Advanced Test Methods for Firewood Stoves

Report on consequences of real-life operation on stove performance

Flaming combustion phase of a wood log in a firewood stove. Photo: Bioenergy2020+

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Summary

Biomass room heating appliances are the most commonly used technology for providing renewable heat in residential buildings. They are categorized in different technologies by harmonized European standards (e.g. firewood room heaters – EN 13240, insets and open fireplaces – EN 13229, biomass cookers – EN 12815, slow heat release appliances – EN 15250). Those standards contain specific testing procedures which aim to guarantee a minimum emission and efficiency performance as well as safe operation for the end-user. Each type of product has to be tested before market introduction.

For firewood room heaters, which represent the majority of the stock of the room heating appliances installed in the field as well as in numbers of yearly sold products, the official type test (oTT) method is defined in the standard EN 13240. The testing procedure evaluates the stove performance regarding emissions and thermal efficiency only under well-defined conditions. This enables a high reliability of test results, but leads to test results which are usually out of reach in real-life operation. However, since emission limit values (ELVs) are correlated with the oTT method, technological development focuses on achieving the best oTT results instead of customer needs. That is for example robust real-life performance with high efficiency, low emissions and a low error-proneness.

The situation of air pollution in correlation to stove performances was critically evaluated in many studies. As a consequence the ELVs of oTT results were tightened in the last years in many European countries. In the year 2022, the ELVs of the new ecodesign and ecolabelling directive will come into force and will set a general benchmark regarding emissions and efficiency. However, also those ELVs focus on the testing procedure of the EN standards. Therefore, it can be assumed that the effect of meliorating air pollution will still be limited.

In this study an overview of the most important test methods worldwide is presented. The major differences regarding the testing procedure and applied measuring methods are presented. In different scientific studies test protocols which should better reflect real-life operation were applied, for example to investigate emission factors for different stove technologies. In this study those test procedures (e.g. the beReal test protocol) are presented and the emission and efficiency results are compared with oTT results, results of field tests and proposed emission factors.

The comparison of field test results showed by tendency a technological improvement of firewood stoves over the last decades. But in comparison with oTT results improvements are significantly higher. Furthermore, retests of serial-production stoves according to the EN 13240 standard showed much higher emissions and lower efficiency results compared to oTT results of the respective stove models. The beReal test concept showed a good conformity of test results in the lab compared to test results in the field. However, the thermal efficiency is still overestimated by the test stand results compared to field test results.

Comparing the field test results of advanced stoves with the proposed emission factors a good conformity for CO and PM emissions is evident. However, for OGC emissions it seems that the EEA (European Environment Agency) emission factor for advanced stoves is too high (by a factor of 2).

Concluding, an implementation of a real-life reflecting test protocol (e.g. beReal) as a quality label or standard should be considered as an instrument to push technological development further towards optimized real-life operation. Additionally, this would also enable a better differentiation of good and poor products for the end customer regarding typical real-life use.

The use of a real-life oriented test protocol (as in beReal) for determination of emission factors seems possible, but needs further investigations. The standardized measurement of emission factors according to a suitable test concept could be used for a regular update of emission inventories.

Key Findings

Testing conditions of current European standards (EN) evaluating emissions and thermal efficiency of firewood room heating appliances are well controlled and provide the basis for optimal test results for the tested appliance.

A major difference of the EN type test standards compared to international standards is that in most cases only nominal load is evaluated whereas for example Canadian or US test protocols evaluate the performance of the appliances at several load settings. A further essential difference is the definition of how much fuel is used for one batch. According to several international standards the combustion chamber volume defines the mass of wood whereas according to the EN standard the fuel mass can be defined by the manufacturer.

Comparing the different test protocols there are three fundamental different approaches for measuring particulate matter emissions (PM):

- Sampling of particles on a heated filter in hot and undiluted flue gas
- Sampling of particles on a filter in cold and diluted flue gas
- Sampling of particles with an electrostatic precipitator in cold and diluted flue gas

For these three methods there are different ELVs defined in the ecodesign requirements. It can be assumed that this could result in an impossibility of comparability of test results. There is a need to define a commonly used PM measurement method in Europe which is currently developed.

The comparison of field test results showed a tendency of technological improvement of firewood stoves over the last decades.

Comparing the field test results of advanced stoves with the proposed emission factors it seems that the emission factor proposed by the European Environment Agency (EEA) for OGC emissions of advanced stoves is too high (by a factor of 2).

The comparison of official type test (oTT) results with field tests confirmed that typical real-life heating operation results in significantly higher emissions and lower efficiencies.

The oTT results were not reproducible with serial-production stoves in comprehensive lab tests. The implementation of a market surveillance concept is suggested as an effective measure to guarantee a constant product quality of sold devices.

The new ecodesign requirements will set an equal benchmark for new stove technologies all over Europe. However, the effect towards improving the real-life situation is limited since the new requirements still refer to the official type test results.

Real-life oriented test concepts (e.g. beReal) are capable to better reflect real-life performance of the appliances compared to existing EN standards. An implementation of a real-life oriented test protocol as a quality label or standard should be considered as an instrument to push technological development towards optimized real-life operation and to enable a better differentiation of good and poor products for the end customer.

The utilization of a real-life oriented test protocol (e.g. the beReal test protocol) for determination of emission factors seems possible, but needs further investigations. A standardized measurement of emission factors according to a suitable test concept could be used for a regular update of immission inventories and to update and evaluate the progress of technological development.

1 Introduction

Harmonized European standards (EN) for type testing, which evaluate the combustion performance of new products before market introduction, have clearly driven the technological development of biomass small-scale heating appliances towards low emissions and high efficiency in the last decades [1].

In general, testing of new products shall guarantee a minimum of product quality concerning operation performance and safety aspects. Testing conditions and procedures shall be well-defined and transparent in order to offer equal opportunities for manufacturers.

In real-life operation efficiency and emissions depend on the whole heating system which can be categorized in the three main components – the appliance, the chimney and the user (**Figure 1**).

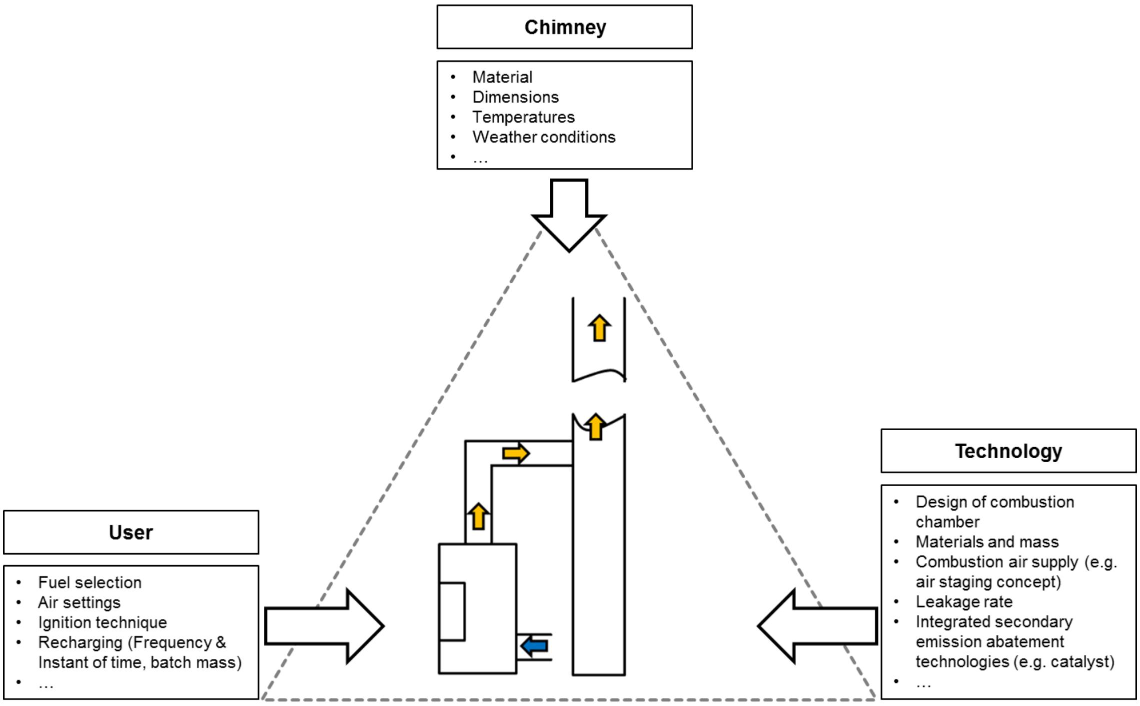


Figure 1: Components for a heating system of firewood stove in real-life operation

The official type test (oTT) methods for firewood stoves, as defined by the EN standards (see 2.1.5), typically evaluate the appliance performance only at nominal load. However, the ignition of the first fuel batch and the heating-up of the stove is not considered, except for the testing procedure for slow heat release appliances (EN 15250). Generally, ignition, different loads, load changes and the cooling down phase are not included in the evaluation of EN test protocols. Consequently, testing according to EN test protocols in a nearly steady-state operation mode and thermal equilibrium leads to best possible emission and efficiency results and should be highly repeatable. However, operating conditions referring to typical user behaviour and transient conditions, like ignition, heating-up and cooling down, which occur in each heating operation in real-life, are not evaluated.

This leads to oTT results of low emissions and a high thermal efficiency. However, those results are never reached during real-life operation [2] [3]. In addition, the differentiation of product qualities concerning emissions and thermal efficiency which refer mainly to transient operating conditions and user related aspects is poor. Consequently, customers have insufficient information about real-life performance for their buying decision. Furthermore, legal authorities cannot ensure the desired effect of reduced emissions and increased efficiency in the field by tightening emission limit values (ELVs) which refers to oTT results.

Consequently, there is a need to find suitable test concepts which evaluate firewood stoves closer to real-life operation in order to support low emission and high efficiency technologies, not only on the test stand under well controlled steady-state conditions, but also during typical daily heating operation.

The objective of this study is to provide an overview of the most relevant international and European standards and to compare the test procedures regarding important differences. Furthermore, new test concepts for firewood stoves are presented which aim at an evaluation of real-life performance of the appliances. The real-life relevance is evaluated by comparing lab test with field test results. Furthermore, an evaluation of real-life relevance by comparing those data with proposed emission factors is conducted.

The main focus of this study refers to biomass roomheaters, which are tested according to the standard EN 13240. They represent the majority of biomass room heating appliances in the field and are also the most frequently sold type of firewood stove in Europe [4] [5]. Pellet stoves are not included in this study.

2 Testing of appliances

2.1 Overview of existing test standards

In the following chapter an overview of existing International and European standards for type testing of firewood stoves is presented. The findings are based on reviewing the standards itself or reviewing available literature about the standards.

In detail, the research focused on following parameters:

- Fuel characteristics (e.g. fuel species, fuel dimensions, moisture content of fuel)
- Operating conditions (e.g. draught conditions, room temperatures)
- Testing procedure (e.g. fuel loads, fuel charge, burn rates)
- Measurement methods evaluating emissions and efficiency (e.g. PM measurement, thermal efficiency determination)

2.1.1 International draft/DIS 13336

For this international draft [6] a comparative study was done in 1999 by GAEGAUF & MACQUAT [7]. In the frame of this study the ISO/DIS 13336 was compared with the CEN/prEN 13240:1998. Therefore, the test facility was established according to the ISO/DIS 13336 standard using a calorimeter room and a full flow dilution tunnel for efficiency and emission determination. Additionally, a measurement section for emission and efficiency determination according to the prEN 13240 standard was integrated in the test facility. **Figure 2** presents the test facility according to ISO/DIS 13336 standard.

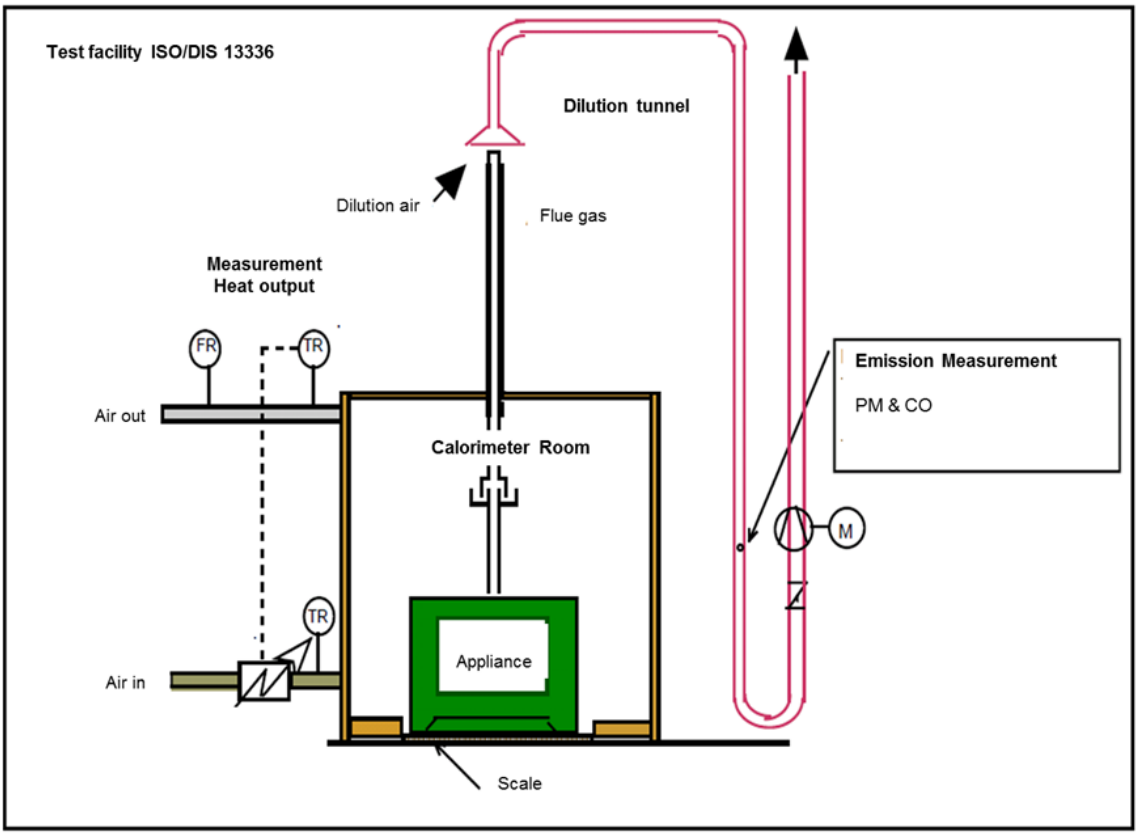


Figure 2: Test facility according to the draft version of ISO/DIS 13336 standard. Source: GAEGAUF & MARCQUAT [7]

The main characteristics of the testing procedure of ISO/DIS 13336 are:

- Calculation of the fuel mass according to the volume of the combustion chamber (20% of the available combustion chamber volume is loaded)
- Firewood without bark is used
- Testing is started after an ignition batch when the mass of basic firebed is 25 wt.-% of first fuel batch
- Test of three burn rates using three batches for each burn rate
    - Minimum burn rate – Adjustment with damper settings after 20 wt.-% of batch mass is consumed
    - Maximum burn rate – No change of damper settings
    - Medium burn rate – Adjustment with damper settings after 20 wt.-% of batch mass is consumed
- Direct efficiency determination via the released heat to surroundings using a calorimeter room
- Natural draft conditions induced by a chimney with a total height of 4.6 m
- Emission measurements are carried out in diluted flue gas (CO, TSP)

The comparative study of GAEGAUF & MACQUAT showed similar results of both methods (ISO/DIS 13336 and CEN/prEN 13240) regarding emissions and efficiency. However, the testing according to DIS/ISO 13336 costs nearly twice as much as the testing according to CEN/prEN 13240 standard [7]. According to GRAS et al. the draft of this standard was not ratified [8].

2.1.2 Australian/ New Zealand Standards

For type testing of firewood room heating appliances according to the Australian/ New Zealand standards three standards are relevant:

- AS/NZS 4012:1999: Domestic solid fuel burning appliances – Method for determination of power output and efficiency [9]
- AS/NZS 4013:1999: Domestic solid fuel burning appliances – Method for determination of flue gas emission [10]
- AS/NZS 4014:1999: Domestic solid fuel burning appliances – Test fuels [11]
    - 4014.1-Hardwood
    - 4014.2-Softwood

The test methods as well as the test procedures of the Australian/ New Zealand standards correspond predominantly to the draft of the ISO/DIS 13336 standard. The test methods apply to domestic solid fuel burning appliances including two types of technology:

1. Space-heating appliances
2. Space-heating appliances that include water-heating devices

The standards do neither apply to masonry, central heating, cooking appliances nor appliances intended solely for water heating.

The main characteristics of the testing procedure of AS/NZS 4012:1999 are:

- Calculation of the fuel mass according to the volume of the combustion chamber (16.5% of available combustion chamber volume is defined as “test fuel load nominal volume”)
- Firewood without bark is used (hardwood & softwood allowed)
    - Length of firewood pieces calculated according to the firebox dimensions
    - Cross section of each firewood piece is defined (> 75 mm & < 110 mm)

- Number of firewood pieces has to be calculated according to the combustion chamber dimensions

- Testing is started after an ignition batch. The basic firebed has to be between 24 wt.-% to 26 wt.-% of first fuel batch
- Test of three burn rates using (at least) three batches for each burn rate
  - Low burn rate – Adjustment with damper settings after 20 wt.-% of batch mass is consumed
  - High burn rate – No change of damper settings, damper settings are fully open
  - Medium burn rate - Adjustment with damper settings after 20 wt.-% of batch mass is consumed
- Consecutive tests for each burn rate are not obligatory
- A test batch is terminated when mass balance is reached (fuel load is consumed to within ±0.5 wt.-% of the test fuel load)
- Direct efficiency determination via the released heat to surroundings using a calorimeter room
- Natural draft conditions induced by an effective chimney height of 4.6 m
- Particulate emission measurements in diluted flue gas

Figure 2 shows the test facility according to AS/NZ 4013:1999.

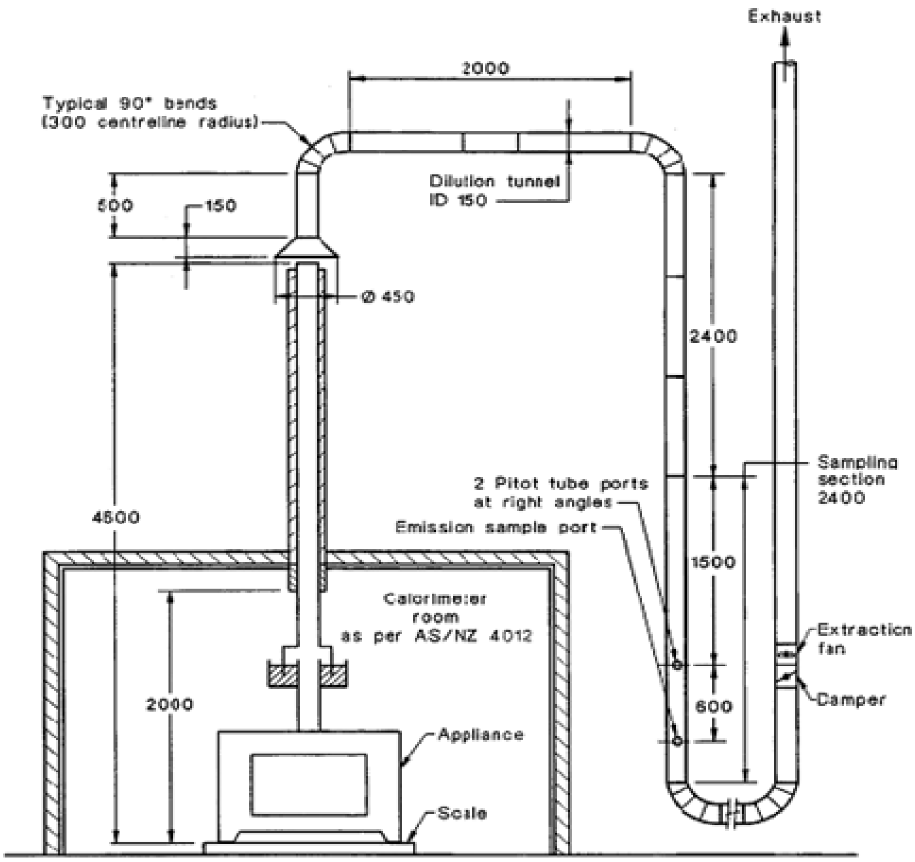


Figure 3: Scheme of test facility according to AS/NZS 4013:1999.
Source: GRAS et al. [8]

The requirements regarding maximum allowable particulate emission factors are 4.0 g/kg_{fuel} for appliances without a catalytic combustor and 2.25 g/kg_{fuel} for appliances with a catalytic combustor.

2.1.3 British recommendations for testing

The relevant document for testing of biomass room heating appliances regarding PM emissions in Great Britain is the PD 6434 – "*Recommendations for the Design and the Testing of Smoke Reducing Solid Fuel Burning Domestic Appliances*" [12]. PD 6434 adopts the BS 3841-1:1994 and BS 3841-2:1994 for "*Determination of smoke emission from manufactured solid fuels for domestic use*" [13].

The testing is done at several burn rates – high, medium and low burn rates. The appliance is operated according to the specifications given by the manual of the manufacturer. Also some tests under off-specification conditions according to the PD 6434 are performed (e.g. combustion chamber door is left ajar). For the measurement of particulate matter emissions an electrostatic precipitator is used. Additionally, the optical density of the smoke is also monitored by a suitable measurement device, working across the chimney. **Figure 4** shows the construction of the electrostatic precipitator.

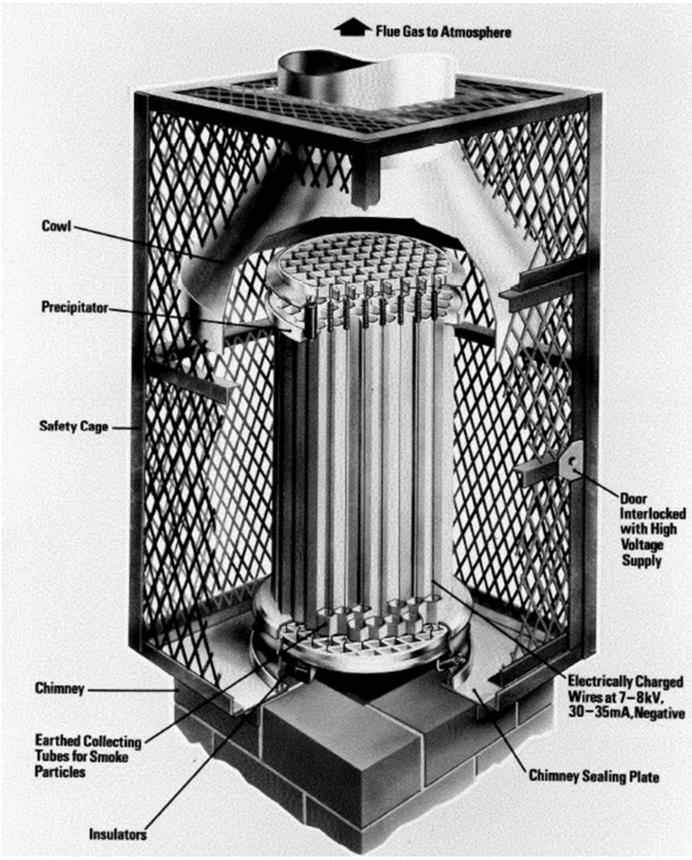


Figure 4: Cross section of the electrostatic precipitator
Source: GASTEC at CRE Ltd. (LOT15) [14]

For testing five repetitive tests are performed at each burn rate. The thermal heat output of the appliance over each test period is determined and the average is reported in kW. The particulate matter emissions are calculated by the mass of the collected particles. For this the precipitator is weighed on a suitable balance at the beginning and at the end of each test period.

The particulate matter emission is expressed in grams per hour over the duration of the test period. The mean result of replicate measurements is compared with the maximum emission limit of 5 g/h.

Additionally to the limits of the particulate emissions the optical density of the smoke, as recorded throughout each test, is examined to check to be within acceptable limits. The emissions over short periods (e.g. times of refuelling or de-ashing) should not reach unacceptable high levels. However, if the tests confirm that the appliance can operate continuously without undue trouble to the user then ignition smoke is ignored [14].

2.1.4 Canadian Standard

The Canadian testing procedure of biomass room heating appliances is defined in the CSA B415.1-10:2010 standard: "*Performance Testing of solid-fuel-burning heating appliances*" [15]. This standard defines the determination of the heat output, the measurement of emissions and efficiency and the measurement of the flue gas flow rates.

The CSA B415.1-10:2010 standard applies to manually and automatically fuelled stoves and fireplace inserts with a burn rate less than 5 kg/h. The CSA B415.1-10:2010 applies also to hydronic heaters and furnaces below 150 kW output. Not included in this standard are site-built masonry fireplaces and heaters as well as factory built fireplaces with a minimum burn rate greater than or equal to 5 kg/h. The CSA B415.1-10.2010 is consistent to the test method US EPA Method 28, PM test method 5G. This means that particulate emissions are determined by the use of a full flow dilution tunnel. The test scheme facility is presented in **Figure 5.**

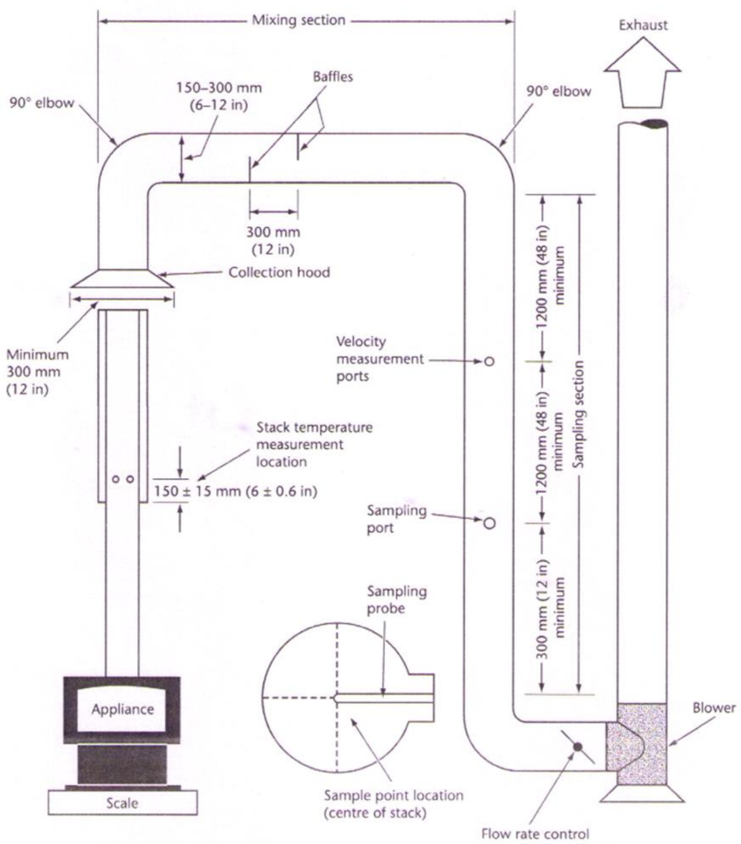
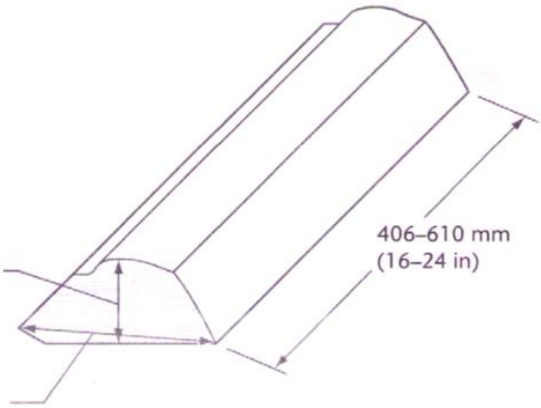


Figure 5: Scheme of test facility for solid-burning appliances according to CSA B415-1:2010
Source: CSA B415-1:2010 [15]

The PM sampling is done over the whole batch duration of the single burn rate categories. The appliances are tested in four different burn rates defined either in kg/h or in percent of nominal heat load. At least one test in each category/ burn rate has to be performed:

- Category 1: < 35% of nominal load
- Category 2: ≥ 35% and ≤ 53% of nominal load
- Category 3: 53% to 76% of nominal load
- Category 4: 100% (nominal load)

A test run starts after an ignition and preheating period. The burn rate is adjusted by the air supply settings. As test fuel either squared Douglas timber or firewood pieces are used. The fuel load is defined according to the volume of the combustion chamber and fuel density. For firewood the fuel density is defined at 162 kg/m³, for squared Douglas timber at 112 ± 11.2 kg/m³. The moisture content of the used firewood must be in a range between 18% and 28% (dry basis). **Figure 6** presents the specifications of the used firewood.



Firebox volume, m^3 (ft^3)	Cross-section of piece, mm (in) Minimum	Maximum	Minimum weight of piece, kg (lb)	Maximum weight of piece, kg (lb)	80% piece weight range, kg (lb)	Number of pieces
< 0.11 (< 4)	51 (2)	152 (6)	1 (2.2)	6 (13.2)	1.5–5 (3–11)	4–7
≥ 0.11 and < 0.28 (≥ 4 and < 10)	64 (2.5)	203 (8)	2 (4.4)	8 (17.6)	3–7 (6.7–15.5)	5–10
≥ 0.28 and < 0.56 (≥ 10 and < 20)	76 (3)	254 (10)	3 (6.7)	10 (22)	4–9 (9–20)	8–15
≥ 0.56 (≥ 20)	76 (3)	305 (12)	4 (9)	12 (27)	4–10 (9–22)	> 12

Figure 6: Dimensions and specifications of firewood used as test fuel
Source: CSA B415-1:2010 [15]

In addition to the room and flue gas temperature also several temperatures on the surface of the appliance are measured. The flue gas concentrations of CO and CO_2 are measured over the whole test cycle.

The average PM emissions of the complete test are required to be ≤ 4.5 g/h for appliances without a catalyst. For appliances equipped with a catalyst the PM emissions have to be ≤ 2.5 g/h. The calculation of the average emissions is done according to a specific calculation method including the combustion tests of all burn rate categories. Additionally, the average CO emissions and the average efficiency including all tests are calculated. However, there are no limits set for CO as well as for the efficiency according to CSA B415.1-10:2010.

2.1.5 European Standards

The European EN standards are documents that have been ratified by the respective European standard organization. For biomass room heating appliances the EN standards are elaborated by the technical committee (TC) 295 of the European committee for standardization (CEN TC 295). There are several harmonized European standards for biomass room heating appliances that are operated with firewood:

- EN 13240: Roomheaters fired by solid fuel – Requirements and test methods [16]
- EN 12815: Residential cookers fired by solid fuel – Requirements and test methods [17]
- EN 15250: Slow heat release appliances fired by solid fuel – Requirements and test methods [18]
- EN 13229: Inset appliances including open fires fired by solid fuel – Requirements and test methods [19]
- EN 15821: Multi-firing sauna stoves fired by natural wood logs – Requirements and test methods [20]

These EN product standards include requirements concerning the design, manufacturing, construction, performance (efficiency and CO emissions), safety, use instructions and identification. They also provide methods for appliance type testing evaluating emissions and thermal efficiency. The testing conditions as well as the requirements for test fuels are defined in these standards.

With the exception of slow heat release appliances (EN 15250) and sauna stoves (EN 15821) the performance testing is done after an ignition and preheating period of at least two batches. The tested appliance is representative for the current as well as for future products with identical construction. No significant changes at the respective stove model are allowed after type testing. For testing two or three test batches are necessary. As fuel firewood is used with moisture content between 12% and 20% of mass. For safety aspects relevant temperatures at the surface of the appliance are measured (e.g. at the handle of the door, temperatures at the wood storage space). The efficiency is determined indirectly by calculation of the thermal and chemical flue gas losses. The flue gas temperature used for indirect efficiency determination is measured by using a suction pyrometer. Additionally CO and O_2/ CO_2 are measured. According to the EN standards only minimum requirements respecting CO emissions and efficiency are defined. However, more stringent CO emission and efficiency limits as well as emission limit values regarding organic gaseous carbon (OGC), PM and nitrogen oxides (NO_x) of the EU Member States have to be taken into account.

In some cases national limits require testing of emissions and thermal efficiency at part load operation[1]. Generally, specific requirements which are not part of the harmonized EN standards are defined in national prefaces. In the following, the most relevant characteristics of performance testing procedure according to the respective EN standards for firewood room heating appliances are listed.

[1] Part load is only considered by national amendments, e.g. Austria requires measurements in part load which means at a maximum load of 50% of nominal load.

Testing Procedure of EN 13240:

- Constantly controlled flue gas draught of 12 ± 2 Pa
- Three test batches at nominal load (number of test batches is not limited; no consecutive test batches required)
- Start and stop of test batches at basic firebed (constant mass ± 50 g)
- Duration and requirements of test batch:
  - Intermittent burning appliance: at least 45 minutes
  - Continuous burning appliance: at least 90 minutes
  - No adjustment of combustion air supply
  - Difference of thermal heat output between the test batches < 10%
- Temperature measurements in the flue gas pipe with a suction pyrometer and surrounding temperature measurements at the test corner (wall, floor, bottom), room, wood storage tank and handle
- Emission requirements: CO <1 vol.-%
- Thermal efficiency requirements: ≥ 50%

Testing Procedure of EN 13229:

- Constantly controlled flue gas draught of 12 ± 2 Pa
- Two test batches at nominal load (number of test batches is not limited; no consecutive test batches required)
- Start and stop of test batches at basic firebed (constant mass ± 50 g)
- Duration and requirements of test batch:
  - Intermediate burning appliance at least 45 minutes
  - Continuous burning appliance: at least 60 minutes
  - Insets of tiled stoves: at least 70 to maximum 90 minutes
  - No adjustment of combustion air supply
  - Difference of thermal heat output between the test batches < 10%
- Temperature measurements in the flue gas pipe with a suction pyrometer and surrounding temperature measurements at the test corner (wall, floor, bottom), room, wood storage tank and handle
- Emission requirements:
  - Insets CO < 1 vol.-%
  - Insets of tiled stoves < 0.2 vol.-%
- Thermal efficiency requirements:
  - Insets ≥ 50%
  - Insets of tiled stoves ≥ 75%

Testing Procedure of EN 12815:

- Constantly controlled flue gas draught of 12 ± 2 Pa
- Two test batches at nominal load (number of test batches is not limited; no consecutive test batches required)
- Start and stop of test batches at basic firebed (constant mass ± 50 g)
- Duration and requirements of test batch:
  - At least 60 minutes
  - no adjustment of combustion air supply
  - Difference of thermal heat output between the test batches < 10%
- Temperature measurements in the flue gas pipe with a suction pyrometer and surrounding temperature measurements at the test corner (wall, floor, bottom), room, wood storage tank and handle
- Emission requirements: CO < 1 vol.-%
- Thermal efficiency requirements: ≥ 60%

Testing Procedure of EN 15250:

- Constantly controlled flue gas draught of 12 ± 2 Pa
- First fuel batch used for performance testin
- Second fuel batch used for efficiency determination
- Start of test batches from cold conditions (no ignition and preheating)
- Stop of test batch when CO_2 of flue gas measurements corresponds either to 4 vol.-% CO_2 or 25% of the maximum CO_2 peak of test batch (parameter which occurs later is valid)
- Duration of test batch:
  - Until the average envelope temperatures decreased to 50% of maximum surface temperatures (≥ 4h); temperatures are measured on the surface of the envelope of the appliance
  - Ignition according to manual or by using 500 g/ 10% of complete batch mass
- Temperature measurements in the flue gas pipe with a suction pyrometer (flue gas temperature: < 140°C to 160°C) and surrounding temperature measurements at the test corner (wall, floor, bottom), room, wood storage tank and operating devices
- Emission requirements: CO < 0.3 vol.-%
- Thermal efficiency requirements: ≥ 70% (at least two burn cycles)

Testing Procedure of EN 15821:

- Constantly controlled flue gas draught of 12 ± 2 Pa
- Number of test series according to manual, 90°C are necessary in the sauna
- Start of test batches from cold conditions (no ignition and preheating)
- Stop of test batches at CO_2 content of 4.0 vol.-% after performance of the number of test batches as specified in the manual
- Duration and requirements of test batch:
  - At least 30 minutes,
  - Defined sauna room have to be heated up to 90°C
- Temperature measurements in the flue gas pipe with a suction pyrometer and surrounding temperature measurements at the test corner (wall, floor, bottom) and operating devices
- Emission requirements: CO < 1 vol.-%
- Thermal efficiency requirements: ≥ 50% (at least two burn cycles)

prEN16510:2013

Regarding solid biomass room heating appliances new standards are under development. Currently, the new draft version prEN16510 is published and under final preparation. There are two parts of prEN 16510. In part 1 general requirements, the test methods as well as relevant calculations are defined. In part 2 the specifics for each type of technology are defined in single parts for each technology group.

The structure of EN 16510, "Residential solid fuel burning appliances", is as follows:

- Part 1: General requirements and test methods
- Part 2-1: Roomheaters
- Part 2-2: Inset appliances including open fires
- Part 2-3: Cookers
- Part 2-4: Independent boilers – Nominal heat output up to 50 kW
- Part 2-5: Slow heat release appliances

In the draft of prEN 16510-1:2013 measuring methods for determination of OGC, NO_x and PM emissions are provided. Procedures for measuring PM emissions either in hot and undiluted or in cold and diluted flue gases by using a full flow dilution tunnel are described. Further, a procedure for leakage rate determination of roomsealed appliances is given. Referring to the testing procedure the most relevant difference compared to the current standards is the permission for adjusting the air settings during the first three minutes of a test batch. Furthermore, the possibility to use a thermocouple centrally located in the measuring section instead of a suction pyrometer for flue gas temperature measurement is new.

2.1.6 Norwegian Standards

For type testing of firewood room heating appliances according to the Norwegian Standards two standards are relevant:

- NS 3058 (1994) – Enclosed wood heaters, Smoke emissions
  - Part 1: Test facility and heating pattern [26]
  - Part 2: Determination of particulate emission [27]
  - Part 3: Determination of organic micro contaminations (PAH) [28]
  - Part 4: Determination of the content of carbon monoxide (CO) and carbon dioxide (CO_2) in the flue gas [29]
- NS 3059 (1994) – Enclosed wood heaters, Smoke emissions, Requirements [30]

Solid fuel appliances are to be tested according to the Norwegian standards in four burn rate categories (**Table 1**). There are two grades in the single categories of burn rates. The grade that is used for a specific wood stove depends on the thermal output of the appliance. Stoves tested according Grade 1 can be operated with burn rates below 0.8 kg/h whereas appliances tested in burn categories of Grade 2 achieve the lowest burn rate between 0.8 kg/h and 1.25 kg/h.

Table 1: Burn rate categories (Average burn rates in kg/h)

	Burn rate category 1	Burn rate category 2	Burn rate category 3	Burn rate category 4
Grade 1	< 0.80	0.80 – 1.25	1.25 – 1.90	> 1.90
Grade 2	< 1.25	1.25 – 1.90	1.91 – 2.80	> 2.80

The mass of fuel for testing is determined according to the burning chamber volume and a specific fuel charge density that is defined to be between 101 kg/m³ and 123 kg/m³ (112 ± 11 kg/m³). As test fuel air dried squared wood of spruce has to be used with dimensions of 49 × 49 mm and moisture content between 16% to 20% of mass. The length of the firewood is derived from the obligatory fuel charge density. The space between the single wood logs is defined at 10 mm (**Figure 7**).

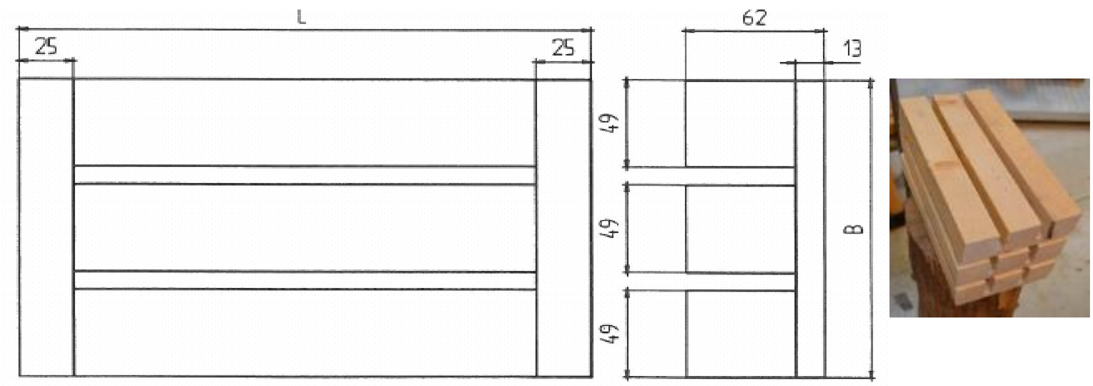
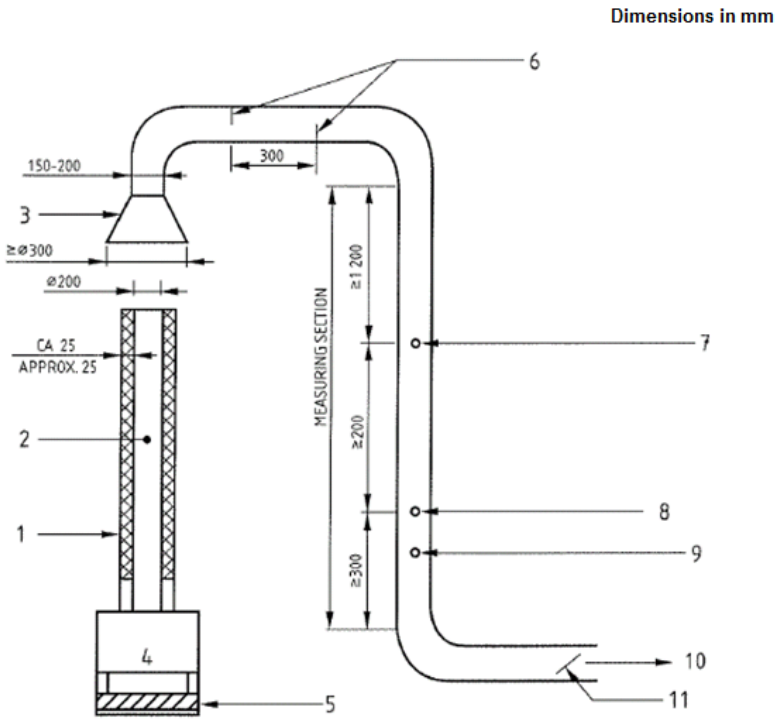


Figure 7: Arrangement of the standard test fuel (left) and example picture (right)
Source: left: NS 3058-1:1994 [26] ; right: example picture: [32]

The test runs are done from preheated wood heater. The average value of the surface temperatures may differ up to 70°C from the start to the end of the test run, but not more. During testing the particulate matter emissions are measured under diluted flue gas conditions. For this a test facility according to **Figure 8** is used.



Legend

1: Insulation
2: Chimney
3: Collection hood
4: Appliance
5: Scale
6: Baffles

7: Measurement flue gas velocity
8: PM & PAH measurement
9: CO- and CO_2 measurement
11: flap valve

Figure 8: Scheme of test facility according to the Norwegian testing standard NS 3058:1994-2
Source: NS 3058:1994-2 [27]

Based on the single measurements of each burn rate the PM emissions are calculated by a specific calculation mode. The requirements that have to be met are given for catalyst equipped and non-catalyst equipped wood heaters. **Table 2** shows the emission requirements for these both groups of appliances.

Table 2: Emission requirements of enclosed wood heaters according to the Norwegian test method

	Maximum allowable emission for one test	Maximum weighted mean value
Catalyst-equipped wood heaters	10 g/kg	5 g/kg
Non-catalyst wood heaters	20 g/kg	10 g/kg

2.1.7 United States Standards

The testing of wood stoves in the USA is done according to the requirements of the US EPA method 28 – "Certification and Auditing of wood heaters" [33]. Wood stove model lines that are certified meet the "*2015 Standards of Performance for New Residential Wood Heaters, New Residential Hydronic Heaters and Forced-Air Furnaces, Subpart AAA*". A US EPA certified wood heater has been independently tested by a US EPA accredited laboratory to determine if it meets the particulate emissions limit of 4.5 g/h for non-catalytic and catalytic heaters [34].

The EPA Method 28 establishes standard stove operating procedures that are used to measure PM emissions from a wood heater burning a prepared test fuel crib. Thereby air-dried squared Douglas timber with a moisture content of 16% to 20% of mass is used. The fuel charge depends on the volume of the combustion chamber and the defined fuel density of 112 ± 11 kg/m³. The dimensions as well as the placement of the test fuel are determined according to the volume of the combustion chamber and are listed in the following as well as in **Figure 9** and **Figure 10**.

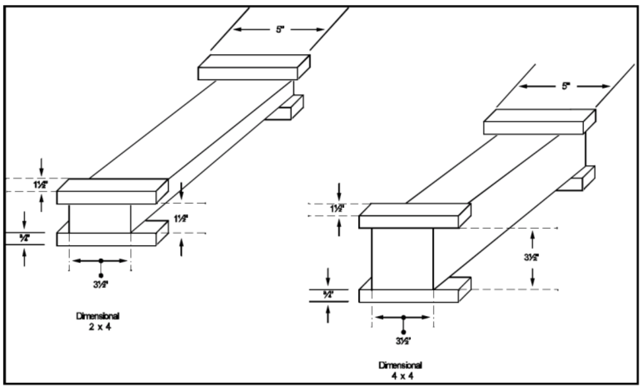


Figure 9: Dimensions of Spacer and test fuel, Source: US EPA Method 28

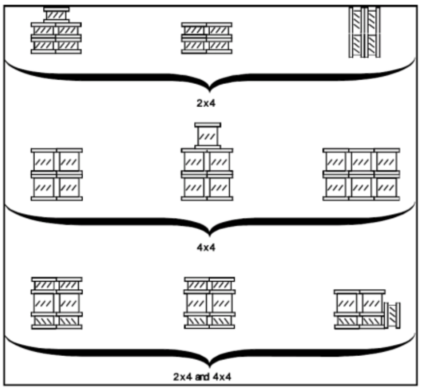


Figure 10: Example of potential placements of the test fuel in the combustion chamber Source: US EPA Method 28

- Combustion chamber volume ≤ 0.043 m³: Squared Douglas timber of 2 × 4 inch (50 mm × 100 mm) is used
- Combustion chamber volume ≥ 0.043 m³ and ≤ 0.085 m³: Squared Douglas timber of 2 × 4 inch (50 mm × 100 mm) and 4 × 4 inch (100 mm × 100 mm) with equal shares of mass is used
- Combustion chamber volume ≥ 0.085 m³: Squared Douglas timber of 4 × 4 (100 mm × 100 mm) is used

- The length of the used squared timber pieces is respectively 5/6 of the length of the combustion chamber. The arrangement of the test fuel crib is done by using uncoated nails.

For testing the appliance is operated at four different burn rates as illustrated in **Table 3**. The adjustment of the single burn rates is done by variation of the primary air supply settings.

Table 3: Overview of tested burn rate categories according to US EPA Method 28; in kg/h/ (lb/h)

Category 1	Category 2	Category 3	Category 4
< 0.80	0.80 to 1.25	1.25 to 1.90	Maximum burn rate
(< 1.76)	(1.76 to 2.76)	(2.76 to 4.19)	

The particulate emissions are determined either in the hot and undiluted flue gas according to the US EPA Method 5H or according to the US EPA method 5G in the cold and diluted flue gas. The determination of the efficiency is not obligatory.

US EPA Method 5G:

EPA Method 5G, "Determination of Particulate Matter Emissions from Wood Heaters (Dilution Tunnel Sampling Location)" [35], is used to determine PM emission rates. In this method, the flue gas from a wood heater is collected with a total collection hood and is mixed with ambient dilution air to mimic the expected atmospheric cooling and condensation. Particulate matter is withdrawn proportionally from a single point in a sampling tunnel and is collected on two glass fibre filters in series. The filters are maintained at a temperature of no greater than 32°C. The particulate mass is determined gravimetrically after the removal of uncombined water.

US EPA method 5H:

EPA Method 5H, "Determination of Particulate Matter Emissions from Wood Heaters from a Stack Location [36]", is an alternative method used to determine PM emission concentrations. According to this method PM emissions are withdrawn proportionally from the wood heater flue gas and are collected on two glass fibre filters separated by impinges immersed in an iced water bath. The first filter is maintained at a temperature of no greater than 120°C. The second filter and the impinge system are cooled such that the temperature of the gas exiting the second filter is no greater than 20°C to include condensable particulates. The particulate mass collected in the probe, on the filters and the impinges, is determined gravimetrically after the removal of uncombined water.

As test result the average PM emission rate (g/h) is calculated. By relating the average emission rate to the consumed mass of fuels the PM emission factor is determined.

Table 4 illustrates the main differences of the mentioned test protocols:

Table 4: Overview of main characteristics of International and European test standards

	Performance criteria	Tested load settings	Fuel	PM measurement	Minimum number of test batches	Mass of test batch
International draft/ DIS 13336	CO, TSP, η (direct measured)	Three – minimum, maximum and medium	Firewood without bark	Dilution tunnel (DT)	Three tests for each burn rate	Calculated based on combustion chamber volume (20%)
Australian/ New Zealand Standards	TSP, η (direct measured)	Three – minimum, maximum and medium	Firewood without bark (hardwood or softwood)	DT	Three tests for each burn rate	Calculated based on combustion chamber volume (16%)
British recommendations for testing	TSP	High, medium and low burn rate & tests under off-specification conditions	Firewood	Electrostatic precipitator and optical smoke density analysed	Five tests per burn rate	-
Canadian Standard	CO, η (indirect), TSP	Four burn rate categories tested	Firewood or squared timber (Douglas)	DT	One test per burn rate	Calculated based on combustion chamber volume (112±12 kg/m³)

	Performance criteria	Tested load settings	Fuel	PM measurement	Minimum number of test batches	Mass of test batch
European Standard	CO, η (indirect)	Generally only nominal load	Firewood (hardwood)	Not defined by the standards	Two to three batches to evaluate	Defined by the manufacturer based on the thermal heat output (THO)
Norwegian Standards	TSP	Four burn rate categories tested	Squared timber (Spruce)	DT	One test per burn rate	Calculated based on combustion chamber volume (112±12 kg/m^3)
Unites States Standards	TSP	Four burn rate categories tested	Squared timber (Douglas)	DT or out-stack measurement	One test per burn rate	Calculated based on combustion chamber volume (112±12 kg/m^3)

2.2 Advanced test methods reflecting real-life operation

In scientific literature firewood stoves have been frequently tested with the intention to evaluate their performance closer to real-life operation. In some studies, e.g. SCHMIDL et al. [37], KELZ et al. [38], the ignition and preheating batch were included in the data analysis, but the testing procedure was close to the procedure of the EN standard (e.g. only nominal load was tested).

In the last years three test methods were developed which based on previous investigations regarding typical end-user heating operation in real-life. In all three cases a user survey and long-term field monitoring at a limited number of appliances were carried out in order to consider typical aspects of user behaviour in the test concept.

In the following, a short overview and literature for further details about the three test concepts is presented.

<u>Austria:</u>
In Austria two different surveys investigating the typical user behaviour for firewood room heating appliances were conducted.

- Survey 1: This survey was conducted by the Austrian "Umweltbundesamt". The results are presented in the report SCHIEDER et al. 2013 (report only in German) [39].
- Survey 2: This survey was conducted by the company "BIOENERGY 2020+ GmbH" in the frame of an R&D project called "Ofenprüfung 2020" ("Stove Testing 2020"). The results were published in REICHERT et al. 2016 [40].

In REICHERT et al. [40] the most relevant results of survey 1 and survey 2 were compared and the typical heating operation for firewood stoves, biomass cookers and tiled stoves were derived. The findings of both surveys (in total about 750 users) and the analysis of long term field monitoring (3 firewood stoves/ 6 weeks of monitoring during the winter season in Austria) [3] were the basis for developing the "Stove Testing 2020" test concept (ST2020) which aims to evaluate firewood roomheaters (EN 13240).

This test approach consists of five consecutive batches using firewood of hard-or softwood starting from cold conditions (**Figure 11**). At least half of the used firewood pieces have to offer only two cleaved areas and subsequently some amount of bark. The moisture content of used firewood shall be between 8% and 16% of mass. A Quick-User-Guide (QUG) which has to be delivered obligatorily by the manufacturer describes the ignition technique, fuel specifications and air inlet flap settings. All described parameters are also illustrated by suitable pictures of the respective appliance. The mass of the ignition batch is defined by the QUG. Test batches 2 to 5 are conducted at nominal load (100% batch mass). The whole test cycle is conducted under controlled flue gas draught conditions of 12 ± 2 Pa. The test facility is consistent to the requirements of the standard EN 13240 [16].

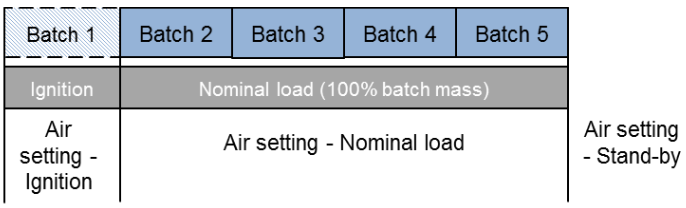


Figure 11: Test procedure of "Stove Testing 2020" test concept

Based on the results of the user survey a test batch is terminated when the "flames are extinguished" [40]. During testing according to ST2020 test method this qualitative parameter is defined by a CO_2 flue gas content of 25 vol.-% of maximum measured CO_2 flue gas content of the respective batch. If the maximum CO_2 content in the flue gas is higher than 16 vol.-% during the batch the refilling CO_2 content is defined at 4 vol.-% absolutely.

The air valve settings of the appliance for adjustment of the combustion air supply can be adjusted once at the beginning of the second or third batch after heating up the appliance. After finishing heating operation air valve settings are closed in order to avoid thermal heat losses during the cooling down phase.

For determination of the emission and efficiency performance gaseous (CO/ OGC) and particulate emissions as well as efficiency is measured. Gaseous composition and flue gas temperature monitoring is carried out continuously during the whole test cycle.

Basically, PM measurements are carried out gravimetrically in the hot and undiluted flue gases during batch 1, 3 and 5 according to the "German and Austrian method" described in the technical specification CEN/TS 15883 [41]. However, the PM sampling in the hot and undiluted flue gas is conducted during the whole batch duration and not only during 30 minutes as proposed by CEN/TS 15883. The PM sampling started just before the combustion chamber door is opened for lighting or recharging a new fuel batch. The PM sampling is terminated when the CO_2 content of flue gas that defines refilling of the next fuel batch is reached. The particles are retained by stuffed quartz cartridges (3.0 ± 0.5 g quartz wool per cartridge) that are conditioned before and after measurement 1 h in a drying oven at 160°C and subsequently cooled down for at least 8 h in a desiccator. The sampling nozzle diameter is defined at 12 mm and is placed centrally in the flue gas pipe. The sampling rate is determined at 600 ± 10% liters per hour (STP: 273.15 K/ 101,325 Pa). The sampling line is heated at 160°C. Finally, the conditioned unloaded and loaded filters are weighed on a precision balance with a accuracy of at least ± 0.1 mg). All three PM measurements are summarized to calculate one PM test result value.

The thermal efficiency is determined according the indirect calculation method according to the standard EN 13240 [16]. Therefore, thermal and chemical flue gases losses as well as the losses due to combustibles in the residue are considered.

All test batches and measurements are considered to calculate a time-weighted test result for emissions (CO, OGC, PM) and thermal efficiency.

More details about the project ST2020 and the development process for the test procedure can be found in REICHERT et al. [42].

<u>Italy:</u>
The study of OZGEN et al. [43] aimed at a determination of emission factors (e.g. CO, OGC, NO_x, PM) of residential heating appliances (firewood and pellet stoves) under real-life operating conditions. For firewood stoves the combustion tests were performed using five different types of firewood (beech, hornbeam, oak, false acacia, spruce) which are typically for the northern Italian market. It is important to mention that the intention of this publication was not primarily the definition of a new test concept (as it was explicitly for the Austrian "ST2020" and European beReal test concept). Therefore, the focus of the following description is set on the testing procedures which should reflect real-life operation conditions for different firewood stove technologies. Moreover, basic information is given about the applied measuring methods and the data evaluation concept.

Different real-life test cycles were specified which were based on a survey and long term field monitoring in northern Italy. Based on the analysis of in total 1,300 combustion hours of field monitoring (12 houses) and the evaluation of questionnaires of the users (house owners of field monitoring) about their common operating habits three different test cycles (Cycle A/ Cycle B/ Cycle C) were defined (**Figure 12**– **Figure 14**). ~~The test setup is established according the Norwegian method NS3058:2 [27]. Accordingly, the tests are conducted under natural draught conditions with a 4.5 m height chimney.~~

Batch 1	Batch 2	Batch 3	Batch 4
Ignition	Nominal load (100% batch mass)		
Air setting - Ignition	Air setting - Nominal load		

Figure 12: Test procedure of "real-life" test cycle (Cycle A)

Test cycle A (**Figure 12**), the so called "*real-life*" cycle, was defined with the aim "*to be representative of the average user behaviour*" [43]. Therefore, three batches in nominal load are performed after an ignition phase with a small amount of wood sticks (0.7 kg).

Refilling of a new fuel batch is carried out in specific time intervals. The second batch is loaded in the combustion chamber 20 minutes after ignition. The third fuel batch is loaded 60 minutes after loading the second fuel batch. In total the heating operation of the measuring Cycle A lasts 200 minutes. The mass of fuel load is defined according to manufacturer's specifications.

In order to emulate a typical user habit when operating the combustion appliance at the evening the fourth batch is performed with 50% more mass of a fuel batch and totally closed air inlet flap settings in test Cycle B (**Figure 13**).

Batch 1	Batch 2	Batch 3	Batch 4
Ignition	Nominal load (100% batch mass)		High load (150% batch mass)
Air setting - Ignition	Air setting - Nominal load		Air setting - Closed

Figure 13: Test procedure of real-life test cycle "late evening" (Cycle B)

For open fireplaces the test cycle C is applied. Accordingly, the mass of the three nominal load batches are loaded in three charges in the combustion chamber (**Figure 14**). This is necessary in order to avoid the release of smoke out of the combustion chamber.

Batch 1	Batch 2			Batch 3			Batch 4		
	Batch 2.1	Batch 2.2	Batch 2.3	Batch 3.1	Batch 3.2	Batch 3.3	Batch 4.1	Batch 4.2	Batch 4.3
Ignition	Nominal load (100% batch mass), but total mass divided into three batches								
Air setting - Ignition	Air setting - Nominal load								

Figure 14: Test procedure of real-life test cycle adapted for "open fireplaces" (Cycle C)

For the mentioned test cycles gaseous composition is monitored continuously over all test batches. The gas analysis is conducted in diluted flue gases using a heated sampling probe (160°C).

PM sampling is carried out in diluted and cold flue gas using a full flow dilution tunnel according to the Norwegian method NS3058:2 [27]. Thereby, the flue gas is diluted about 10 times with ambient air which resulted in sampling conditions of about 30-35°C. Therefore, condensation of volatile organic compounds is promoted. PM emissions are sampled on quartz fiber filters which were preconditioned at 850°C for 3 h, subsequently cooled down in desiccator, weighed and stored at -20°C until the measurement. After the measurements filters were not heated, but only conditioned in a desiccator for 24 h and subsequently weighed for PM determination.

Thermal efficiency was not determined.

The calculation of the dilution ratio is based on parallel CO_2 measurements in diluted and undiluted flue gas. Test results represent emission factors (EFs) which were calculated based on measurements and combustion calculations. Thereby, the continuous emission concentration measurement was weighed by the specific flue gas volume (m^3/kg dry fuel). Therefore, transient combustion conditions, like ignition or load changes, as well as different volume flow conditions (due to adaption of air settings) have been respected in the data evaluation.

More details about the measurements and data evaluations can be found in the study of OZGEN et al. [43]

Europe:

A European wide survey was conducted in the R&D project "*beReal*" [44]. The most relevant findings can be found in WÖHLER at al. [45]. Around 2,000 completed online questionnaires were available for data evaluation. Most respondents were from Italy (35%) followed by respondents of Germany (34%), Austria (12%) and Sweden (11%). Based on the evaluation of the survey and long term field monitoring of 19 firewood roomheaters for a period of three months during the winter a novel test concept, called "*beReal-Firewood*" was developed [46]. Only firewood roomheaters tested according the standard EN13240 [16] (or prEN 16510-1 [21] and prEN 16510-2-1 [22]) are in the scope of this test protocol [48].

The beReal test cycle consists of eight consecutive batches using firewood of hardwood. After the ignition batch there are 4 batches carried out in nominal load (100% batch mass), followed by three batches in partial load (50% batch mass) and a cooling down phase (**Figure 15**). The test facility is in general consistent with the measurement section suggested by prEN 16510-1 [21]. However, the test point for the PM sampling is located downstream the flue gas analysis and flue gas temperature measurement in order to avoid any influence of leak air on emission and efficiency test results. Additionally, two test points for measuring the flue gas velocity and the flue gas temperature at the velocity measurement are defined [48].

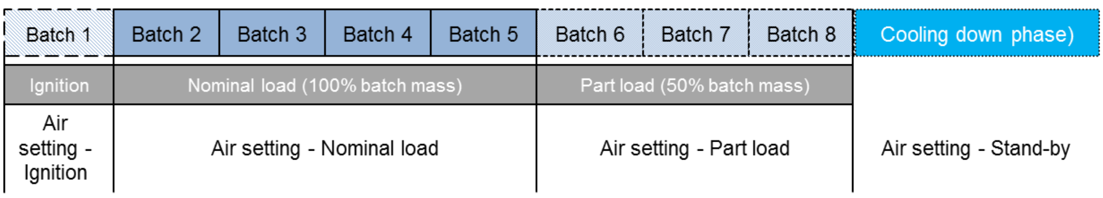


Figure 15: Scheme of "beReal" test procedure

Heating operation during beReal testing is conducted according to the specifications provided in a Quick-User-Guide (QUG). Manufacturers have to provide the QUG obligatorily. The QUG defines all relevant operating parameters specifically for each appliance on one or two pages. The information about -

- Preparations before heating operation
- Ignition mode

- Refilling
- Fuel properties
- Air settings

- shall be given by text and pictures. The QUG shall be handed unchanged to the end-costumer. Therefore, the QUG can be used as an effective instrument to enhance a correct and appliance specific best-practice heating operation in real-life. The principal of a QUG is exemplarily shown in **Figure 16**.

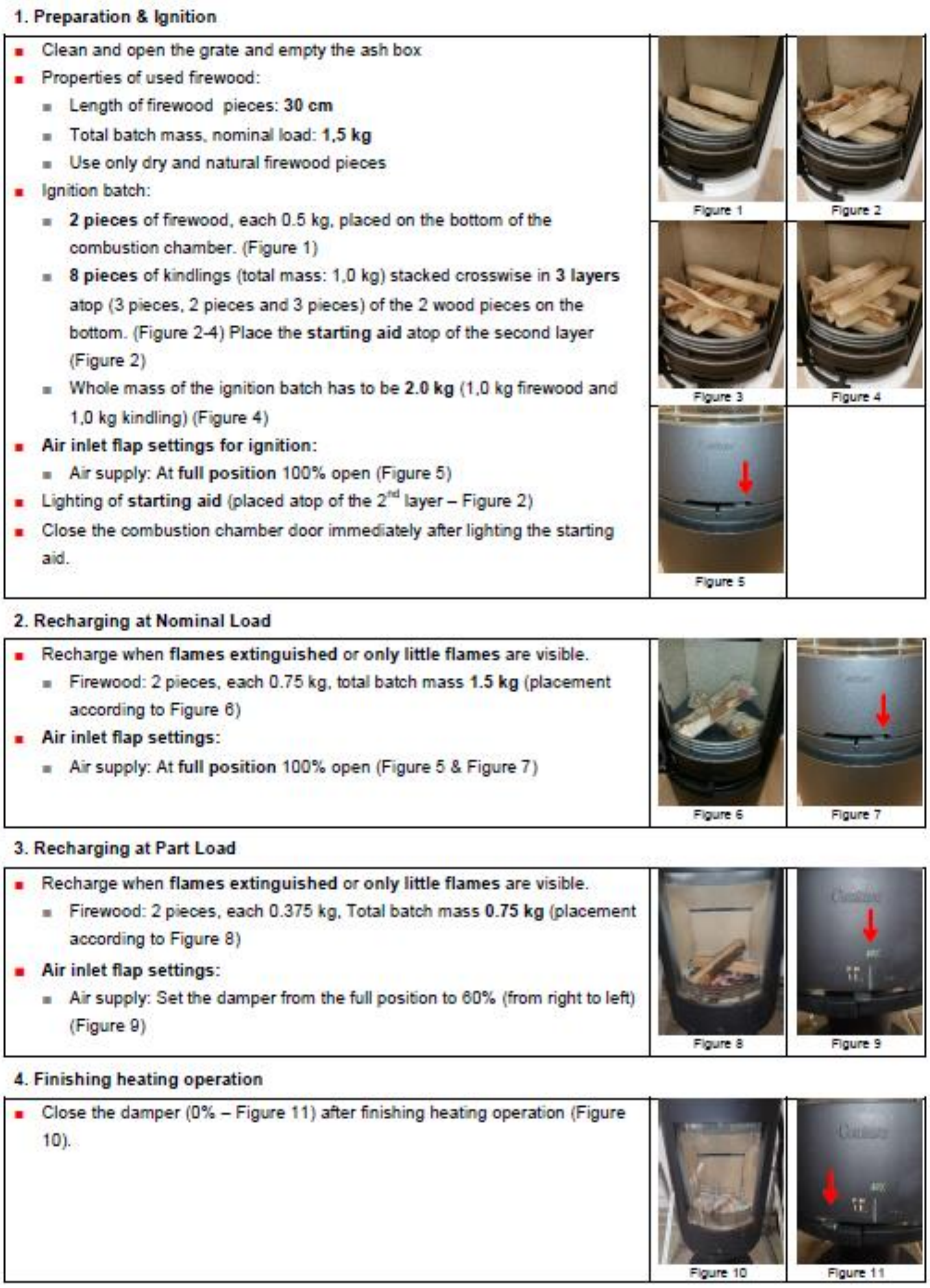


Figure 16: Illustration of the QUG principle for appliances specific best practice heating
Source: [46]

Refilling of a new fuel batch is defined according to the curve of the CO_2 content in the flue gas. If the maximum CO_2 flue gas content of the respective batch is >16 vol.-% refilling is required at 4 vol.-% CO_2. If the maximum CO_2 flue gas of the respective batch is <12 vol.-% refilling is required at 3 vol.-% CO_2. In all other cases refilling is required at a CO_2 flue gas content representing 25% of maximum CO_2 flue gas content. This criterion represents the quantitative criteria for the qualitative criteria "flames extinguished" or "only little flames visible" which was identified by the European user survey [45]. For appliances equipped with an automatic control indicating the recharging time, this signal shall be followed rather than following the procedure described above.

The air valve settings of the appliance for adjustment of the combustion air supply can be adjusted both after the first or second fuel batch to "nominal load" and after the fifth test batch to "partial load". Furthermore, manufacturers have to define adjustments of air valve settings after finishing heating operation. If the test appliance offers an automatically controlled combustion air supply the adaption of air settings is done by the automatic control system.

Gaseous composition (O_2, CO_2, CO, OGC as THC, NO_x) and flue gas temperature monitoring is carried out continuously during the whole test cycle..

PM measurements are carried out gravimetrically in the hot and undiluted flue gases during batch 1, 3, 5 and 7 according to VDI-Guideline 2066-1 (out-stack measurement). Isokinetic PM sampling is conducted over the whole batch duration and is started right before loading the fuel. During the complete PM measurement the filter casing and probe shall be continuously heated to 180 ± 3°C.

A combination of a stuffed filter cartridges and a downstream located plane filters (particle retention rate > 99% according to Dispersed Oil Particulate (DOP) test) are used. After a beReal test cycle rinsing of the PM sampling probe with acetone is required. The filter cartridge and plane filters are pre-and post-conditioned at 180°C for 1 h and subsequently cooled down for at least 8 h in a desiccator. The collected PM mass (filter cartridge, plane filter, rinsing) is determined by a precision balance with a accuracy of at least ± 0.1 mg. Based on the total PM mass and the total sampled flue gas volume (STP, dry) the PM test result was calculated.

Thermal efficiency is determined according to the indirect determination approach. Therefore, thermal and chemical flue gas losses are determined including also the cooling down phase (until the flue gas temperature reaches 50°C). The losses due to combustibles in the residue are calculated based on the total mass of residues and its share of combustibles after the test cycle.

For calculating CO, OGC and NO_x test results all batches of the beReal test cycle are considered (batch 1 to 8, without cooling down phase). Different loads are respected by volume-weighted averages. Therefore, the continuous monitoring of the flue gas velocity is necessary. All emission test results represent emission concentrations referred to dry flue gas conditions, STP, and 13 vol.-% O_2. For referring to 13 vol.-% O_2 the volume-weighted measured O_2 value is used.

More details about the development process, measurement methods and the data evaluations of the beReal test procedure can be found in the following references [47] [48] [49].

All the three different methods cannot cover the whole scope of situations which influence the emission release and the thermal efficiency of a heating system in real-life operation (**Figure 17**).

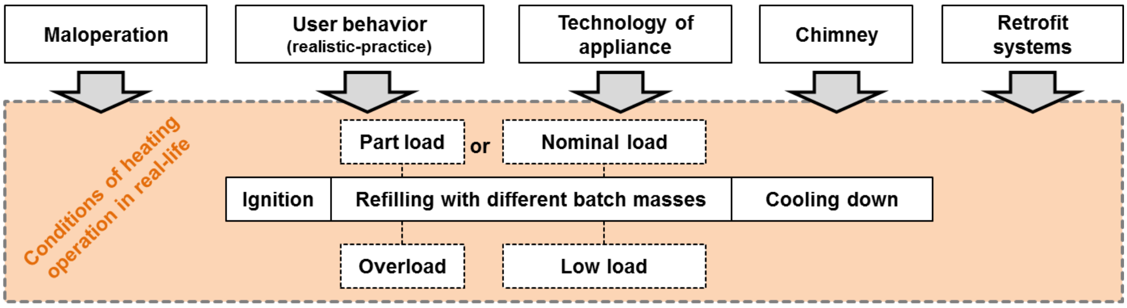


Figure 17: Parameters influencing the appliance performance regarding emission and thermal efficiency performance in real-life operation.

For example, the mentioned test concepts base on specific draught conditions, either constantly controlled ("ST2020" and "beReal") or induced by a specific chimney set-up (Cycle A-C). Consequently, varying draught conditions which can significantly influence emissions and thermal efficiency [50] are not respected by the different test concepts. Potential retrofit devices for secondary emission abatement (e.g. electrostatic precipitator) or external draught control devices are also not respected in the testing concepts. Maloperating conditions, i.e. overload conditions and incorrect air valve settings, are partly respected by Cycle B of OZGEN et al. [43]. But there are further potential maloperating conditions, e.g. the use of wet fuel or litter, or even too low load, which are not covered by the different test concepts. The cooling down phase after heating operation was found to contribute significantly to thermal heat losses, especially when air settings are not closed [51] or when appliances are untight [52]. This aspect is included in the beReal test concept which respects thermal heat losses during cooling down phase for thermal efficiency determination [48].

Concluding, EN test method evaluates the technology of appliances under defined steady-state operating conditions and often with a sophisticated operation (e.g. special preparation of wood logs) which is far from typical real-life operation. In contrast, real-life oriented test concepts include transient operating conditions and try to respect typical real-life operating conditions of the heating systems, especially aspects of user behaviour (**Figure 1**).

The main differences of the real-life oriented test concepts compared to the EN test protocol for firewood stoves (roomheaters and fireplaces) are:

- Testing of the appliance from cold conditions since the ignition and preheating batch are always part of real-life heating operation
- Load changes and different loads are respected
- Each batch of the test cycle is considered for performance evaluation, no batches can be eliminated

3 Real-life relevance of advanced test methods

This chapter aims at an evaluation of the real-life relevance of the official type test protocol (oTT) compared to the different test concepts mentioned in the section before. Thereby, data of selected field tests and lab tests are presented and compared with oTT results of the used type of appliance (if data is available).

In order to have comparable data, emission factors (EF in mg/MJ) are presented. For test results which were only available as emission concentrations the emission factors (EFs) were calculated based on combustion calculations [53] (**Equation 1**).

Equation 1: Calculation of emission factors (EF)

$$EF = \frac{E_{mg/m^3\,(STP,\,dry,\,13\,vol.-\%\,O2)} \times V_{min,\,STP,\,dry} \times 2.625}{H_{u,\,f}} \quad (1)$$

$$V_{min,\,STP,\,dry} = 1.87\,c + 0.7\,s + 0.79 \times L_{min} \quad (1a)$$

$$L_{min} = \frac{1.87\,c + 5.6\,h + 0.7\,s\; - 0.7\,o}{0.21} \quad (1b)$$

EF	Emission factors based on the energy of the fired fuel; in mg/MJ
$E_{mg/m^3\,(STP,\,dry,\,13\,vol.-\%\,O2)}$	Emission concentration (mg/m³) in the dry flue gas based on standard temperature and pressure conditions (STP: 273.15 K, 101325 Pa) and referred to 13 vol.-% O_2
$V_{min,\,STP,\,dry}$	Dry flue gas volume of stoichiometric combustion at STP conditions; in m^3/kg_{fuel}
L_{min}	Stoichiometric minimum combustion air demand at STP conditions; in m³/kgfuel
c, h, s, o	Elemental content of test fuel (as fired basis); in in kg/kg_{fuel}
$H_{u,\,f}$	Net calorific value of the test fuel (as fired basis); in kJ/kg

If the elemental compositions and the net calorific values of the used fuel for the single measurements were not known typical values for beech firewood according to **Table 5** were used.

Table 5: Properties of fuel used for calculating the EFs based on emission concentrations

	Moisture content* w (kg/kg)	Net calorific value* H_u (MJ/kg)	Carbon (c) (kg/kg, d.b.)	Hydrogen (h) (kg/kg, d.b.)	Sulfur (s) (mg/kg, d.b.)
Fuel (beech firewood)	0.16	14.88	0.485	0.061	95

*as received/ d.b. = dry base/

In some studies only EFs for non-methane volatile organic compounds (NMVOC) are given. The corresponding OGC-EFs were determined according to **Equation 2** based on the share of methane of total VOC emissions as suggested by NUSSBAUMER et al. [54].

Equation 2: Calculation of OGC EFs based on EFs proposed for NMVOC

$$\mathrm{EF_{OGC}} = \frac{\mathrm{EF_{NMVOC}}}{0.6} \tag{2}$$

EF_{OGC} …EF for OGC emissions based on EF proposed for NMVOC emissions; in mg/MJ

The approach (**Equation 1**) was also applied to transfer the ELVs of the new ecodesign requirements [55] to mg/MJ.

- CO: 1500 mg/m³ (STP, dry, 13 vol.-% O_2) corresponds to 977 mg/MJ
- OGC: 120 mg/m³ (STP, dry, 13 vol.-% O_2) corresponds to 78 mg/MJ
- NO_x: 200 mg/m³ (STP, dry, 13 vol.-% O_2) corresponds to 130 mg/MJ
- PM: 40 mg/m³ (STP, dry, 13 vol.-% O_2) corresponds to 26 mg/MJ

NO_x emissions of biomass combustion are predominantly fuel dependent [56] and currently not limited for firewood stoves in most European countries (except Austria). Therefore, NO_x emissions were not included in this study. However, in future this parameter might become more relevant even for firewood combustion in stoves.

3.1 Official type test results

In the study of SCHIEDER et al. [39] comprehensive data of official type test results of manually fired room heating appliances which were collected in a database are presented.

Data for CO emissions derived from 941, for OGC from 219, for PM emissions from 996 and for the thermal efficiency from 1577 appliances (**Figure 18**). In total, the database covers 76 manufacturers from 13 European countries. Therefore, the data can be seen as typical for the European stove market.

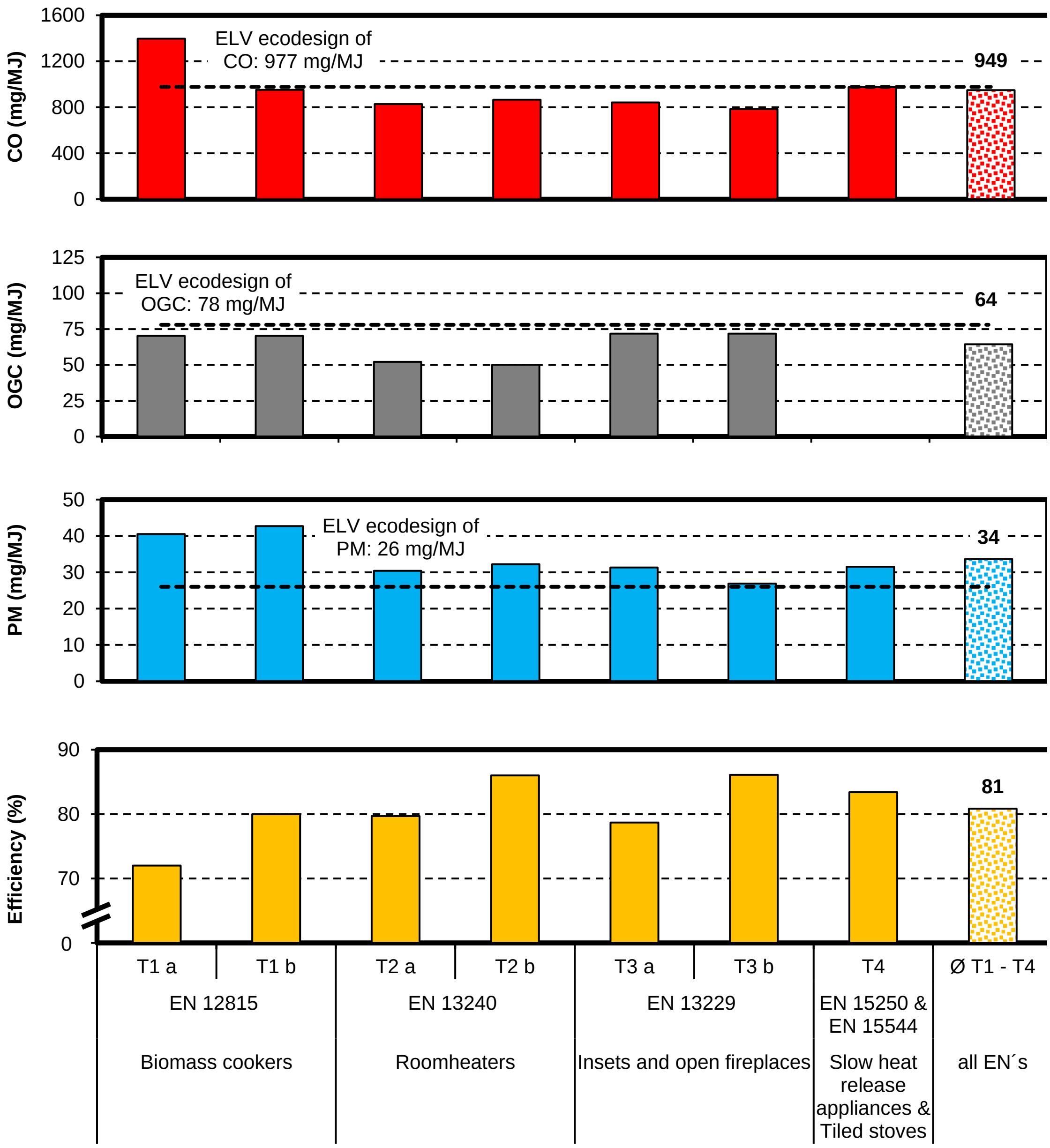


Figure 18: Overview of official type test results for different technologies of manually fired room heating appliances (conventional technologies…a / modern technologies…b). The dashed black lines represent the ELVs of future ecodesign requirements for local space heaters (closed fronted) and cookers.

Average EFs for CO emissions are 949 mg/MJ, for OGC emissions 64 mg/MJ and for PM emissions

34 mg/MJ. The average thermal efficiency is higher than 80%. The results between the single technologies are very similar. Except for biomass cookers (EN 12815) the differences of oTT results between conventional (T1a) and advanced technologies (T1b) are marginal.

The highest emissions and lowest thermal efficiencies were generally observed for conventional biomass cookers (T1a). The EFs for conventional and advanced firewood roomheaters (EN 13240) are better than the average values. Highest thermal efficiencies were observed for advanced firewood roomheaters (86.0%) and advanced fireplace insets (86.1%).

Comparing the data with future ecodesign ELVs it can be seen that most of the technologies already meet the ELV for CO and OGC, whereas the PM ELV is exceeded by all technologies (even for T3 b: 29.6 mg/MJ).

Regarding thermal efficiency the new ecodesign requirements defined the so called "seasonal space heating energy efficiency" (SSHEE) which aims at representing more the "real-life" thermal efficiency. The minimum requirement of the SSHEE for closed fronted local space heaters and cookers is 65%. The SSHEE is calculated based on specific features of the appliance and the thermal efficiency results evaluated by the official type test [55]. In most cases the SSHEE is approximately the thermal efficiency of oTT results minus 10%. This results in an SSHEE value of about 70% which can be reached by all technologies except conventional cookers (T1a).

3.2 Field test results

Selected studies presenting field measurements were collected and results of EFs are presented in **Figure 19**. The studies were conducted in a long time interval and cover a broad range of appliances of different construction years. This was respected in order to identify a technologic development process. Important to mention is, that the measurement procedure of the single studies were not homogeneous. However, all presented data in **Figure 19** refers to measurements when the users operated their appliances with firewood. This means that data represent a heating operation cycle starting with the ignition of the first fuel batch and followed by several batches (either only at nominal or also at partial load).

In the following list the type and the total number of appliances which are illustrated in **Figure 19** are summarized.

- **SPITZER et al. 1997/98** – (SPITZER) [57]:
  The evaluated EFs for 28 firewood room heating appliances (1 inset, 2 tiled stoves, 9 roomheaters, 16 cookers) represent field test results, where the users operated the stoves according their typical habits during the measurements. The year of construction of tested appliances was between 1950 and 1997. The median of construction years of the tested appliances was 1975.

- **HÜBNER et al. 2005** – (HÜBNER) [58]:
  The evaluated EFs represent field measurements of 3 roomheaters, 3 cookers and 3 tiled stoves which were operated with firewood by the respective users. The year of construction of the appliances ranged between 1956 and 1998. The median of construction years of the tested appliances was 1985.

- **REICHERT et al. 2014** – (REICHERT) [42]:
  The evaluated EFs represent 9 field measurements at 3 different firewood roomheaters (three test cycles for each appliance). All stoves were classified according to the EN 13240 standard. The measurements were carried out under operation by the users according to the manual and

the procedure of the test concept "Stove Testing 2020" (only nominal load/ see **Figure 11**). The year of construction of the three devices was in 2012.

- **RÖNNBÄCK et al. 2016** – (RÖNNBÄCK) [59]:
  The evaluated EFs represent field test results at 13 different firewood roomheaters (EN 13240). The year of construction of the stoves ranged between 2013 and 2015. The field tests were conducted under operation by the end users. At one day the users operated the stove according to their common practice at nominal and or part load (field/ user). At another day the users operated the appliance according to a Quick-User-Guide (field/ user with QUG). The QUG is a standardized short manual which briefly instructs the user about ignition technique, refilling procedure and air settings of the respective appliance [48].

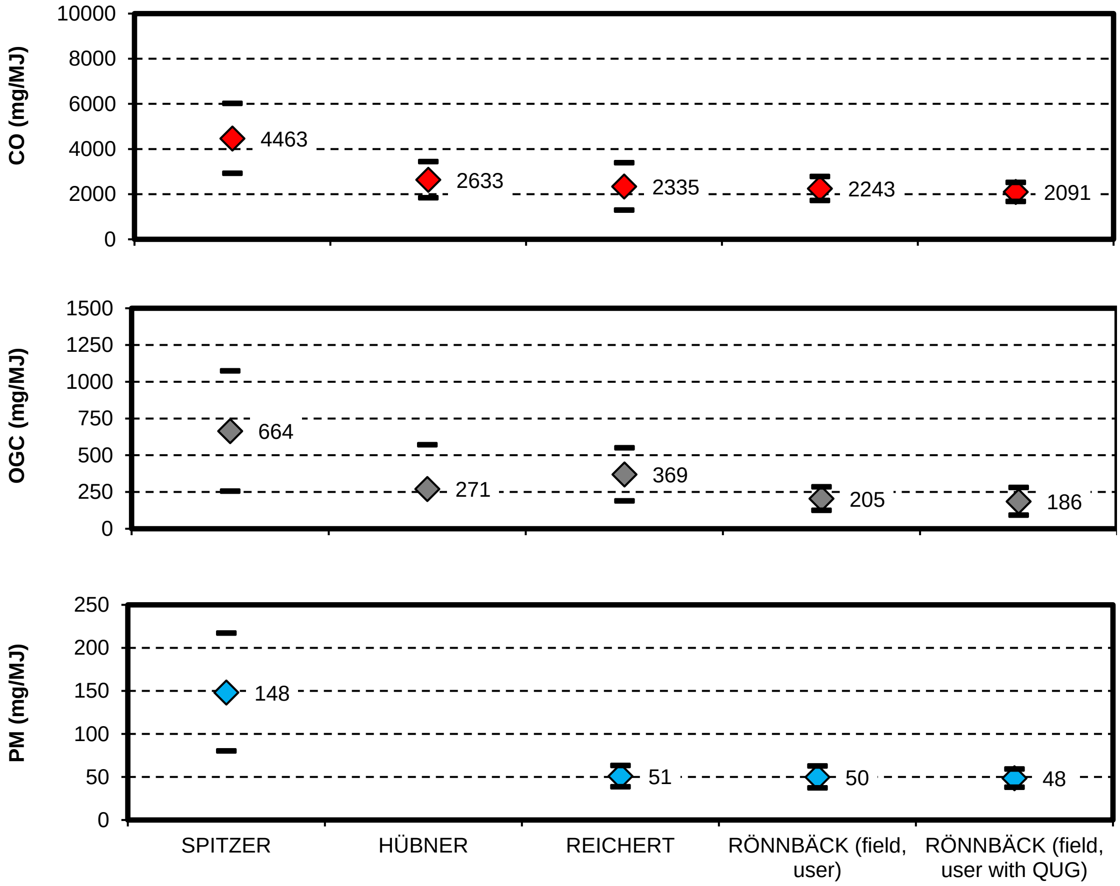


Figure 19: Overview of average field test results of manually fired room heating appliances from different studies. The black lines represent the 95% confidence level of measurement results.

The highest EFs for CO, OGC and PM emissions were measured by the study of SPITZER et al. [57]. In this study the average CO EF was at around 4500 mg/MJ, 660 mg/MJ for OGC and 150 mg/MJ for PM emissions. In contrast, the lowest EFs were observed during field testing in RÖNNBÄCK et al. [59] when the users operated their appliances according to the QUG. In that case average CO EFs were around 2100 mg/MJ for CO, 190 mg/MJ for OGC and 50 mg/MJ for PM emissions [59].

The oldest appliances were evaluated by the study of SPITZER et al. [57]. Comparing these results [57] with the ones of REICHERT et al. [42] or RÖNNBÄCK et al. [59] a clear improvement towards lower emissions at newer technologies is evident. This could indicate the technological development of firewood room heating appliances, e.g. by implemented primary measures, like air staging or better insulated combustion chambers.

However, it has to be considered that the appliances tested in the study of HÜBNER et al. [58] were in average as old as the appliances monitored in the study of SPITZER et al. [57]. Comparing the results of REICHERT et al. [42] or RÖNNBÄCK et al. [59] with the results of HÜBNER et al. [58] the differences of average measurement results are quite low although the difference of construction years was about 15 to 20 years between the used appliances. Consequently, the technological improvement is not clearly confirmed by the reviewed field measurement results.

Comparing the field test results referring to end-user heating operation (**Figure 19)** with the high number of oTT results (**Figure 18)** it is obvious that oTT results in general are significantly lower compared to field performance. CO emissions of field tests are higher by a factor of around 2.5 in average, OGC emissions are even higher by a factor of about 3. Interestingly the lowest difference between field test results and oTT results are obvious for PM emissions. In the field average PM emissions are higher by a factor of 1.4 compared to oTT test results.

3.3 Lab test results emulating real-life operating conditions

The field test results were compared with results of different scientific studies using testing concepts with the intention to evaluate emissions closer to real-life operation or even to evaluate some aspects of maloperating conditions in the lab (**Figure 19**, see also **Figure 17)**.

The following list provides a brief description of selected tests of different studies. The results are illustrated in **Figure 20**:

- **PETTERSSON et al. 2011** [60] – (1)
  EFs were determined at different modes of heating operation. The average EFs (1) include combustion experiments with different types of firewood species, different air settings and a variation of the moisture content and dimensions of the firewood pieces. In total, 6 combustion experiments were conducted. Each combustion experiment consisted of two batches.

- **SCHMIDL et al. 2011** – (2a-d) [37]
  A simple stove (a, b) and a sophisticated stove (c, d) were tested with hardwood and softwood firewood at standard heating operation (2a/ 2c). Additionally, tests under off-specification heating operation were conducted (overload, starved air conditions: 2b/ 2d). For all combustion experiments a heating cycle consisting of three consecutive batches was carried out. The heating cycle started from cold conditions.

- **KELZ et al. 2012** – (3a & b) [38]
  Comparative combustion tests at a modern (3a) and an old firewood stove (3b) (EN 13240) were conducted. Therefore, a separate ignition batch with a small amount of kindling material followed by 5 batches at nominal load was carried out. The EFs represent an average of two test runs for each stove.

- **ORASCHE et al. 2012** – (4) [61]
  Combustion experiments simulating normal heating operation were carried out. Therefore, a heating cycle consisting of four batches – the ignition batch followed by three batches at nominal load – was carried out. The EFs represent the total heating cycle.

- **OZGEN et al. 2014** – (5) [43]
  Real-life tests were carried out according to specific test cycles (**Figure 12**: Cycle A/ **Figure 13**: Cycle B). The results represent average data of 15 combustion experiments – 5 according to test cycle A and 10 according to test cycle B.

- **RÖNNBÄCK et al. 2016** – (6) [59]
  The data (6) represent average measurement results of 13 firewood roomheaters (EN13240) tested in the lab according to the beReal test procedure (**Figure 15**).

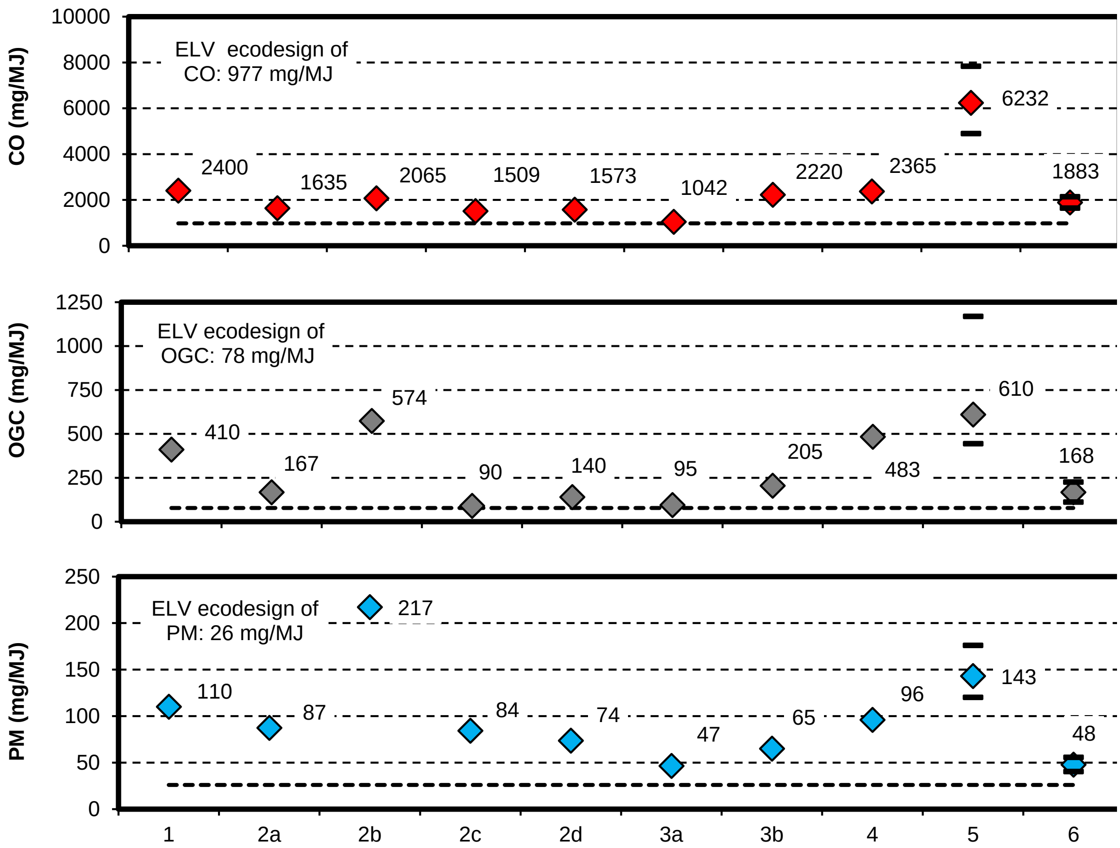


Figure 20: Overview of lab test results of manually fired room heating appliances from different studies. The black lines represent the 95% confidence level of measurement results (where available). The dashed black lines represent the ELVs of future ecodesign requirements for local space heaters (closed fronted) and cookers.

CO emissions of the selected lab tests ranged around 2000 mg/MJ except for the results of OZGEN et al. [43] (5) where in average about 6000 mg/MJ CO emissions were measured. Average measured OGC emissions were between about 100 mg/MJ and 600 mg/MJ and PM emissions between about 50 mg/MJ and 100 mg/MJ. In two cases the average PM emissions were about 140 mg/MJ (OZGEN et al. [43] (5)) and 220 mg/MJ (SCHMIDL et al. [37] (2)). In both cases the high PM emissions can be explained by the evaluation of maloperating conditions within the testing procedure. Furthermore, it has to be mentioned that OZGEN et al. [43] (5) evaluated the PM emissions by a dilution tunnel which results in significantly higher measurements compared to the hot sampling in undiluted flue gas [62].

Comparing the data with the new ecodesign requirements it is obvious that the "modern" or "sophisticated" stove models under normal heating operation (2c/ 3a) perform close to the ELVs for CO and OGC emissions. The beReal test results for the "modern" stoves (6) were in the same range. However, PM ELV of the ecodesign requirements was not achieved by all tested appliances. This corresponds to the findings about oTT results, illustrated in **Figure 18,** where it is indicated that PM ELV of the ecodesign requirement is the most ambitious requirement for oTT tests. Comparing the data of simple (2a) or old (3b) stoves with, for example, the beReal test results of modern stoves (6) there is a low difference regarding CO and OGC emissions but a clear difference regarding PM emissions.

In general, the results illustrated in **Figure 20** were close to the field test results presented in **Figure 19** with the exception of the results of OZGEN et al. [43] and the tests of 2b of SCHMIDL et al. [37]. In those cases maloperating conditions at the tested stoves by starved air conditions led to very high emissions.

3.4 Lab and field test results compared by proposed emission factors

The field test (**Figure 19**) and lab test (**Figure 20**) results are compared with emission factors (EFs) proposed by different studies which are listed below:

- **NUSSBAUMER et al. 2010** [54]
  - Emission factors suggested for 2008 (NU 2008)
  - Emission factors suggested for 2035 (NU 2035)
- **EEA Report No 21/2016** [63]
  The EMEP/EEA Pollutant Emission Inventory Guidebook 2016 represents a technical guidance to prepare national emission inventories (EMP ... European Monitoring and Evaluation Programme/ EEA … European Environment Agency). For different types of technologies EFs are proposed. For the comparison three different categories were selected:
  - Conventional stove (EEA: conv. stove)
  - High-efficiency stoves (EEA: high-eff. stove)
  - Advanced/ ecolabelled stoves and boilers (EEA: adv. stove)

In **Figure 21** the proposed EFs of the mentioned studies are presented.

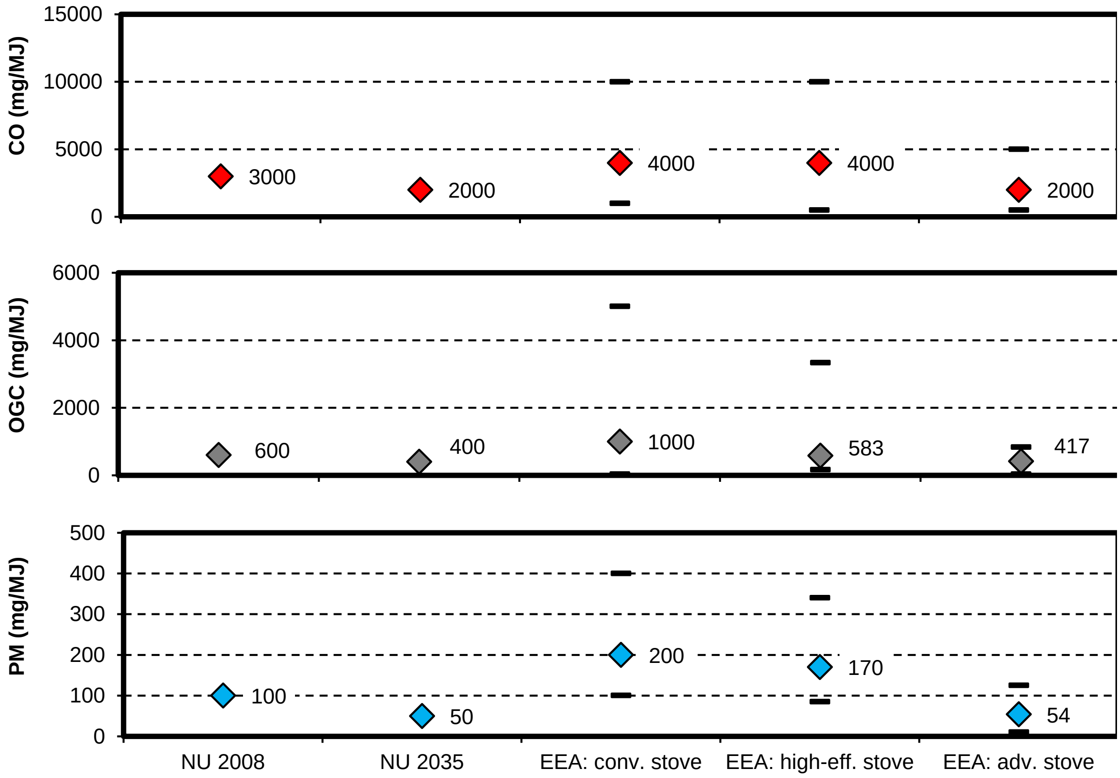


Figure 21: Overview of emission factors proposed by different studies. The black lines represent the 95% confidence level (where available).

The proposed EFs for advanced stoves can be compared with the field test results of REICHERT et al. [42] and RÖNNBÄCK et al. [59]. For CO and PM emissions the proposed EFs represent quite well what was measured in the field. The PM EFs of EEA Guidebook represent the total suspend solid particles (TSP) measured in hot and undiluted flue gas. Regarding OGC emissions a difference compared to field test results is evident. The proposed EFs for OGC by NUSBAUMER [54] for 2008 and by the EEA Guidebook [63] seem by tendency too high. The proposed EFs are 400 mg/MJ or nearly 600 mg/MJ whereas in the field measured values ranged from about 190 mg/MJ to 370 mg/MJ.

Based on the assumption that in 2035 the stock of biomass room heating appliances changed significantly towards more state-of-the-art appliances, the OGC EF of 400 mg/MJ projected for the year 2035 by NUSBAUMER [54] seems also too high. However, the suggested EF was already revised in a recent publication. According to the latest recommendations an OGC EF of 150 mg/MJ for 2035 is suggested which seems quite realistic [64].

The trend of decreasing emission factors due to the modernization of the stock of residential heating appliances is also illustrated by the German study of TEBERT et al. [65]. Depending on the policy framework conditions they suggested decreasing specific EFs for different scenarios – "current policy scenario" or "energy transition scenario" (**Table 6**).

Table 6: Projected EFs representing the stock of residential wood combustion technologies in Germany for different policy scenarios

Scenario	Year	CO (mg/MJ)	OGC (mg/MJ)	PM (mg/MJ)
Current policy	2015	1,632	173	76
	2025	1,221	163	52
	2030	1,121	162	49
Energy transition	2015	1,590	164	74
	2025	1,123	143	48
	2030	1,018	143	44

It is important to mention that the data presented in **Table 6** is based on the share of central and indirect heating devices (biomass boilers and stoves) of the total stock. The "energy transition scenario", therefore, assumes a more widespread utilization of modern boilers (pellet and firewood) as well as pellet stoves.

3.5 beReal – Evaluation of real-life relevance

In the following section an evaluation of measurement data provided in RÖNNBÄCK et al. is presented. The evaluation based on the figures given in the appendix of the respective report [59]. In this study comprehensive tests in the lab and in the field were carried out with the same appliances. Thus, a direct comparison from field to lab performances is possible. The used stoves were 13 serial-production appliances, all of them classified according to the EN 13240 standard. The following tests were conducted:

- **Retesting of EN 13240 type test** – [RTD Type Test (EN13240)]
- **beReal test in the lab** – ["beReal" – Lab]
- **beReal test in the field** – ["beReal" – Field]
- **Test day when the stove was operated according the users own habit** – [User (own habit)]
- **Test day when the stove was operated by the user with the Quick-User-Guide** – [User (QUG)]

The retests of the EN 13240 type tests and the beReal tests in the lab were carried out before the room heaters were installed in the field. The tests, which were performed by several RTD partners of the beReal project consortium [44], were compared with the oTT results – "Official Type Test (EN 13240)" – of the respective stove models.

In **Figure 22** the average results of the different tests are presented.

Comparing the official type test results with beReal test results in the lab (CO: 1883 mg/MJ / OGC: 168 mg/MJ / PM: 48 mg/MJ / thermal efficiency: 70%) it becomes obvious that there are significant differences: At the beReal tests emissions are higher and thermal efficiency is lower. In comparison with the respective stove models CO emissions are higher by factor 3.4, OGC emissions by a factor of 4 and PM emissions by a factor of 3.4 in average. Thermal efficiency is absolutely 11% lower compared to official type test results. Consequently, the test cycle according to the beReal test protocol including typical aspects of real-life heating operation resulted in significant different test results compared to official type test results (higher emissions and lower thermal efficiency). Moreover, with two exceptions for OGC emissions, beReal test results did not meet the future ecodesign ELVs.

Official type tests are performed with appliances provided by the manufacturer. Usually, the final prototype of the newly developed stove model is used for testing. According to the standard EN 13240 any substantial changes are not allowed after testing or the appliance needs a new approval by the testing institute [16]. The retests according to EN 13240 standard showed that it was not possible to reproduce the official type test results of the used stove models with serial-production appliances. In average, emissions were higher by a factor of around 2 and efficiency was about 11% lower compared to official type test results.

The used stove models had already official type test results that meet the future ecodesign ELVs. However, the test results of RTD performers resulted in most cases in higher test results as required by future ecodesign ELVs. None of the tested stoves meet all ELVs of future ecodesign requirements.

Real-life emissions of the serial-production stoves were significantly higher compared to official type test results of the respective stove models. In average, CO emissions were higher by a factor of 4, OGC emissions by a factor of 4.9 and PM emissions by a factor of 3.6. The average thermal efficiency of field tests was observed at 64.5% which is 16.5% lower compared to the results of official type tests. Comparing the field test results according to the common user habits with beReal test results at the test bench it is evident that there is good conformity regarding emissions. The difference of

CO, OGC and PM emissions is low (factor < 1.3).

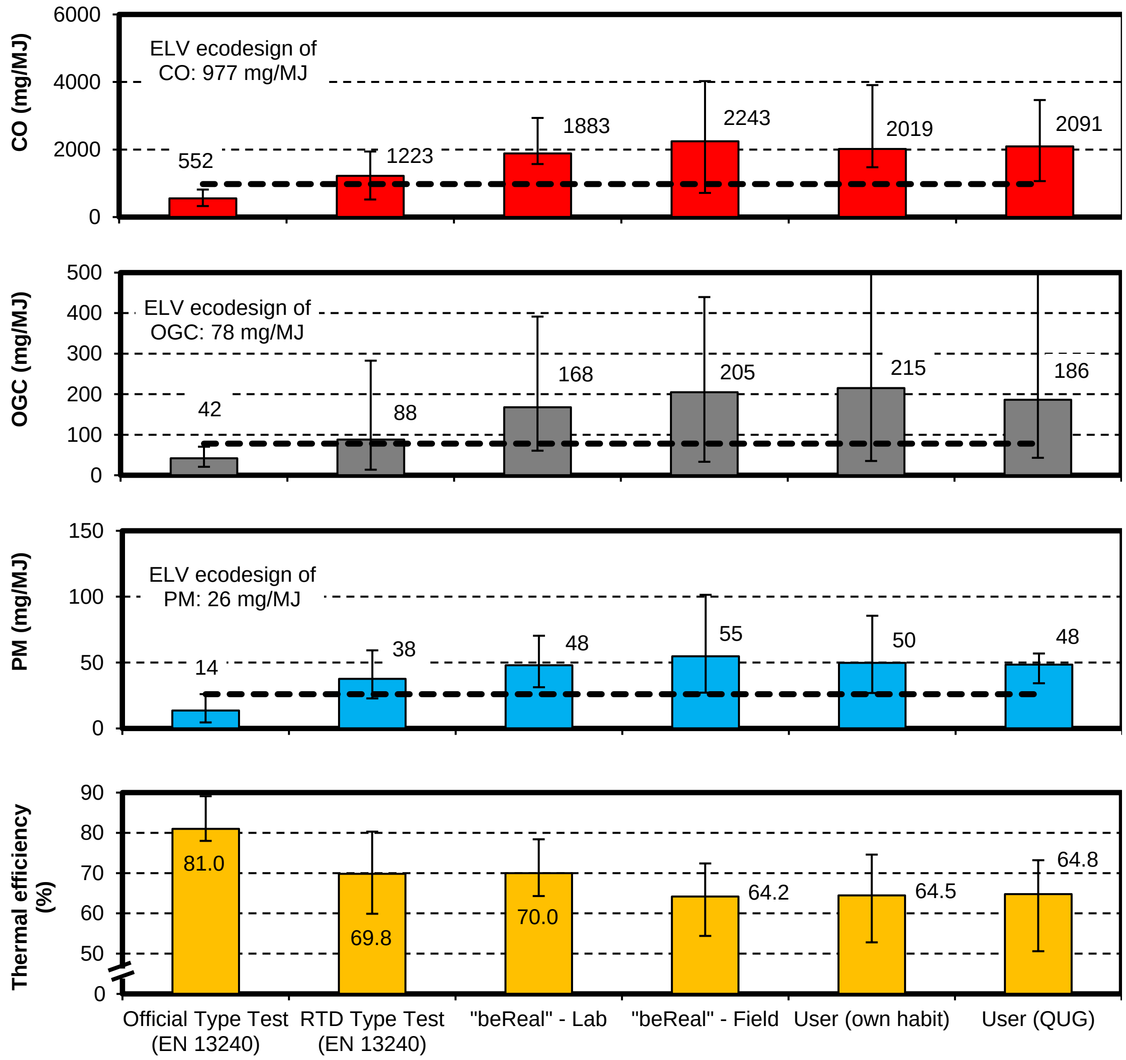


Figure 22: Comparison of official type test results with lab and field test results. Lab and field test results were measured with the same appliances (all EN 13240). Error bars represent the minimum and maximum values determined. The dashed black lines represent the ELVs of future ecodesign requirements for local space heaters (closed fronted) and cookers.

Regarding thermal efficiency the conformity is better compared to official type test results but there is still a difference of 5.5% evident ("beReal" – Lab compared to "User (own habit)"). This difference could be explained by the difference of draught conditions between the lab and the field [46]. Experimental combustion tests comparing the emissions and efficiencies of three different firewood roomheaters at 12 Pa, 24 Pa and 48 Pa showed that increased draught conditions significantly reduce thermal efficiency [50]. Comparing the field tests of common user operation and "beReal" field test results the conformity is still satisfying for emissions and even for thermal efficiency. Additionally it has to be mentioned that the connecting flue gas pipe to the chimney increases thermal efficiency in real-life operation since the thermal heat is directly released in the room. The evaluation of combustion experiments of RÖNNBÄCK et al. showed that 1 m of connecting flue gas pipe of the stove to the chimney could increase the thermal efficiency by about 10% absolutely [59].

Consequently, the “beReal” test protocol seems feasible to evaluate the appliance emission performance in the lab close to real-life. Regarding thermal efficiency beReal test results seem to be too high compared to real-life, but strongly depends on installation patterns in the field (e.g. chimney height and thus draught conditions, connecting pipe to chimney).

The Quick-User-Guide was developed as a potential instrument to improve the user behaviour in real-life operation (see also **Figure 16**). Comparing the test days of user operation according the own habits with the test days when the users operated the stove according to the QUG the potential of the QUG is demonstrated. The average emissions decreased and also the variation of the results decreased (see error bars). Thermal efficiency decreased marginally. However, it has to be mentioned that in some cases the operation according to the own habits led to better results compared to heating operation according to the QUG.

4 Summary and Conclusions

This study revealed an overview of most relevant International and European test protocols for performance evaluation of firewood stoves regarding emissions and thermal efficiency. Alternative testing concepts for firewood stoves, especially for firewood roomheaters, which are based on a user survey and field monitoring were presented. The potentials and limitations of those new testing concepts compared to the existing test protocol (i.e. EN 13240) regarding their real-life relevance were discussed and critically evaluated by comparing of lab test results and field test results when the appliance was operated by the end-user.

The review of various literature data lead to following key findings and conclusions:

- Testing conditions of current European standards evaluating the emissions and thermal efficiency of firewood room heating appliances are well controlled and provide the basis for optimal test results for the tested appliance. The most relevant difference of EN type test standards compared to International standards is that in most cases only nominal load is evaluated whereas for example Canadian or American test protocols evaluate the performance in several load settings.

- PM emission results highly depend on the applied measuring method. For better comparability of different test results a commonly used PM measurement method in Europe is needed in order to achieve sufficient comparability between different products.

- The comparison of field test results showed a trend of technological improvement of firewood stoves over the last decades. However, the comparison of official type test results with field tests confirmed that typical heating operation results in significantly higher emissions and lower efficiencies.

- Comparing the field test results of advanced stoves with the current emission factors used for that technology it seems that OGC emission factors are too high (approximately by a factor of 2).

- Official type test results were not reproducible with serial-production stoves in comprehensive lab tests. The implementation of a market surveillance concept represents an effective measure to guarantee a constant product quality of sold appliances.

- In future, the new ecodesign requirements will set an equal benchmark of performance criteria for new stove technologies in Europe. However, the effect towards improving the real-life situation is limited since the new requirements still refer to official type test results.

- Real-life oriented test concepts (e.g. beReal) are capable to reflect the real-life performance of the appliances better compared to existing EN standards. An implementation of a real-life oriented test protocol as a quality label or standard should be considered as an instrument to push technological development towards optimized real-life operation and to enable a better differentiation of good and poor products for the end customer.

- The utilization of a real-life oriented test protocol (e.g. the beReal test protocol) for determination of emission factors seems possible, but needs further investigations. A standardized measurement of emission factors according to a suitable test concept could be used for a regular update of immission inventories and to update and evaluate the progress of technological development.

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