESPs are extremely low residence time, the cleaning of the electrodes, the removal of the collected particles, material deterioration due to harsh conditions, and the need for specific chimney/appliance tuning. Moreover, long-term testing is scarce. Long-term testing (2009–2013) in Saas-Fee in the Swiss Alps using the OekoTube outside ESP across 74 installations showed achievable emitted particle mass reduction between 31%–91%, with a median of 70% (Rainer, 2021).

Financial Considerations

The purchase price for an ESP, including mounting and installation, is about €1,500–€2,200 (Obernberger & Mandl, 2011). It is advised to have the installation performed by a professional installer. For poorly walkable roofs or chimneys that protrude over 1.50 m, an aerial work platform must be used for the installation at an additional cost of nearly €150. The costs of the ESP OekoTube-Outside for end-users (without potential financial incentives and installation costs) range between €1,500–€3,000. This is in the same range specified for similar ESPs from other manufacturers, for example, the Airjekt 1 from Kutzner and Weber, which costs around €1,700–€2,000. Exodraft's ESP systems costs between €2,000–3,000, not including chimney instalment. In several European countries, authorities refund part of the investment costs.

The operating cost of an ESP mainly comprises the electricity consumption of the electrodes and the fan. With a power of between 10–100 W, for an occasional user (18 weeks/yr), this corresponds to a consumption of 1.8–18 kWh/yr. For users heavily dependent on their wood stove (18 weeks/yr), this corresponds to a consumption of 9.6–96 kWh/yr.

On the question of either replacing one's old stove for a new one or keeping the old one with ESP installation, at least one study (Schleicher and Fuglsang, 2011) concludes that exchanging an old wood stove for a new one is a much better option. One important reason is that ESPs only reduce the particle emissions, while new units have much lower documented emissions for all pollutants: CO, particles, condensables, and PAH.

According to the distributors, a manual electrostatic precipitator should be cleaned once or twice a year, depending on the appliance and its use. In Europe, a service visit costs around €100–€150, depending on the number of flue gas pipes that need to be cleaned. The maintenance of the electrode is usually done with the annual chimney cleaning and does not result in a significant additional cost. It is important not to use a steel brush, as it may damage the electrode.

Most European countries have, in recent years, acted to push for better and cleaner wood burning. In Germany, the federal government has created binding guidelines for the emission of fine dust and CO for small and medium combustion devices.

Existing fireplaces and stoves can continue to be used if they can meet the emission limit values of the First Federal Emmission Control Ordinance (1st BImSchV). The deadline for stove owners in Germany to comply was 31 December 2024, either by changing to a modern stove or by equipping existing stoves with a particle filter. For example, this could be achieved by installing a PM filter (approved by Deutsches Institut für Bautechnik [DIBt])—either an active ESP filter or a passive catalytic filter. However, the user must consider what is profitable—retrofitting or buying a

new stove. In public debates and in German media, experts advice to install a certified particle filter only if one owns a unique and valuable stove, such as a tiled stove. Otherwise, most are advised to replace old stoves for modern ones due to the small price difference and the otherwise many benefits of a new stove, as previously mentioned. Most German distributors offer and promote active ESP solutions rather than passive catalytic solutions. Table 3 in Appendix O provides a list of approved German ESPs.

ESPs should, in general, be maintained and cleaned at regular intervals, which adds to their running costs.

To improve future implementation of ESPs as a real alternative, one should

1. dilute flue gas with ambient air to around 30°C to force the condensation of condensable matter into particles, which then can be captured by the ESP to ensure that any sticky condensables can be removed from the electrodes and the inner walls of the ESP;
2. ensure sufficient residence time to improve capture efficiency. Industrial ESPs have much higher residence times and much higher efficiencies;
3. develop more self-cleaning features, resulting in less hassle with deposition of collected particles and in fewer and simpler maintenance cycles. The best available automated cleaning technology comes with a self-cleaning feature and catalytic-like technology, while other so-called automated cleaning systems usually have mechanical cleaning of the electrodes, and the collected particles then need to be removed manually.

3.2. Catalytic Converter

Description of Technology

In addition to ensuring adequate residence time and thorough mixing of intermediate combustion products with combustion air, maintaining a temperature in the range of 600°C–1000°C is imperative to facilitate the reaction kinetics governing the oxidation mechanisms within the combustion process. The absence of these requisite conditions leads to emissions resulting from incomplete combustion.

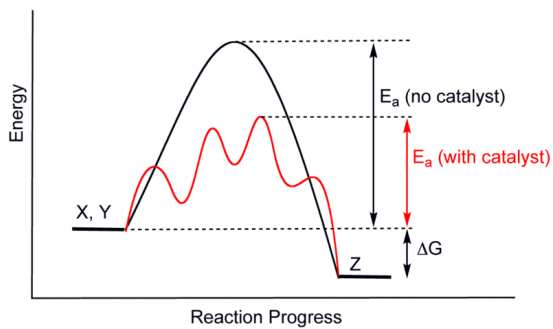


Figure 11: General reaction mechanism of an exothermic reaction ($X + Y \rightarrow Z$) with and without catalyst ("Wikimedia Commons, Generic potential energy diagram," 2008)

Catalysts can be used to facilitate and accelerate chemical reaction mechanisms by reducing the activation energy to avoid this issue (Figure 11).

However, since the Gibbs enthalpy (ΔG) is not changed, the thermodynamics of the overall chemical reactions are also unchanged. The catalyst itself is not consumed during the catalytic process, which comprises various reaction mechanisms. Depending on the aggregation state (its physical state or form—whether it is in a solid, liquid, or gaseous state) of the catalyst and the reacting agents, catalytically supported reaction mechanisms are classified either as homogeneous or heterogeneous catalysis. For the application of catalysts in stoves, heterogeneous catalysis, the reaction of gaseous reactants at a solid catalyst, is essential. The application of honeycomb catalysts or catalytic foamed ceramics, as shown in Figure 12 a) and b), respectively, exemplifies the state-of-the-art use of catalysts in wood stoves (Cork, 2013; VDI 3476 Blatt 1, 2015; Wöhler et al., 2017).

These catalysts include a carrier material (e.g., either ceramic or metallic), an intermediate layer for increasing the geometric surface area of the catalyst, and the catalytic active sites (see Figure 13). The intermediate layer is the wash-coat, made from aluminum oxides (Al_2O_3), and the active sites are specific combinations of metals; the noble metals platinum (Pt for oxidation of VOC and CO) and palladium (Pd for oxidation of CO) are most often used. For oxidation of NO, Rh can be applied. The specific catalytic reactions take place at the active sites (e.g., oxidation of CO and O_2 to CO_2).

If the flue gases can reach very high temperatures ($600^\circ C$ – $900^\circ C$), such as in vicinity of the combustion chamber, non-precious metals, such as nickel (Ni), copper (Cu), and magnesium (Mg), can achieve similar conversion rates (Mack and Hartmann, 2017).

A key indicator for the design of catalysts is the gas velocity (GSV) through the catalysts pore volume. The GSV (gas space velocity) relates to the wet flue gas volume flow (STP), while the volume of the catalyst (V_{cat}) indicates the mean residence time of flue gases within. Hence, a high GSV is linked to a short residence time of flue gases within the catalytic reactor, and vice versa.

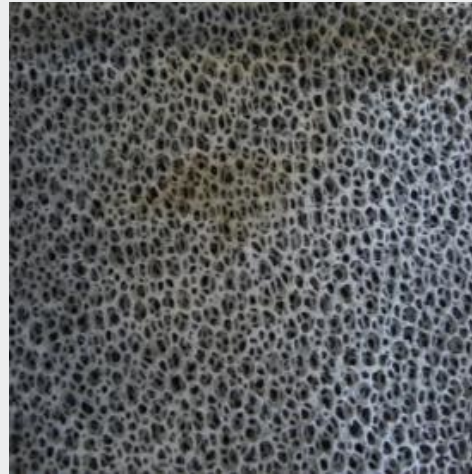
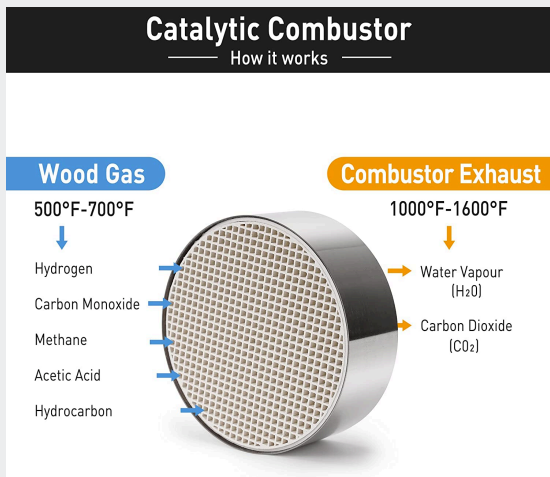


Figure 12a: Honeycomb catalyst with ceramic carrier

Figure 12b: catalytic foamed ceramic

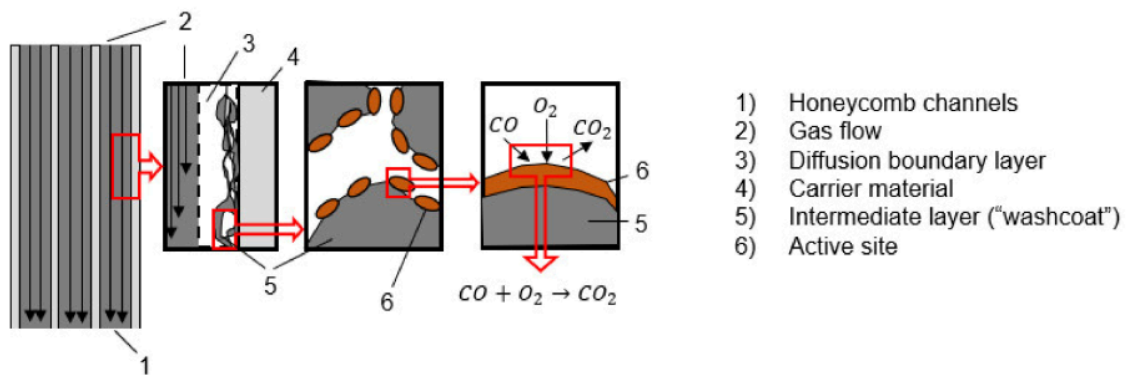


Figure 13: Construction design of a honeycomb catalyst and characteristics of a catalytic reaction (Reichert and Schmidl, 2023a)

Heterogeneous catalytic conversion within honeycomb catalysts can be categorized into seven typical phases, as illustrated in Figure 14 (Wikimedia, 2010):

1. Diffusion of reactants (e.g., CO, O₂) through the boundary layer (boundary layer diffusion)
2. Diffusion of reactants into the pores of the wash-coat (pore diffusion)
3. Chemisorption of reactants/educts at the active sites
4. Chemical reaction of reactants/educts at the active sites
5. Desorption of products from the active sites
6. Diffusion of products out of the pores of the wash-coat (pore diffusion)
7. Diffusion of products (e.g., CO₂) through the boundary layer into the flue gas flow through the honeycomb cells (boundary layer diffusion).

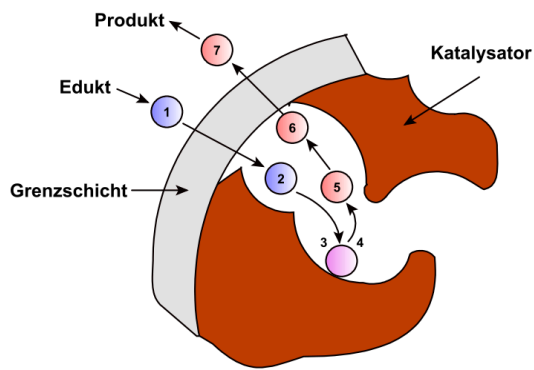


Figure 14: Heterogeneous catalyst

The overall reaction kinetics are influenced by catalytic selectivity, the concentrations of the reactants/products, and temperatures. The limiting effects of catalytic conversion are transport mechanisms, assuming the temperature is sufficiently high, or reaction mechanisms, if temperatures are in the lower limits. For the application of catalysts in stoves, they can either be integrated inside the stove (usually as factory installations) or retrofitted into the chimney, close to the chimney inlet. Relevant design parameters are (Reichert and Schmidl, 2023b)

- Temperatures (minimum, maximum, average);
- Pressure drops;
- By-pass according to requirements of respective European Standards, e.g., 3% of sectional area or at least 20 cm² of the flown-through sectional area (BLUEFIRE GmbH, 2023);
- Accessibility for cleaning, maintenance, and exchange.

Regarding wood stoves, an overall and local oxygen deficit must be avoided in the flue gas passing the catalyst (which can happen at very high combustion rates, for example) by ensuring good air/flue gas mixture through appropriate design of the combustion chamber and air nozzles.

The reactions that the catalyst promotes are temperature-dependent. When the flue gas temperature exceeds a certain threshold, the catalyst is activated and the exotherm reactions heat it up. This is known as the activation temperature and is usually between 200–300 °C for CO reduction, while reduction of hydrocarbons usually requires higher temperatures (Mack and Hartmann, 2017). When the flue gas is below the activation temperature, the catalyst will not work. Several factors contribute to efficient combustion and ensure a sufficiently high combustion temperature above the activation temperature.

For ceramic catalysts, an overly low temperature is disadvantageous because some oils and tar in the combustion gas will be deposited on the catalyst, which will significantly increase the cleaning frequency of the catalyst. This is why most integrated catalysts are equipped with a bypass supplied with a thermometer or some bi-metallic opening/closing mechanism. At flue gas temperatures lower than

the activation temperature, the flue gas must by-pass the catalyst using a manual/automatic valve, while when reaching the activation temperature it passes through the catalyst (White Beam, 2023).

A metal catalyst suffers less from this problem because the high conductivity of the metal structure inside triggers a self-cleaning process that burns the aromatic compounds from tar. Installing a bypass is therefore not necessary, and a manual by-pass option is often sufficient. The upper temperature limit of the catalyst is determined by the structural and chemical limit for the carrier material, the wash-coat and active material, and the production process. The choice of catalyst will therefore determine the operating temperature and catalyst placement. The implementation of a high temperature catalyst at the outlet of the post-combustion chamber is not recommended as tests have indicated unstable reduction efficiencies. The decreasing reduction efficiencies over time are attributed to catalyst deactivation due to blocking of active sites by aerosol condensation. Therefore, the mounting position of the catalyst has to be carefully evaluated in terms of flue gas temperatures in order to minimize risks of aerosol deposition (Mack and Hartmann, 2017).

The aim for all catalyst installations is to ensure fast heating of the catalyst and then to keep it activated through the combustion period assuring that it does not exceed the maximum temperature. In addition, the catalyst must remain easily accessible to the user for removal, cleaning, and replacement. If possible, the location should be chosen so that most of the heat released by the catalyst can still be utilized for heating and does not dissipate in the chimney (White Beam, 2023). A limitation of the ceramic catalyst is the reduction in natural airflow due to high-pressure drops; this can be remedied by increasing the cross-section of the flue gas pipe to reduce the pressure drop while maintaining catalyst efficiency. To further remedy the pressure drop induced by the catalyst, the installation of a flue gas fan may be beneficial (Mack and Hartmann, 2017).

The laboratory tests of Reichert et al. (2018a, 2018b) using five different woodstoves according to EN 13240 ("EN 13240," 2003) revealed clear emission reduction potential for firewood stoves by integrating ceramic or metallic honeycomb converters (EnviCat® Long Life Plus [EnviCat® VOC, 2023]). Depending on the type of honeycomb catalyst, CO emissions are reduced by 93% (metallic) or 83% (ceramic), OGC emissions by about 30%, and PM emissions by about 20%. The emission limit values for CO, OGC, and PM emissions set during the Ecodesign and Energy labeling process of the European Commission were met by most of the tested catalyst integrated solutions, even when ignition and preheating batch were included. Interestingly, all tested catalysts were integrated in the post-combustion chamber upstream of the flue outlet, with no bypass.

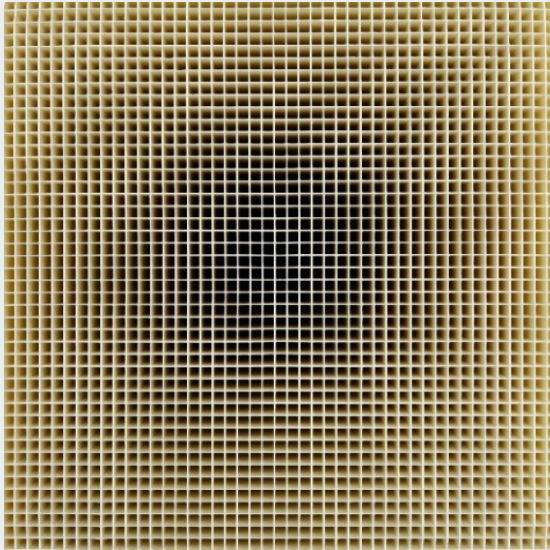


Figure 15: Clariant Catalysts (EnviCat® VOC, 2023)

In a report from "Technologie- und Förderzentrum im Kompetenzzentrum für Nachwachsende Rohstoffe" (TFZ; Mack et al., 2018), clear emission reduction potential is described for integrated catalytic foamed ceramics (active sites: Pt, Pd, Rh). According to experimental tests, the emission conversion efficiencies were 45% for CO, 25% for VOC, and 0% for PM emissions. The conversion efficiencies were evaluated for heating cycles consisting of eight successive batches (batches 1–5 at nominal load with 100% batch mass and batches 6–8 at partial load with 50% batch mass). These tests were performed without any bypass in the flue gas pathway (i.e., bypass closed). The operation of the stove was based on a quick user guide from the user manual. The current tests revealed no CH₄ conversion efficiency; this concurs with other studies and is explainable by the average temperature levels in the range of 300–450 °C, which are far too low for catalytic CH₄ oxidation (≥ 650 °C; Mack et al., 2018; Reichert et al., 2018b).

Similar results were observed in the measurements by Wöhler et al. (2017), which evaluated an integrated metallic honeycomb catalyst and an integrated catalytic foamed ceramic. During these measurements, the stove was also operated using several batches at nominal (100% batch mass) and partial load (50% batch mass). In contrast to the findings of Mack et al. (2018), PM emission conversion efficiency of about 30% was observed.

For ceramic catalysts tested in the Woodstoves 2020 research project (TFZ, 2020) aiming to develop innovative measures and technologies to further reduce wood combustion emissions, three ceramic catalysts (EnviCat 2520 and two in-house made units) were integrated at different locations in a stove and tested. These tests showed that catalysts fitted to the outlet of the combustion chamber reduced emissions by an average of 70% for CO and 32% for OGC. However, the

emission removal efficiencies dropped as the test period (100 hours) progressed to 70% of their initial values. Moreover, cleaning the catalyst was not sufficient to avoid the decline in efficiency; this was due to deactivation by aerosol deposits, mainly as K_2SO_4 and KCl, which partially blocked the active centers (Mack and Hartmann, 2017).

Emission reductions with metal catalysts in various tests showed a 66% reduction in particulate matter emission (DBFZ, 2018) under lab conditions with an initial concentration of 101 mg/m^3 . Test results from the SP Technical Research Institute of Sweden revealed a 66% reduction in CO (Rönnback et al., 2016). The test was carried out with a Pd-catalyst covering the whole chimney cross-area, and the duration of the test included four combustion cycles and an average inlet concentration of CO before the catalyst of 3500 ppm. In the same study, a 10%–50% reduction in hydrocarbons was reported in a test including four combustion cycles and 50% according to a short duration test by the DBFZ (DBFZ, 2018).

However, according to the literature (VDI 3476 Blatt 1, 2015) as well as experimental tests (Mack et al., 2018; Reichert et al., 2017), long-term operation will eventually result in agglomerations on the catalyst surface area that reduce the conversion efficiency. Hence, both integrated and retrofitted catalysts must be cleaned and maintained regularly. Some manufacturers recommend only a mechanical cleaning of the catalysts (Brunner et al., 2009), but another possibility is additional cleaning with water, which removes water-soluble agglomerations on the catalyst surface (Reichert et al., 2017).

In addition, different deactivation mechanisms can result in premature losses of conversion efficiencies. Generally, potential deactivation mechanisms of heterogeneous catalysis are classified into three categories (Bartholomew, 2001; Moulijn et al., 2001). *Chemical deactivation* is caused by selective or non-selective poisoning, which results in a deactivation of active sites by gaseous components (e.g., Pb, Zn, P or SO_2). Furthermore, leaching is a type of chemical deactivation caused by undesired chemical reactions between gaseous compounds in the flue gas and the active sites of the catalyst, leading to a loss of those sites. Chemical deactivation mechanisms are mostly irreversible; the operating conditions and the type of catalyst used must therefore be adjusted and critical components (e.g., Pb, P, Zn, and SO_2) avoided for Pt- and Pd-based catalysts. *Thermal deactivation* is caused by the reduction of the surface area of active sites or the porous surface of the wash-coat due to sintering processes. Thermal deactivation is also irreversible and can be avoided by the appropriate design and operation of the appliance. In particular, maximum temperature conditions must be considered for the application of certain catalysts. *Mechanical deactivation* is caused by fouling processes, namely the deposition of particles on pores and/or active sites, or due to attrition, meaning the loss of active sites due to abrasion or mechanically induced crushing. Both mechanisms lead to a decrease in catalytic conversion efficiency.

However, deactivation by fouling is often reversible by cleaning the catalyst or via oxidative regeneration of carbonaceous deposits (Greet et al., 2020).

Financial Considerations

Passive particle filters or catalyst modules cost around €300 or more (Selber machen, Magazine, 2023). Amazon in Germany offers catalytic converter replacements for wood stoves for around €160, which seems to match the starting price of other European suppliers for replacements. The cheapest catalysts are likely produced in China and can probably be bought cheaper than catalysts made in European countries. The ABCAT® Holzrauchfilter retrofit filter costs between €340–€380 (ABCAT®, 2023). Ceramic catalysts are available starting at €700 excluding installation (Chimcat, 2019). At very high temperatures, non-precious metals (e.g., Ni, Cu, and Mg) are also suitable as catalysts. Due to the lower temperature in the case of a chimney retrofit, only precious metals (Pt, Rh, and/or Pd) can be used, which have a lower activation temperature; this may result in higher costs compared to integrated catalysts. (Mack R., et al., 2017).

The Bullerjan (Chimcat type) is offered in Europe, whereas the Firecat (for combustor ACI-68C/ACI-2C) is mainly offered in the United States. Distributors of metal catalysts include Condar (SteelCat type), mainly offered in the United States. The Ecolink (PALCAT and ABCAT type) is mainly available in Europe.

The maintenance and cleaning of a chimney can be more difficult than with standard combustion appliances because the catalyst must be removed during cleaning and in some cases (e.g., ceramic catalysts) is fragile. The catalyst itself is removed manually by the user and cleaned with water or dusted off. Unfortunately, the catalyst does not have a sensor to warn the user that the unit needs to be cleaned. The correct operation of the catalyst thus depends entirely on the common sense of the user.

Ceramic catalysts are susceptible to damage resulting from physical contact, thermal shocks, and obstructions stemming from an incorrectly adjusted bypass or when burning moist wood. Over time, the catalyst honeycomb gradually deteriorates and requires replacement. In contrast, metal catalysts exhibit a slightly greater level of resilience due to their full-metal composition, with the precious metal applied through electroplating. This characteristic renders them more impervious to abrupt temperature fluctuations and aggressive substances, making them less susceptible to damages during cleaning. In a global context, the anticipated operational lifespan of a catalyst under standard usage conditions ranges from five to 10 years. In adverse conditions, such as burning moist or low-quality wood and neglecting proper maintenance, catalyst pores may become obstructed, potentially rendering the unit nonfunctional in as little as a few years or even months. Consequently, it is imperative to exercise additional caution when selecting appropriate fuel and performing regular maintenance.

4. Summary and Conclusion

Summary

Several technologies, both primary and secondary measures, can be leveraged to reduce emissions from Solid Fuel Local Space heaters (SFLSH). In this report the focus is on log wood stoves. It is important to operate and design wood stoves correctly to reduce these emissions. According to experts, both operation and design are equally important to reducing emissions. To optimally minimize emissions, the entire system, including the stove, chimney, and additional equipment, should preferably be optimized as one common unit and tested for correct functionality after installation.

It is essential to make sure the stove has proper draft (because most chimneys do not have a flue gas fan, which is used when stoves are certified) and uses appropriate fuel. The draft is affected by downstream equipment like particle filters and flue gas fans. However, the draft should neither be too low nor too high, as many times seen in real life

For the last two decades combustion control for wood stoves have made great leaps to prove that the technology works. ACC was initiated by a few industries and now many have followed, particularly the largest companies. Due to the cost of development, most systems are proprietary to each manufacturer, with each developing their own system. The main purpose of an AAC system is to adjust the combustion airflows during the different phases of the combustion process. While substantially improving the combustion, additional secondary measures can be added downstream of the combustion chamber to further reduce emissions. Both unburnt gases and particles can be catalytically oxidized, while remaining particles can be removed using ESPs. There are currently no practical secondary measures to address NO_x emissions from wood stoves.

Secondary measures require additional investment costs and have limited effect during the ignition, refilling, and the charcoal phases. Electric power is necessary for ESPs. In addition, they also impose higher maintenance costs and effort on end-users. Some secondary technologies also suffer from a lack of user acceptance due to, for example, additional costs, effort, noise, contamination by flakes (ESPs), low availability, or short periods of operation between cleaning requirements. As mentioned in this report, installing separate secondary measures in an already existing stove-chimney system might affect its intended operation (e.g., reduced draft, etc.) if not installed by professionals and tuned specifically for each application.

Ideally, secondary measures should be most effective during operating phases when technical and non-technical primary measures are the least effective, such as in the cold start, start-up, refill, and charcoal phases. However, tests seem to imply that secondary measures primarily reduce emissions during the main combustion phase. Scientific studies have concluded that the highest emission reduction potential for both gaseous and particulate emissions combine primary measures with both a catalyst and an ESP. The studies show that extensive technical primary optimization based on appliance-specific best-practice user behavior, combined with a catalyst and an ESP, would represent a suitable system to achieve significant emission reduction during real-life operation.

In Germany, around nine million wood stoves nationwide were at risk of being forced out of service at the end of 2024 due to the amendment to the German Federal Emission Control Act, which stipulates lower limits for particle emissions and CO. If an appliance does not meet these values, it must either be replaced, retrofitted, or shut down. This means that Germans who owned an old stove had to decide whether to exchange their stove for a modern replacement, shut it down, or retrofit it with an approved secondary technology. As ESPs only remove particles and yield gaseous emissions that are still too high, adding a complementary catalyst is necessary. At this point, the cost of the secondary measures and their effect on emissions and efficiency must be evaluated against exchanging the old stove for a new one.

For comparison, CoPilot Microsoft 365 GPT v5 was used, with references QA controlled by the author, to collect indicative emission reduction potentials for the three wood stove technologies of ACC, ESP, and catalyst. The reduction potentials for PM, OGC, and CO are shown in Figure 16. Note that actual performance varies with appliances, fuel, and operation. Sources: [1,9,11,14].

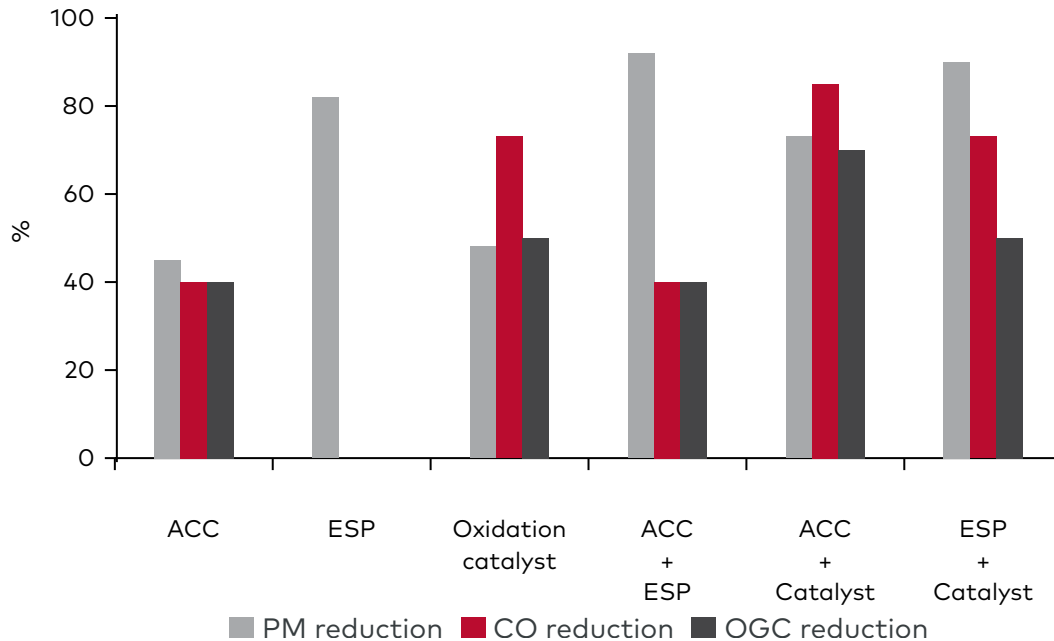


Figure 16: Indicative emissions reduction chart

A table is provided in Appendix A3 with additional information on PM reduction, CO reduction, OGC reduction, efficiency impact, maturity and availability, approximate cost, and notes on lifetime and maintenance. The additional information in Appendix A3, collected by Copilot GPT v5, as well as the emission reduction potentials vary slightly but are mostly in line with the information provided in this report.

Conclusion

Several technologies can be applied to reduce emissions from SFSHs, applying both primary and secondary measures. Most ACC solutions are tightly integrated into the stove, which is necessary for optimum functionality. If ACC, a primary measure, is integrated into the appliance, the cost versus a manually operated SFSH is expected to increase between €700–€2,000, depending on the level of sophistication. Sometimes sales prices are boosted due to the value of the novelty and to cover the expenses of development. A certain sales volume is also necessary to reduce production costs and retail prices. ACC reduces all emissions and improves efficiency (see details in the report). Adding an ESP, as a secondary measure, costs between €1,500 to €3,000 and reduces particle emissions by 40%–80% (not including condensed particles because the flue gas is not diluted upstream), especially emissions of larger particles, depending on each specific installation. A catalyst, as a secondary measure, can either be integrated into the

appliance (preferred and most efficient way due to temperature requirements) or retrofitted close to the stove's flue gas outlet. Prices for external products start at €250 and can reach up to €1,000, depending on the material. The reduction potential depends on the active material, mainly targeting CO and volatile organic compounds (VOCs), with reductions of approximately 50% and 25%, respectively. Catalysts typically have a limited lifespan and need to be replaced periodically (5–10 years). Both catalysts and ESPs require maintenance to ensure proper functioning.

The complementary application of technical primary and secondary measures is necessary to achieve (nearly) zero-emission technologies. Long-term field evaluation under real-life end-user operation and natural draught conditions using different firewood room-heating technologies is essential. There are still open questions, such as user acceptance of flakes around the chimney when using ESPs and the pros and cons of appliance-integrated ESPs versus ESPs integrated into rooftop chimneys. Further research and development are necessary for these aspects, as well as for maintenance efforts and costs between potential secondary emission abatement technologies. Ideally, secondary measures should be effective during transient combustion conditions, involve low maintenance efforts, be cost-efficient, and enhance user comfort.

Due to increasingly stringent legal requirements regarding emissions and thermal efficiency, there is a trend towards (nearly) zero-emission technologies. Therefore, advanced combustion ideas combining both technical primary measures and complementary secondary emission abatement technologies strongly focusing on appliance-specific best-practice heating operation (ideal user behavior) are essential.

ESPs have become much better within the past five to 10 years. There are already ESPs on the market that are self-cleaning and can operate for several months with little degradation of capture efficiency. However, ESPs are designed with an upper limit in terms of rate of PM capture and flue gas throughput, which should not be exceeded. This requires knowledge of both the selected ESP and the specific appliance. Flue gas composition also plays a role in influencing capture efficiency. Smoke with high amounts of salts and carbon particles have a significantly higher capture rate than flue gas with high amounts of condensed organic components. Carbon particles are readily captured but might cause short circuits due to their high conductivity. Short circuits may lead to re-entrainment, in which the collected particles "catch fire" and thereby release a plume of secondary particles. High amounts of organic compounds in the flue gas, condensing as tar in the ESP, might also lead to short circuits and re-entrainment due to the low conductivity of tar. Furthermore, experimental tests seem to indicate that ESP technology increases the number of ultrafine particles emitted, produces "flaking" around the outlet, and alters the chemical and toxicological properties of the captured particles. Noise

from the discharges has also been mentioned on several occasions. Based on the various studies and articles cited in this report, many measurements have been performed on ESPs, both under laboratory and real-life conditions, with a high degree of variation in the capture efficiencies reported. It is therefore difficult to assess the general reduction potential of ESPs as the reduction efficiency depends significantly on each specific installation. More development is recommended, especially for flue gas dilution before ESP and higher capture efficiencies of at least 99%. ESPs are mainly recommended for newer, less polluting stoves.

Regarding catalysts, their integration in domestic wood-burning appliances can be an efficient secondary measure to reduce emissions from wood burning and remedy potential odor nuisance. The highest emission reduction is usually achieved for carbon monoxide. The reduction of hydrocarbons and unburnt organic particles is also possible. The catalyst also works as a sort of filter, retaining some of the fine particles (fly ash). Usually, the investment and installation cost for a catalyst is lower than for an ESP. The highest reduction potential seems to be when the catalyst is integrated into the appliance itself, close to the combustion chamber. The catalyst will work best in a nominal combustion regime. On the downside, a catalyst may increase the flow resistance in case of bad maintenance, leading to poor combustion with higher emissions. Insufficient draught in the chimney also increases the risk of potentially dangerous flue gases leaking into the room, and an additional flue gas fan might be necessary. Catalysts are better suited for new stoves, and not that much if retrofitted in old ones, with high emissions of both particles and pollutant gases. Temperature peaks of at least 300 °C are required for proper operation of the catalyst, which is hard to comply with when retrofitted outside of the appliance.

As with all technology invented by humans, when the above-mentioned primary and secondary measures are used in real life, user errors occur. The emission reductions reported here are mostly taken from either the industry itself or from laboratory tests. To be certain of actual improvements, either a more true-to-life certification method should be developed or long-term field measurements should be gathered. All these technologies function properly only when using the correct fuel type, in the right amount, with the appropriate moisture content and log size. Additional technology may be necessary to monitor and guide the user in proper usage.

5. References

AEOLUS - Novel combustion air supply regulation systems for increased robustness of wood stove operation and maximum thermal comfort, IPN project, 2018 – 2019, [https://prosjektbanken.forskningsradet.no/en/project/FORISS/282372?](https://prosjektbanken.forskningsradet.no/en/project/FORISS/282372?Kilde=FORISS&distribution=Ar&chart=bar&calcType=funding&Sprak=no&sortBy=score&sortOrder=desc&resultCount=30&offset=0&Fritekst=Aeolus)

[Kilde=FORISS&distribution=Ar&chart=bar&calcType=funding&Sprak=no&sortBy=score&sortOrder=desc&resultCount=30&offset=0&Fritekst=Aeolus](https://prosjektbanken.forskningsradet.no/en/project/FORISS/282372?Kilde=FORISS&distribution=Ar&chart=bar&calcType=funding&Sprak=no&sortBy=score&sortOrder=desc&resultCount=30&offset=0&Fritekst=Aeolus)

AEOLUS+ New generation digital wood stoves, 2020 – 2022,

[https://prosjektbanken.forskningsradet.no/en/project/FORISS/309966?](https://prosjektbanken.forskningsradet.no/en/project/FORISS/309966?Kilde=FORISS&distribution=Ar&chart=bar&calcType=funding&Sprak=no&sortBy=score&sortOrder=desc&resultCount=30&offset=0&Fritekst=Aeolus)

[Kilde=FORISS&distribution=Ar&chart=bar&calcType=funding&Sprak=no&sortBy=score&sortOrder=desc&resultCount=30&offset=0&Fritekst=Aeolus](https://prosjektbanken.forskningsradet.no/en/project/FORISS/309966?Kilde=FORISS&distribution=Ar&chart=bar&calcType=funding&Sprak=no&sortBy=score&sortOrder=desc&resultCount=30&offset=0&Fritekst=Aeolus)

SusWoodStoves, Sustainable wood stoves through stove, building integration and value chain optimization,

[https://prosjektbanken.forskningsradet.no/en/project/FORISS/319600?](https://prosjektbanken.forskningsradet.no/en/project/FORISS/319600?Kilde=FORISS&distribution=Ar&chart=bar&calcType=funding&Sprak=no&sortBy=date&sortOrder=desc&resultCount=30&offset=0&Prosjektleder=%C3%98yvind%20Skreiberg)

[Kilde=FORISS&distribution=Ar&chart=bar&calcType=funding&Sprak=no&sortBy=date&sortOrder=desc&resultCount=30&offset=0&Prosjektleder=%C3%98yvind%20Skreiberg](https://prosjektbanken.forskningsradet.no/en/project/FORISS/319600?Kilde=FORISS&distribution=Ar&chart=bar&calcType=funding&Sprak=no&sortBy=date&sortOrder=desc&resultCount=30&offset=0&Prosjektleder=%C3%98yvind%20Skreiberg)

ABC News, 2023. They can offer “nostalgic charm and comfort” but the ACT government says wood heaters will be gone by 2045.

[https://www.abc.net.au/news/2023-08-24/canberra-to-phase-out-wood-heaters-by-2045/102769162.](https://www.abc.net.au/news/2023-08-24/canberra-to-phase-out-wood-heaters-by-2045/102769162)

ABCAT®, 2023. Lower emissions with the ABCAT® [WWW Document]. EcoCat. URL

<https://ecocat.eu/en/home-english/>

Ban on wood burning stoves. Government confirms no ban [WWW Document], 2023. URL <https://www.hetas.co.uk/ban-on-wood-stoves/>

Bartholomew, C.H., 2001. Mechanisms of catalyst deactivation. Applied Catalysis A: General, Catalyst Deactivation 212, 17–60.

Blauer Engel, Kaminöfen für Holz, DE-UZ 212, [https://www.blauer-engel.de/de/produktwelt/kaminoefen-fuer-holz?](https://www.blauer-engel.de/de/produktwelt/kaminoefen-fuer-holz?url=https%3A%2F%2Fwww.blauer-engel.de%2Fde%2Fproduktwelt%2Fkaminoefen-fuer-holz)

[url=https%3A%2F%2Fwww.blauer-engel.de%2Fde%2Fproduktwelt%2Fkaminoefen-fuer-holz](https://www.blauer-engel.de/de/produktwelt/kaminoefen-fuer-holz?url=https%3A%2F%2Fwww.blauer-engel.de%2Fde%2Fproduktwelt%2Fkaminoefen-fuer-holz), 2020

BLUEFIRE GmbH, 2023. the Blue Fire GmbH [WWW Document]. URL <https://blue-fire.org/en/>

Brunner, T., Obernberger, I., Scharler, R., 2009. Primary measures for low-emission residential wood combustion—comparison of old with optimised modern systems. Proc. of the 17th European Biomass Conference, June 2009, Hamburg, Germany.

Brunner, T., Wuercher, G., Obernberger, I., 2018. 2-Year field operation monitoring of electrostatic precipitators for residential wood heating systems. Biomass and Bioenergy 111, 278–287.

Carrington, D., editor, D.C.E., 2023. Wood burners in effect banned in new and refurbished homes in London. The Guardian
<https://www.theguardian.com/environment/2023/feb/08/wood-burners-in-effect-banned-new-refurbished-homes-london>.

Cheminées Poujoulat, 2023. Cheminées Poujoulat [WWW Document]. Cheminées Poujoulat - filtration. URL <https://www.poujoulat.com/solutions/residential-housing/chimney-systems-for-residential-applications/filtration-1/top-clean>

CMR, <https://www.cognitivemarketresearch.com/>, 2025

Cork, T., 2013. Here is how a catalytic combustor works in a wood burning stove, <http://firecatcombustors.blogspot.com/2013/02/here-is-how-catalytic-combustor-works.html> [WWW Document]. Woodstove catalytic combustors. URL <http://firecatcombustors.blogspot.com/2013/02/here-is-how-catalytic-combustor-works.html>

DBFZ, 2018. Partikelabscheider in häuslichen Feuerungen. Fachgespräch, DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH.

Digitalarkivet, Næs Jernverksmuseets samling av historiske ovnskataloger, NESJ/NJM-006/01/L0021: Jøtul Oslo, p.5, <https://media.digitalarkivet.no/view/191197/5>, 1927

Ecodesign 1189, 2015. Commission Regulation (EU) 2015/1189 of 28 April 2015 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to eco-design requirements for solid fuel boilers (Text with EEA relevance), OJ L.

EN 13240:2001 - Roomheaters fired by solid fuel - Requirements and test methods [WWW Document], 2003. . iTeh Standards. URL <https://standards.iteh.ai/catalog/standards/cen/6933be25-61b7-4ee4-bec4-b3260a63bdb3/en-13240-2001>

EnviCat® VOC, C.L., 2023. EnviCat® VOC [WWW Document]. Clariant Ltd. URL <https://www.clariant.com/en/Solutions/Products/2019/07/22/08/50/EnviCat-VOC>

EU, State of the Union, https://energy.ec.europa.eu/topics/energy-efficiency/heating-and-cooling_en, 2025

Exodraft a/s, 2023. The Exodraft ESP particle filter [WWW Document]. URL <https://exodraft.co.uk/product/particlefilter/esp-particle-filter/>

Greet, J., Kristof, C., Diane, H., 2020. Best Available Techniques (BAT) for Domestic Wood Heating. The Flemish Knowledge Centre for Best Available Techniques (BAT-knowledge centre).

Hartmann, H., Turowski, P., Kiener, S., 2010. Electrostatic precipitators for small scale wood furnaces, <https://landtechnik-online.eu/landtechnik/article/download/2010-65-5-342-345/2010-65-5-342-345-en-pdf/>. Landtechnik 65, 342–345.

HWAM, <https://www.hwam.com/>, 2025

IEA, Task 32, Technical Guidelines for the Design of Low Emission Wood Stoves, Report, https://www.ieabioenergy.com/wp-content/uploads/2022/11/IEA-Bioenergy-Task-32_Report-D1-2_Low-emission-wood-stove-design_final.pdf, 2022

Jaworek, A., Sobczyk, A.T., Marchewicz, A., Krupa, A., Czech, T., 2021. Particulate matter emission control from small residential boilers after biomass combustion. A review. Renewable and Sustainable Energy Reviews 137, 110446.

König, M., Hartmann, I., Varas-Concha, F., Torres-Fuchslocher, C., Hoferecht, F., 2021. Effects of single and combined retrofit devices on the performance of wood stoves. Renewable Energy 171, 75–84.

Kutzner und Weber, 2023. Particle separator | Customerportal [WWW Document]. URL <https://shop.kutzner-weber.de/kw/en/shop/159528/159566/>

Lauber, A., Nussbaumer, T., 2010. Charakterisierung der Partikelarten aus der Holzverbrennung und Eigenschaften in Elektroabscheidern, <https://docplayer.org/33638605-Charakterisierung-der-partikelarten-aus-der-holzverbrennung-und-eigenschaften-in-elektroabscheidern.html>.

Lid, Kr. "Fyr riktig med ved!", p.13, Utg. Halvorsens Bokhandel, Oslo, <https://www.nb.no/items/42c00363a9c548a545fc6fa6c925e0c5?page=13>, 1940

Mack, R., Daniel, K., Schön, C., Hartmann, H., 2018. Optimierungspotenziale bei Kaminöfen, https://www.tfz.bayern.de/mam/cms08/festbrennstoffe/dateien/tfz_bericht_57_optimierungspotenziale_kaminoefen_ges.pdf.

Mack, R., Hartmann, H., 2017. Guidelines for Low Emission and High Efficiency Stove Concepts, https://www.tfz.bayern.de/mam/cms08/en/dateien/stoves2020-guidelines_low_emission_concepts.pdf.

Mandl, C., Obernberger, I., et al., Guidelines for automated control systems for stoves, ERA-NET Bioenergy Project "Woodstoves2020", https://www.tfz.bayern.de/mam/cms08/en/dateien/stoves2020-guidelines_automated_control_systems.pdf, 2017

Moulijn, J.A., van Diepen, A.E., Kapteijn, F., 2001. Catalyst deactivation: is it predictable?: What to do? Applied Catalysis A: General, Catalyst Deactivation 212, 3–16.

Nussbaumer, T., Hartmann, H., Hofbauer, H., Good, J., Kaltschmitt, M., Karl, J., Spliethoff, H., Werther, J., 2009. Direkte thermo-chemische Umwandlung (Verbrennung). In: Kaltschmitt, M., Hartmann, H., Hofbauer, H. (Eds.), Energie aus Biomasse: Grundlagen, Techniken und Verfahren. Springer, Berlin, Heidelberg, pp. 463–598.

Obernberg, I., Mandl, C., 2011. Survey of the present state of particle precipitation devices for residential biomass combustion with a nominal boiler capacity up to 50 kW in IEA Bioenergy Task 32 member countries | Bioenergy, <https://task32.ieabioenergy.com/wp-content/uploads/sites/24/2017/03/Filter-study-IEA-final-version.pdf>.

OekoSolve, 2023. Fine dust filters by OekoSolve - produced in Switzerland [WWW Document]. OekoSolve AG - Feinstaubfilter für Holzfeuerungen. URL <https://oekosolve.com/en/products/>

Oregon State University, News, <https://news.oregonstate.edu/news/new-technologies-help-wood-burning-stoves-burn-more-efficiently-produce-less-smoke>, 2025

Purves, R., 2023. UK wood burning stoves ban fears as EU country outlaws appliances. LeicestershireLive <https://www.leicestermercury.co.uk/news/property/uk-wood-burning-stoves-ban-8369814>.

Rainer, K.F., 2021. Case study on the use of electrostatic precipitators in domestic heating systems, https://tftei.citepa.org/images/files/2021-10-28-29/15-Rainer-Kegel-Case_study_ESP_Saas-Fee_-7thTFTEI-meeting2021.pdf.

Reichert, G., Schmidl, C., 2023a. SWOT Analysis of Non-Technical and Technical Measures towards "(Nearly) Zero-Emission Stove Technologies." *Energies* 16, 1388.

Reichert, G., Schmidl, C., 2023b. SWOT Analysis of Non-Technical and Technical Measures towards "(Nearly) Zero-Emission Stove Technologies." *Energies* 16, 1388.

Reichert, G., Schmidl, C., Haslinger, W., Stressler, H., Sturmlechner, R., Schwabl, M., Kienzl, N., Hochenauer, C., 2017. Long term durability and safety aspects of oxidizing honeycomb catalysts integrated in firewood stoves. *Biomass and Bioenergy* 105, 428–442.

Reichert, G., Schmidl, C., Haslinger, W., Stressler, H., Sturmlechner, R., Schwabl, M., Wöhler, M., Hochenauer, C., 2018a. Impact of oxidizing honeycomb catalysts integrated in firewood stoves on emissions under real-life operating conditions. *Fuel Processing Technology* 177, 109–118.

Reichert, G., Schmidl, C., Haslinger, W., Stressler, H., Sturmlechner, R., Schwabl, M., Wöhler, M., Hochenauer, C., 2018b. Catalytic efficiency of oxidizing honeycomb catalysts integrated in firewood stoves evaluated by a novel measuring methodology under real-life operating conditions. *Renewable Energy* 117, 300–313.

RIKA Rikatronic, <https://www.rika.at/technology/rikatronic4>, 2025

Rönback, M., Henrik, P., Jespersen, G., Jensen, J.H., 2016. Deliverable D7.1: Documentation and evaluation of field data demonstration (beReal) (No. D7.1). The Flemish Knowledge Centre for Best Available Techniques (BAT-knowledge centre).

Schleicher, O., Fuglsang, K., 2011. Test of technologies for flue gas cleaning and combustion improvement for existing residential wood burning appliances - Miljøstyrelsen, <http://www2.mst.dk/udgiv/publications/2011/11/978-87-92779-55-7.pdf>.

Scopus, 2023. Scopus preview - Scopus - Welcome to Scopus [WWW Document]. URL <https://www.scopus.com/home.uri>

Selber machen, Magazine, 2023. Ist dein Ofen auch betroffen? Hier musst du den Feinstaubfilter nachrüsten! [WWW Document]. selbermachen.de. URL <https://selbermachen.de/wohnen/heizen/feinstaubfilter-im-kamin-diese-kosten-kommen-auf-sie-zu> (accessed 10.18.23).

Strauss, K., 2016. Kraftwerkstechnik. Springer, Berlin, Heidelberg.

Timpex, <https://timpex.eu/kde-koupit/>, 2025

TFZ, 2020. Wood Stove 2020 – Development of next generation and clean wood stoves [WWW Document]. Wood Stove 2020 – Development of next generation and clean wood stoves. URL <https://www.tfz.bayern.de/en/162907/index.php>

VDI 3476 Blatt 1, 2015. Waste gas cleaning - Methods of catalytic waste gas cleaning - Fundamentals.

Vicente, E., Duarte, M., Tarelho, L., Alves, C., 2022. Efficiency of Emission Reduction Technologies for Residential Biomass Combustion Appliances: Electrostatic Precipitator and Catalyst. *Energies* 15, 4066.

White Beam, 2023. How to use catalytic converters to reduce fumes from wood stoves and boilers [WWW Document]. Medium. URL <https://medium.com/@Whitebeam/how-to-use-catalytic-converters-to-reduce-fumes-from-wood-stoves-and-boil-cbc208c3cecc>

Wikimedia Commons, Generic potential energy diagram [WWW Document], 2008. URL <https://commons.wikimedia.org/wiki/File:CatalysisScheme.png>

Wikimedia, 2010. Wikimedia Commons, Heterogene Katalyse [WWW Document]. URL https://commons.wikimedia.org/wiki/File:Heterogene_Katalyse_2.svg

Wöhler, M., Jaeger, D., Pelz, S.K., Thorwarth, H., 2017. Potential of Integrated Emissions Reduction Systems in a Firewood Stove under Real Life Operation Conditions. *Energy Fuels* 31, 7562–7571.

Wohter, D., Feikus, L., Quicker, P., 2022. Reduction of PAH by the Use of Electrostatic Precipitators at different Positions in the Exhaust... - RWTH AACHEN UNIVERSITY TEER - Deutsch, https://www.nanoparticles.ch/archive/2022_Wohter_PR.pdf.

Appendix A1

German market overview of approved particles separators for small-scale wood log appliances

Table 3: Approved devices according to the German Institute for Building Technology (DIBt) and manufacturers' information, Status 28.11.2022

Product/model	Manufacturers	Application, performance up to [kW]	Effect principle	Admission number
AIRJEKT 1	Kutzner + Weber GmbH www.kutzner-weber.de	manually and automatically fed wooden firings up to 100 kW	electrostatic separator	Z-7.4-3442
AIRJEKT 1 version 2.0	Kutzner + Weber GmbH www.kutzner-weber.de	manually and automatically fed wooden firings up to 100 kW	electrostatic separator	Z-7.4-3442
AIRJEKT 25	Kutzner + Weber GmbH www.kutzner-weber.de	manually and automatically fed wooden firings up to 100 kW	electrostatic separator	Z-7.4-3535
CCA-Mini 20 kW	CCA Carola Clean Air GmbH www.carola-clean-air.com	Biomass plants from 4 to 20 kW	electrostatic separator	Z-7.4-3537
ETA EP for boiler series ePE 7-20 kW	ETA Heiztechnik GmbH www.eta.co.at	Wood firing ETA ePE 7 - 20 kW	electrostatic separator	
ETA EP for boiler series ePE BW 8-14 kW	ETA Heiztechnik GmbH www.eta.co.at	Wood firing ETA ePE BW 8-14 kW	electrostatic separator	
ETA EP for boiler series ePE BW 16-22 kW	ETA Heiztechnik GmbH www.eta.co.at	Wood firing ETA ePE BW 16-22 kW	electrostatic separator	
ETA EP for boiler series eHack or ePE-K 20-50 kW	ETA Heiztechnik GmbH www.eta.co.at	Wood firing ETA eHack or ePE-K 20-50 kW	electrostatic separator	
ESP-10	exodraft a/s www.exodraft.de	Wood firing 10 kW	electrostatic separator	Z-7.4-3536
EC filter 24	Guntamatic Heiztechnik GmbH www.guntamatic.com	Biomass plants up to 24 kW	electrostatic separator	
EC filter 24 P	Guntamatic Heiztechnik GmbH www.guntamatic.com	Biomass plants up to 24 kW	electrostatic separator	

Fireclean	Hark GmbH & Co. KG www.hark.de	Single occupancy / multiple occupancy	electrostatic separator	Z-7.4-3544
	Fireplace and tiled stove	Hand-held and automatically fed room air-dependent or room air-independent closed fireplaces up to 100 kW Nominated heat output for fuel wood for exhaust pipes Ø 130-250		
Fireclean version 2.0	Hark GmbH & Co. KG www.hark.de	Single occupancy / multiple occupancy	electrostatic separator	Z-7.4-3544
	Fireplace and tiled stove	Hand-held and automatically fed room air-dependent or room air-independent closed fireplaces up to 100 kW Nominated heat output for fuel wood for exhaust pipes Ø 130-250		
Future-Refine Ceramic	Karl Schröder Nachf. www.schraeder.com	Wooden firings up to 50 kW	Electrostatic separator / cleaning by the chimney sweep	
Future-Refine	Karl Schröder Nachf. www.schraeder.com	Wooden firings up to 50 kW	Electrostatic separator / cleaning by the chimney sweep	
Future Refine PTI	Karl Schröder Nachf. www.schraeder.com	Wooden firings up to 50 kW	Electrostatic separator / dry cleaning due to manual extraction	
HDG FF-E 40	HDG Bavaria GmbH www.hdg-bavaria.com	Biomass plants up to 40 kW	electrostatic separator	
Heizoclean EF 185	Heizomat GmbH www.heizomat.de	Wood firing	electrostatic separator	
Heizoclean OS 200	Heizomat GmbH www.heizomat.de	Wood firing	electrostatic separator	
Hoval Electrofilter OT-I	Hoval AG www.hoval.de	Wood pellets firing up to 43 kW	electrostatic separator	Z-7.4-3451

Fireplace FILTERCat	Vitesco Technology GmbH www.vitesco-technologies.com	Wood firing 6-10 kW	electrostatic separator	Z-7.4-3549
Fireplace FILTERCat	Bluekat Technologie GmbH www.bluekat24.de	Wood firing 6-10 kW	Particulate filter and oxidation of CO, HC (catalytic)	Z-7.4-3550
NW100 8-12 kW, exhaust gas separator	Viessmann Works www.viessmann.de	Wood firing up to 25 kW	electrostatic separator	Z-7.4-3451
NW130 18-24 kW, exhaust gas separator	Viessmann Works www.viessmann.de	Wood firing up to 25 kW	electrostatic separator	Z-7.4-3451
NW150 32-48 kW, exhaust gas particle separator	Viessmann Works www.viessmann.de	Wooden firings up to 50 kW	electrostatic separator	Z-7.4-3451
OekoTube-Outside OT2	OekoSolve AG www.oekosolve.com	Wooden firings up to 50 kW	electrostatic separator	Z-7.4-3451
Oekotube Inside DN130	Windhager central heating www.windhager.com	Hand-skilled wood firings up to 50 kW and automatically fed biomass plants up to 100 kW	electrostatic separator	Z-7.4-3451
Oekotube Inside DN150	Windhager central heating www.windhager.com	Hand-skilled wood firings up to 50 kW and automatically fed biomass plants up to 100 kW	electrostatic separator	Z-7.4-3451
Oekotube Inside DN180	Windhager central heating www.windhager.com	Hand-skilled wood firings up to 50 kW and automatically fed biomass plants up to 100 kW	electrostatic separator	Z-7.4-3451
Zumikron	Kutzner + Weber GmbH www.kutzner-weber.de	Wooden firing up to 100 kW	electrostatic separator	Z-7.4-3545

Appendix A2

Manufacturers in EU, offering ACC

Table 4: Manufacturers in EU, offering ACC and approx. price

Brand	Model/Series	Automation Technology	Key Features	Price (EUR)	Availability Info	Official Link	Automation Level
RIKA	Fox II, LOOK, SWING, ALPHA II	RIKATRONIC4	Fully automatic ignition, programmable start, sensor-controlled combustion, Eco mode	2950	Available via Kindel Heating and other EU retailers	https://www.rika.eu/stoves/woodburning	Full electronic
Scan	Scan 67 Series (1300, 1600, 1000)	Zensoric	Sensor-based airflow control, USB-C rechargeable, clean glass, reduced emissions	3104	Available via Auldton Stoves and other EU retailers	https://www.scan-stoves.com/zensoric	Full electronic
Aduro	Aduro 1, 9, 15, 17, 22 series	Aduro-tronic	Automatic primary air regulation, up to 40% wood savings, reduced emissions	1739 - 2279	Available via StovesAreUs and other EU retailers	https://www.adurofire.com/aduro-stoves/stoves/	Full electronic
Kratki	K9	ASDP	Automatic air supply control, cast iron body, Ecodesign certified	910	Available via Kratki.com and other EU retailers	https://kratki.com/en/wood-burning-cast-iron-stove-kratki-k9-automatic-air-control-0-150-10-kw-5535	Semi-automatic
Contura	Connect 556	Contura Connect App	App-controlled, automatic air regulation, notifications, overheat protection	3950	Available via Shire Stoves and other EU retailers	https://www.contura.eu/en-gb/stove-collection/stove-series/contura-connect-556	Full electronic
Dik Geurts	Vidar Triple (Small, Medium, Large)	DG Smart Assist	App-controlled air slider, notifications, efficient combustion	3030 - 3306	Available via Stove Supermarket and Direct Stoves	https://www.drufire.com/en-gb/about-dru/innovations/dg-smart-assist	Full electronic

Hwam	5230, 3630, 3120, 5530	Autopilot & IHS	Bimetal spring regulation, SmartControl app, eco-friendly combustion	Request Quote	Available via Arcade Wales and Stove Yard	https://www.hwam.com/advantages/hwam-autopilot	Semi-automatic
AirSmart	AirSmart Boiler Stove Controller	AirSmart Controller	Electronic damper, temperature probe, safety shutdown, vent control	635 - 735	Available via Stovesonline and Firepower Heating	https://www.stovesonline.co.uk/airsmart-boiler-stove-controller	Only electronics, no stove
Timpex spol. s r.o.	TimNet, ECO, REG	Electronic damper controlled by flue gas temperature		€375	https://timpex.eu/kde-koupit/	https://timpex.eu/kde-koupit/	Somewhat simpler and less effective than the specialized integrated ones from each specific stove manufacturer
Otter	Otter Stove Control	Mechanical Flue Sensor	Direct flue temperature sensing, automatic airflow adjustment, robust design	Request Quote	Available via Otter Stove Controls	https://www.otterstovecontrols.com/	Manual assist
Xeos	X5-Series, X8-Series, Special Editions	TwinFire System	Dual combustion chambers, manual lever for TwinFire, 93% efficiency	2999 - 4699	Available via Hagebau and Xeos dealers	https://xeos.de	Manual assist
Wodtke	Sun, Moon, Hot Box 2000	Automatic air combustion control	Automatic air supply, ash removal, optional auto-cleaning	2300 - 4600	Available via Wodtke and appliance retailers	https://www.wodtke.com/en	Semi-automatic
Skantherm	Turn, Emotion S/M, Elements	Advanced combustion design	Rotating body, external air supply, modular design	3270 - 5200	Available via StovesOnline and Tulipalo	https://www.skantherm.de	Manual assist
Schiedel	SIRIUS 1.1 / 3.1, SARGAS	Smart Home Integration (optional)	Self-closing doors, clean burning, optional smart features	2095 - 2501	Available via Eco Fire Centres and Schiedel dealers	https://www.schiedel.com/en-nl/products/stoves	Semi-automatic
DROOFF Kaminöfen	APRICA 2, Garda, Varese, Brunello	fire+ combustion control	Electronic air regulation, Blue Angel certified, catalyst	3000+	Available via DROOFF and Blauer Engel partners	https://www.drooff-kaminofen.de/en	Full electronic
Jøtul	F 170, F 360 Advance, F 500 ECO	Zensoric (on select models)	Automatic draft control, refuel alerts, high efficiency	2500 - 4500	Available via Jøtul and Stove Supermarket	https://www.jotul.com/products/wood-stoves	Semi-automatic
Brunner	Most models, both tiled stoves and fireplaces	Electronic stove control EOS 8, EAS 3	Automatic draft control, refuel alerts, high efficiency		Available via selected appliance retailers	https://www.brunner.com/en	Full electronic

Appendix A3

ACC, ESP and Catalyst technologies - Indicative performance ranges compiled by GPT v5

Indicative performance ranges are compiled from peer-reviewed studies, technical guidelines and product documentation. For combined options, overall reduction is calculated as sequential residual removal: Combined = 1 - (1 - A)x(1 - B). Values will vary with stove design, fuel, operation and installation. See references [1-15], at the end of A3.

Table 5: Comparison of ACC, ESP and Catalyst, including combined options

Technology	PM reduction	CO reduction	OGC reduction	Efficiency impact	Maturity & availability	Approx. cost
ACC (automatic air control)	≈30–60% [1,2,3]	≈30–50% [1]	≈30–50% [1]	Often +5–10% (steadier combustion) [1,4]	Built into many modern stoves (Quadra-Fire ACC, Aduro-tronic, Scan Zensoric) [4–6]	Integrated in stove price (ACC-equipped models ≈\$2.6k–\$3.9k) [7,8]
ESP (electrostatic precipitator)	≈70–95% [9–11]	~0% [1]	~0% [1]	Neutral [9]	Commercial retrofits (OekoTube, Airjekt 1) [9,11]	≈€1,900–€2,700 device + install [10,12,13]
Oxidation catalyst (internal/retrofit)	≈30–66% (mass) [14]	≈60–87% [14]	≈20–80% (esp. WSCOC/PAHs) [14]	Often +5–10% (smoke oxidation) [15]	Catalytic stoves & retrofits available [1,15]	Retrofit ≈€400+; replacements \$100–\$700 [16,13]
ACC + ESP	≈92% (from residuals) [1,9]	≈40% (from ACC) [1]	≈40% (from ACC) [1]	Like ACC; ESP neutral [1,9]	Mature combo [1,9]	Sum of above
ACC + Catalyst	≈73% (from residuals) [1,14]	≈85% (from residuals) [1,14]	≈70% (from residuals) [1,14]	Often higher than ACC alone [15]	Mature combo [1,14,15]	Sum of above
ESP + Catalyst	ESP for PM + Catalyst for gases; recommended combined mitigation [3,14,17]	Strong (via catalyst) [14]	Strong (via catalyst) [14]	Neutral to slight increase	Widely feasible (retrofits) [9,11,14,17]	Sum of above

Lifetime & maintenance

ACC (automatic air control)

What to expect: Stabilizes combustion across phases, reducing user error. [1,3,4]

Lifetime: Integrated in appliance; no consumables. [4–6]

Maintenance: Keep air paths clean and use dry wood; primary measures first. [1,3]

ESP (electrostatic precipitator)

What to expect: Large PM mass reduction (~80–85% typical in field), minimal effect on gases. [9,11]

Lifetime: No sacrificial media; periodic cleaning prevents efficiency drop. [11]

Maintenance: Clean during chimney sweeping; requires 230V and weather protection for rooftop units. [9]

Oxidation catalyst

What to expect: Very strong CO and WSCOC/PAH reduction; PM mass also reduced in studies. [14]

Lifetime: Catalyst deactivates over time (fouling/thermal shock); typical replacement ~6 years. [16]

Maintenance: Use seasoned wood; avoid painted/treated fuels. Many retrofits include a bypass for lighting/refueling. [15]

Appendix 3 - references

[1] IEA Bioenergy Task 32. "Design of Low Emission Wood Stoves – Technical Guidelines" (Oct 2022). https://www.ieabioenergy.com/wp-content/uploads/2022/11/IEA-Bioenergy-Task-32_Report-D1-2_Low-emission-wood-stove-design_final.pdf (accessed 2025-09-19).

[2] IEA Bioenergy. "Technical Guidelines for the Design of Low Emission Wood Stoves" (Nov 2022). <https://www.ieabioenergy.com/blog/publications/technical-guidelines-for-the-design-of-low-emission-wood-stoves/> (accessed 2025-09-19).

[3] TFZ / BIOS et al. "Guidelines for Low Emission and High Efficiency Stove Concepts" (WoodStoves2020, 2017). https://www.tfz.bayern.de/mam/cms08/en/dateien/stoves2020-guidelines_low_emission_concepts.pdf (accessed 2025-09-19).

[4] Quadra-Fire. "Automatic Combustion Control (ACC)" overview. <https://forgenflame.com/pages/quadra-fire-key-technologies-automatic-combustion-control> (accessed 2025-09-19).

[5] Aduro A/S. "Aduro-tronic automatic air regulation". <https://www.adurofire.com/aduro-stoves/aduro-tronic-automatic/> (accessed 2025-09-19).

[6] Scan Stoves. "Zensoric automatic air regulation for wood stoves". <https://www.scan-stoves.com/zensoric> (accessed 2025-09-19).

[7] Quadra-Fire 4300 Step Top – retailer page with pricing. <https://woodheat.com/stoves/wood-stoves/quadra-fire-4300-step-top> (accessed 2025-09-19).

[8] Quadra-Fire 5700 Step Top – manufacturer pricing overview. <https://forgenflame.com/products/quadra-fire-5700-step-top-wood-stove> (accessed 2025-09-19).

- [9] OekoSolve. "OekoTube – Electrostatic filter for wood burning stoves". <https://oekosolve.com/en/products/esp-for-lounge-wood-heating/oekotube/> (accessed 2025-09-19).
- [10] OekoTube price list (2023). https://www.zyndikuss.com/wp-content/uploads/2023/10/202304_Preisliste-OekoTube-Outside_EUR_DE.pdf (accessed 2025-09-19).
- [11] TFZ Merkblatt (July 2025). "Precipitation efficiency of an electrostatic precipitator under real life conditions during two heating periods". <https://www.tfz.bayern.de/publikationen/merkblaetter/384347/index.php> (accessed 2025-09-19).
- [12] Kutzner + Weber Airjekt 1 – price listings. <https://www.idealo.de/preisvergleich/Liste/120752098/airjekt-1-von-kutzner-weber.html> (accessed 2025-09-19).
- [13] Schornsteinmarkt / Feuerdepot shop listings (examples for ESP and components). <https://www.feuerdepot.de/partikelabscheider/feinstaubabscheider-airjekt-1-outdoor-top-mit-wetterschutzkasten-kutzner-und-weber/> (accessed 2025-09-19).
- [14] Laboureur, M. et al. "Abatement of Emissions of a Residential Wood Stove: Effect of the Catalyst ..." ACS Omega (June 11, 2025). <https://pubs.acs.org/doi/pdf/10.1021/acsomega.5c00854> (accessed 2025-09-19).
- [15] Applied Ceramics. "Benefits to Using a Catalytic Woodstove" (product/technical overview). <https://appliedceramics.com/products/hearth-products/benefits-to-using-a-catalytic-woodstove> (accessed 2025-09-19).

About this publication

Nordsyn ecodesign task 2 report: Analysis of technical measures to reduce emissions from solid fuel space heaters

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© Nordic Energy Research 2025

<http://dx.doi.org/10.6027/NER2025-07>

Cover photo: Getty Images

Published: October 2025

Acknowledgements

The authors acknowledge the financial support of Nordic Energy Research.

Nordic Energy Research

Nordic Energy Research is the Nordic institution for joint energy research and research-based policy development, under the Nordic Council of Ministers. www.nordicenergy.org