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Report

Particle emission factors for wood stove firing in Norway

The «BLACKOut» project – SINTEF Energy Research
Commissioned by the Norwegian Climate and Pollution Agency (CPA)

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Summary

This is the first project in which emissions of elemental carbon (EC) and organic carbon (OC) from domestic wood burning have been measured in Norway. The project has also obtained what we believe are more realistic estimates for total suspended particulate (TSP or PM_t) concentrations emitted from domestic Norwegian wood burning. The project also proposes a new tripartite classification of wood-burning stoves based on the year of manufacture; (1) very old (1940 to 1970-80), old (1970-80 to 1998) and new (1998 to present). One of the project's principal challenges has been to obtain accurate measurements of EC due to high particle filter load during sampling using a full flow dilution tunnel, especially at low burn rates, as required by the Norwegian Standard for measurement of PM_t.

The present work aims to provide the best possible estimates of the amounts of EC, OC and total particles (PM_t) emitted from Norwegian wood stoves. Emission factors for these compounds were established by obtaining measurements from experiments on two selected wood-burning stoves regarded as representative; (1) a stove employing old combustion technology and (2) a stove employing new technology. The aim is to detect actual emission factors for EC, OC and total particle concentrations in grams per kilogram of fired dry wood. These two types of stove consume 96% of all firewood used for household heating in Norway.

NBL (Norwegian Fire Research Laboratory) has been executing participant of the test campaign for PM_t from old wood stoves, and UEF (University of Eastern Finland) has been responsible for the analysis of EC/OC in the sampled particles. SINTEF Energy Research has measured PM_t values from new stoves. All wood-burning stove experiments were performed in compliance with the Norwegian national standard for the testing of enclosed wood heaters and smoke emission measurements (NORSK STANDARD NS3058/NS3059). Particulate emissions were collected in filters from flue gas sampled in a dilution tunnel. The filters were stored at -18°C before being shipped in dry ice for analysis in Finland. The method used to analyze OC and EC is based on a thermal-optical approach using a carbon analyzer instrument manufactured by Sunset Laboratory Inc. in the US.

Prior to obtaining measurements, two representative wood-burning stoves had to be selected – the first employing old (pre-1998) combustion technology, and the other (1998 to present) using state-of-the-art technology. The selection was made jointly by SINTEF wood-burning stove experts, Norwegian stove manufactures and the NBL. The Jøtul model 3 series was selected, principally based on criteria such as market availability, time in the market and cost. The selection criteria are discussed in more detail in the main report. Coincidentally, Jøtul 3 series stoves are available both without (Jøtul model 3), and with, new combustion technology (Jøtul F3). The latter was introduced to the market in the period 2000-2001 and has since been on sale throughout Norway in the medium price range.

A brief summary of the history of Norwegian emission factors and the basis on which these factors were established is also included in this report.

The report presents measured emission factors for PM_t, and associated factors for EC and OC for stoves employing both new and old combustion technologies. Emission factors are proposed for both normal (i.e. with night firing) and medium firing (i.e. without night firing). Medium firing was assumed by Statistics Norway (SSB) to be the preferred firing pattern practiced in the largest cities in Norway. Normal firing involves a lower burn rate than medium firing. Present results have been weighted firstly according to the grade 2 Norwegian standard median of 1.6 kg/h for the assumed medium firing pattern, and then against an assumed median of 1.25 kg/h firing pattern to reflect normal firing.

Based on the results discussed in this report, new emission factors are proposed based on the measurements of PM_t and associated factors for EC and OC for both normal and medium firing. It is argued that the proposed emission factors account for real-world particulate emissions from stoves with old (1970-80 to 1998) and new (1998 to present) combustion technologies. It is recommended that the PM_t emission factors for stoves manufactured from 1940 to 1970-80 be kept at 33 g/kg (medium firing) and 40 g/kg (normal firing). No EC and OC factors are currently available for these very old stoves.

Particle sampling in the dilution tunnel as described in the Norwegian standard results in high particle load on the filters, especially at lower burn rates. The main reason for using a dilution tunnel is to mimic the dilution and cooling that occurs when smoke from a wood-burning stove exits a chimney. For stoves in general, but especially for stoves employing an old combustion technology, the lower the burn rate the more non-combusted matter escapes the combustion zone. This results in an increase in formation of condensed matter when the flue gas dilutes and cools at the chimney outlet. This "close to real-world" measurement strategy results in high levels of particle load on the sampling filters, at least in relation to the particle load limitations of the available analyzer from Sunset Laboratory Inc. Ideally, this instrument was designed to analyze ambient concentrations of particulate matter, but was nevertheless judged to be the most suitable for this project. The filter particle load limitations of the instrument thus resulted in higher levels of uncertainty linked to both the EC and OC measurements. To compensate for this and narrow the windows of uncertainty, several control analyses were performed resulting in some slight corrections for the EC and OC factors. One possible way of solving this problem is to measure EC directly in the chimney, which will result in a significant narrowing of EC measurement uncertainties. The OC and PM_t factors should be measured in the dilution tunnel since the present measurements have demonstrated sufficiently low uncertainties for these compounds.

For wood-burning stoves employing new combustion technology, the PM_t factors proposed are 12.2 and 13.4 (g/kg) for medium and normal firing, respectively. These values are approximately double those previously applied in the Norwegian PM emission inventory. For stoves employing the old technology, the factors proposed for PM_t are 17.4 and 22.7 (g/kg) for medium and normal firing, respectively. These values are approximately half those previously applied in the national PM inventory. For stoves employing state-of-the-art technology, the factors proposed for EC are 0.90 and 0.86 (g/kg) for medium and normal firing, respectively, while for stoves using the old technology, the factors proposed for EC are 1.01 and 0.96 (g/kg) for medium and normal firing, respectively. For stoves employing new technology, the factors proposed for OC are 9.26 and 10.47 (g/kg) for medium and normal firing, respectively, while for stoves using the old technology, the proposed factors for OC are 12.89 and 16.74 (g/kg) for medium and normal firing, respectively. For stoves using new combustion technology, the current emission factor is 6.2 (g/kg). For those employing the old technology, current emission factors for the Norwegian particle emission inventory are currently 40 (g/kg) and 33 (g/kg) for normal and medium firing, respectively.

Another important outcome from the project was discovered when the current results were compared with results previously achieved in the SINTEF laboratory showing that stoves which have been in use for several years emit more particulates than brand new ones. Since only a relative small percentage of the stoves currently in use in Norway are brand new, this means that the current results for the new technology stove can be assumed to be more representative of real-life Norwegian wood burning-related emissions than those set out in the type approval tests as these stoves are always tested as brand-new. The results show that emissions concentrations of PM_t from new and old technology stoves are closer than previously anticipated. This does not mean that the impact in terms of reductions in particle emissions of replacing old (1970-80 to 1998) and very old (1940 to 1970-80) stoves with newer and cleaner technologies is less important than before. The objective of the work presented in this report was to provide a sound estimate of what actually is emitted from Norwegian households at the present day. This is why SINTEF selected a

stove employing new technology that had already been in use for several years (introduced to the market as early as in 2001), but which did not inherit current state-of-the-art, highly optimized, combustion technology. The most recent approval tests performed by NBL show that some of the best stoves currently on the market can operate with a weighted particle emission concentration of between 1-2 g/kg. Assuming that the end-user operates these stoves in compliance with the manufacturer's manual, using dry wood, and ensuring that the stove is checked regularly for leakages, weighted real-world PM_t emissions at such levels can actually be achieved. In terms of the accuracy of the PM emission inventories, we are left with the challenge of finding satisfactory estimates of the number of very old and old stoves actually in use. However, based on the selection criteria for representative stoves in Norway, we believe that the majority of wood consumption in pre-1998 stoves takes place in old stoves manufactured in the period 1970-80 to 1998. Total wood consumption in Norway for old and very old stoves is about 50% of the total amount of wood used for domestic heating. The remaining 50% are mainly burned in stoves using new combustion technology, of which only a small percentage represents state-of-the-art technology.

Sammendrag

Utslipp av elementært karbon (EC) og organisk karbon (OC) fra vedfyring i norske husholdninger har blitt målt for første gang i dette prosjektet. Prosjektet har også målt utslipp av partikler (Total Suspended Particulates = TSP eller PM_t), som er mer representative for reelle norske utslipp fra vedfyring i husholdningene enn de som tidligere ble brukt i det norske utslippsregnskapet. Vi foreslår også en ny klassifisering av norske vedovner basert på produksjonsår; veldig gamle ovner (1940 og opp til 1970-80), gamle (1970-80 og opp til 1998), nye ovner (etter 1998). En hovedutfordring i prosjektet har vært å framskaffe nøyaktige målinger av EC noe som skylles for stor masse på flitrene på grunn av måling av partikler i uttynningstunnel og da særlig på lav last som kreves i Norsk Standard for måling av PM_t.

Det gjennomførte prosjektet har som mål å gi et best mulig anslag av mengden av elementært karbon (EC), organisk karbon (OC) og total mengde partikler (PM_t) som slippes ut fra norske vedovner. Utslippsfaktorer for disse forbindelsene ble etablert ved å utføre eksperimentelle målinger på to utvalgte ovner. Ovnene er vurdert å være representative for vedovner med gammel teknologi og vedovner med ny teknologi. Faktiske utslippsfaktorer for EC, OC og total mengde partikler som gram per kilo tørr ved omsatt er etablert ved målinger og analyse. I disse to vedovnstypene forbrukes 96 % av all veden i Norske husholdninger.

NBL (Norsk branntekniske laboratorium) har utført målingene av PM_t på gamle ovner og SINTEF Energi har gjort målinger på nye ovner. UEF (University of Eastern Finland) har utført analysene av EC/OC. Alle vedovnseksperimenter ble utført i henhold til Norsk Standard for testing av lukkede vedovner, NS3058/NS3059. Partikkelutslipp ble fanget på filtre fra røykgass fra fortynningstunnelen. Filtrene ble lagret ved -18 °C før de ble sendt i tørris for analyser i Finland. Metoden som brukes til å analysere OC og EC er basert på en termisk-optisk metode ved hjelp av et karbon analysator instrument produsert av Sunset Laboratory Inc. i USA.

Før oppstart av målekampanjen ble to representative vedovner valgt, en med gammel og en med ny forbrenningsteknologi. SINTEFs vedovnseksperter sammen med norske vedovnsprodusenter og NBL gjennomførte utvelgelsen. Utvelgelsen ble basert på noen spesifiserte forhåndsdiskuterte kriterier, så som tilgjengelighet på markedet, tid i markedet og innkjøpskostnader, ble Jøtul F3-serien valgt. Kriteriene for utvelgelse er videre forklart i hovedrapporten. Ovnsserien er tilgjengelig både uten (Jøtul modell 3) og med ny forbrenningsteknologi (Jøtul F3). Modellen med ny forbrenningsteknologi ble introdusert i markedet rundt 2000–2001 og har siden vært tilgjengelig for kjøp over hele Norge for en kostnad som antas å være i det midlere kostnadssjikt.

Rapporten gir også en historisk oversikt over utslippsfaktorer som har vært brukt i det norske utslippsregnskapet for partikler.

Rapporten presenterer målte utslippsfaktorer for utslipp av PM_t, EC og OC fra vedovner med ny og gammel forbrenningsteknologi. Utslippsfaktorer for både normalt og medium fyringsmønster er foreslått, hvor medium fyring er antatt som det foretrukne fyringsmønster kun i Oslo, Bergen, Trondheim og Drammen. I denne rapporten refererer normal og medium fyring til en median på henholdsvis 1,25 og 1,6 kg tørr ved per time.

Basert på resultatene som drøftes i denne rapporten, er nye utslippsfaktorer foreslått for PM_t og tilhørende faktorer for EC og OC for normal og medium fyring. Utslippsfaktorer målt i dette prosjektet er ment å være representative for reelle partikkelutslipp fra ovner med gammel (1970-80 og frem til 1998) og ny forbrenningsteknologi (nyere enn 1998). Det anbefales at utslippsfaktorer for ovner produsert fra 1940 og fram til 1970-80 holdes på 40 g/kg (normal fyring = med nattefyring) og 33 g/kg (medium fyring = uten nattefyring). Per i dag finnes det ingen dokumenterte utslippsfaktorer for EC og OC for disse ovnstypene, verken i Norge eller internasjonalt.

Partikkelprøvetaking i fortynningstunnelen som beskrevet i Norsk Standard gir store mengder partikler på filtrene, spesielt ved lave brennrater. Dette kan forklares med økningen i kondenserbare komponenter spesielt ved lave brennrate. Den høye partikkelbelastning resulterte i økt måleusikkerhet spesielt for EC, men også for OC målingene, på grunn av begrensning i den benyttede analysatoren fra Sunset Laboratory Inc. For å kompensere for dette å prøve å redusere usikkerheten ble flere kontrollanalyser utført. Dette resulterte i små korreksjoner for EC og OC. En måte å løse dette på er å måle EC direkte i pipen. Måleusikkerheten for EC vil da kunne bli betydelig lavere enn det vi oppnådde i dette prosjektet. OC og PM_t bør fremdeles måles i uttynningstunnelen da forsøkene i dette prosjektet har vist at nøyaktigheten er akseptabel.

I dette arbeidet har utslipp av både nye og gamle vedovner blitt målt for fyringsmønster kategorisert som normal og middels fyring. Det typiske, norske fyringsmønsteret med nattfyring refereres til som normalfyring mens det foretrukne fyringsmønsteret i de største norske byene (uten nattfyring) refereres til som midlere fyringsmønster. For vedovner med ny teknologi er de foreslåtte faktorer for PM_t 12,2 g/kg og 13,4 g/kg for henholdsvis middel- og normalfyring. For vedovner med gammel teknologi, er de foreslåtte faktorer for PM_t 17,4 og 22,7 (g/kg) for middel- og normalfyring, henholdsvis. For vedovner med ny teknologi er de foreslåtte faktorer for EC 0,90 og 0,86 (g/kg) for middel- og normalfyring, henholdsvis, mens for vedovner med gammel teknologi, er de foreslåtte faktorer for EC 1,01 og 0,96 (g/kg) for middel- og normalfyring, henholdsvis. For vedovner med ny teknologi er de foreslåtte faktorer for OC 9,26 og 10,47 (g/kg) for middel- og normalfyring, henholdsvis, mens for vedovner med gammel teknologi, er de foreslåtte faktorer for OC 12,89 og 16,74 (g/kg) for middel- og normalfyring, henholdsvis. For vedovner med ny forbrenningsteknologi har en utslippsfaktor på 6.2 (g/kg) fram til nå vært benyttet i det norske utslippsregnskapet. For vedovner med gammel teknologi er utslippsfaktorene henholdsvis 40 (g/kg) og 33 (g/kg) for normal- og middelfyring.

Et annet viktig resultat fra dette prosjektet er at ovner som har vært i bruk over en periode på flere år, slipper ut mer partikler enn fabrikknye ovner. Dette kommer fram når man sammenligner resultatene fra dette prosjektet (Jøtul F3 som har vært i bruk som laboratorieovn over en periode på 5 år) med resultatene fra typegodkjenningen NBL utfører (fabrikkny Jøtul F3). Dette betyr at våre resultater for ovner med ny teknologi kan antas å være mer representativt for reelle norske utslipp fra vedfyring, fordi få norske husholdninger har helt nye ovner. Dette betyr ikke at effekten av å bytte ut gamle og svært gamle ovner med nye rentbrennende ovner er mindre viktig enn før for å redusere partikkelutslipp fra vedovner. Som

tidligere nevnt er formålet med rapporten å gi et godt estimat på partikkelutslipp fra vedfyring i norske husholdninger per i dag. Dette er grunnen til at vi valgte en ovn med ny teknologi men som allerede har vært i bruk i flere år. Ovnen hadde i tillegg ikke dagens optimaliserte forbrenningsteknologi fordi vår ovn ble introdusert i markedet allerede i 2001. Noen av de beste ovnene i dag er i stand til å operere med et vektet partikkelutslipp (PM_t) på mellom 1-2 g/kg. Forutsatt at husholdningene opererer en slik ovn i henhold til produsentenes manual, bruker tørr ved og vedlikeholder ovnen jevnlig mot lekkasje, så vil utbytting fra gamle og svært gamle ovner til ovner med dagens teknologi, kunne gi en betydelig reduksjon i utslipp, som for det beste ovnene kan være opp i mot 10 ganger lavere. Vedrørende nøyaktigheten i estimatene på partikkelutslipp, er det en utfordring å fordele andel ved som brennes riktig mellom veldig gamle og gamle ovner. Basert på kriteriene for valg av representative ovner som benyttes i norske husholdninger, mener vi at hoveddelen av vedforbruket i ovner uten ny forbrenningsteknologi forbrukes i gamle ovner produsert mellom 1970-80 og frem til 1998. Summen av det som brennes i gamle og veldig gamle ovner er cirka 50 % av det norske vedforbruket mens resten forbrennes i ovner med ny forbrenningsteknologi, og hvorav da kun en liten prosentvis del av dette forbrukes i de aller nyeste ovnene med state-of-the-art teknologi.

Document history

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V1	2012-09-13	Draft
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V6	2013-03-22	Draft
V7	2013-04-11	Final report

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Definitions and abbreviations

PM_t	=	Total particle matter, equivalent to TSP (total suspended particulate matter)
EC	=	Elemental carbon refers to the thermally refractory pure carbon with a graphitic structure which oxidizes above 550-865 °C during thermal analysis
OC	=	Organic carbon released from incomplete combustion, is the amount of carbon which volatilize from the particle sample during thermal analysis in an oxygen free atmosphere below 865 °C
BC	=	BC or soot is an optical term that is commonly used to denote highly light-absorbing carbon, BC contains not only EC but also partly OC
OM	=	Organic Matter, OC multiplied by a factor to account for other elements than carbon in the organic molecules, often 1.1-1.4[1]
TC	=	Total carbon
Klif	=	Klima- og forurensningsdirektoratet/The Norwegian Climate and Pollution Agency
SFT	=	Statents Forurensningstilsyn/ Norwegian Pollution Control Authority; former name for Klif
SSB	=	Statistisk sentralbyrå/Statistics Norway
Emission factor	=	factor used to calculate emissions from defined sources in grams per kilogram dry wood
NS	=	the Norwegian national standard for testing of enclosed wood heaters and smoke emission, NORSK STANDARD NS3058/NS3059
PTFE	=	Polytetrafluorethylene or Teflon filter material
NBL	=	SINTEF NBL as - Norwegian Fire Research Laboratory
LAC	=	Light absorbing carbon
PC	=	Pyrolytic carbon
Normal firing	=	The stove is operated at low wood consumption with a median of 1.25 kg/h, with night firing
Medium firing	=	The stove is operated at medium wood consumption with a median of 1.6 kg/h, without night firing
d.b.	=	Dry basis for fuel wood
Nominal heat output	=	Is the power output (= fire wood consumption per hour) at which the stove should normally be operated and is always specified by the wood stove producer

[1] Bond, T. , Doherty, S. J., Fahey, D. W. et al. Accepted in JGR, 15. January 2013

1 Background and goals

The project proposal for the current work was prepared to comply with a contract call-off made by the Norwegian Climate and Pollution Agency (CPA) in December 2011. The CPA required measurements of particulate emissions from wood burning in Norwegian households in order to establish specific emission factors for the two carbonaceous components contained in such emissions; Black Carbon (BC) and Organic Carbon (OC). BC or soot is an optical term commonly used to denote highly light-absorbing carbon. Its chemical equivalent term is Elemental Carbon (EC), which refers to thermally refractory pure carbon with a graphitic structure[2]. BC not only contains EC but also possibly light absorbing OC[3]. The respective definitions of BC and EC suggest that both compounds are specific to their respective methods of investigation. During the call-off proposal phase, SINTEF initially decided to employ the thermal-optical method to provide experimentally-based emission factors for EC using the expertise at the University of Eastern Finland, which offers particulate matter analysis using its Sunset Laboratory Inc. instrument. Since the call-off specifically requested measurements of BC, the CPA asked SINTEF to discuss the relationship between BC and EC in the report. In addition, SINTEF would be required to provide emission factors for organic carbon (OC), also determined from the measurements. If possible, links should be investigated between the emissions of both EC and OC and the discharge of total particulate matter (PM_t) and/or PM10 and/or PM2.5. The client's project description is found in Annex A.

The main objective of the current project is to propose emission factors for EC (as defined by SINTEF's initially selected measurement method), OC and PM_t for wood burning using data obtained from one new[4] and one old representative stove type in Norway. Since SINTEF does not have at their disposal the necessary equipment to make measurements of BC, nor EC, researchers from the University of Eastern Finland were invited to join the project to perform the EC-OC analysis. Both before and during the project proposal face SINTEF performed a survey to decide on the most appropriate method to analyze carbonaceous components and particle matter collected from wood stove firing. The most appropriate method found was the one that applies the thermal-optical approach. This method has been used for several years by researchers at the University of Eastern Finland to analyze particle matter from wood burning appliances. Throughout the proposal phase, SINTEF made Klif aware of this decision.

To be able to develop a national emission inventory it is important to develop a good enough estimate of Norwegian BC emissions from residential wood burning, since this is a large source of particular matter. As SINTEF has proposed, and in accordance with the tender call, the most natural approach is to perform experiments in sufficient numbers to provide statistical robust values for a number of representative wood stoves.

When it comes to burning of wood in Norway, the current figures from Statistics Norway (SSB) show that it was burned in excess of 1.2 million tons in Norwegian households in 2011, a decline of 19 % from 2010. For the country as a whole, 2011 was one of the warmest years on record with an average temperature of 1.8 °C above normal temperatures for the period 1961-1990. The sharp decline in wood consumption from 2010 to 2011 must be viewed in the context that 2010 was an exceptionally cold year. This is why the wood consumption reached an all-time high this year. In addition, it was burned in excess of 210 000 tons in cottages in 2011, down 16 % from the year before. Wood used in cottages accounted for about 15 % of the

[2] Chow, J.C. et al., 2009. Aerosol light absorption, black carbon, and elemental carbon at the Fresno Supersite, California. Atmospheric Research, 93(4), pp.874–887

[3] Hansson, H-C., Kindbom, K. et al. (2011). " Black carbon – Possibilities to reduce emissions and potential effects", ITM report 202

[4] New stoves are stoves manufactured after 1998. Old stoves are manufactured before 1998

total Norwegian wood consumption in 2011. It was burned about 280 000 tons less in 2011 than in 2010. The preliminary estimates from SSB show that the decline was largest for stoves with new technology, i.e. stoves manufactured after 1998. It was burned about 160 000 tons less wood in stoves with new technology in 2011 than the year before. In 2011 44 % of the households consuming wood, used stoves with new technology. The number of households reporting that they mainly use new stoves has increased by 45 % since 2005. In 2011, 47 % of the wood was burned in stoves with new technology. This is 29 % more than in 2002, but 2 % less than in 2010[5].

In 2010, 53 863 tons of particulate matter was emitted as PM10. These figures come from the emission inventory produced by Statistics Norway and the Norwegian Climate and Pollution Agency. Included in these emissions is wood combustion which is responsible for 61.4 %, or 33 072 tons, originating from both dwellings and cottages.

Table 1 shows that it was burned in excess of 1.34 million tons of wood in Norwegian households in 2011.

Table 1. Fuel wood use in dwellings from SSB[6]

Statistisk sentralbyrå
Statistics Norway

Energy balance. Fuel wood use in dwellings, by region, firing technology, time and contents

	2011
	Households using fuel wood (1 000 households)
The whole country	
All technologies	1 338,7
Open fireplace	115,7
Enclosed stove, new technology (produced after 1998)	630,2
Enclosed stove, old technology (produced before 1998)	592,8

Figure 1 illustrates yearly evolution of fuel wood used in Norwegian dwellings from 2005 – 2011 consumed in stoves with different combustion technology.

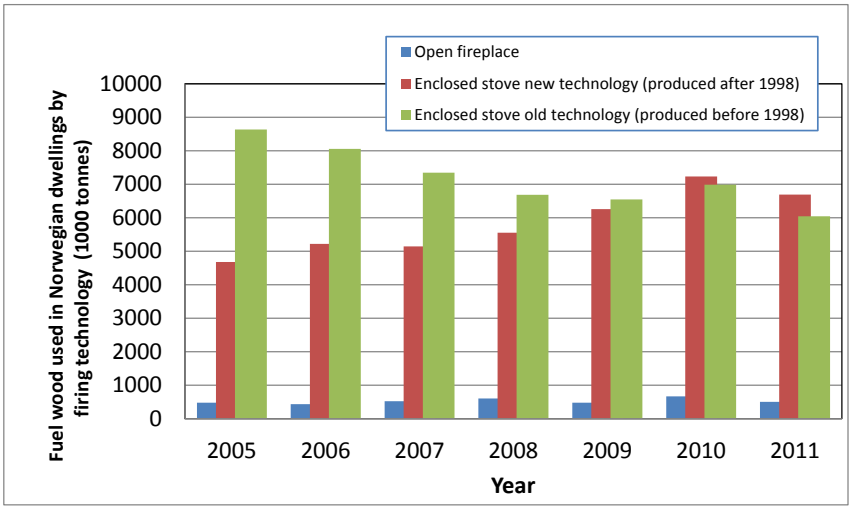


Figure 1. Fuel wood use in dwellings, by firing technology[6]

[5] http://www.ssb.no/magasinet/miljo/art-2012-06-05-02.html

[6] http://statbank.ssb.no/statistikkbanken/Default_FR.asp?PXSid=0&nvl=true&PLanguage=1&tilside=selectvarval/define.asp&Tabellid=09703

In a report by the Arctic Council[7], it is concluded that a main source of BC affecting the Arctic is wood burning and oil boilers operated in adjoining countries. Since the mid-80s, when the first findings emerged on the effect of carbonaceous components as short-lived climate forcing agents, there has been a steadily increasing focus on these compounds. Smoke or soot was the first pollutant to be recognized as having a significant environmental impact, yet one of the last to be studied by the contemporary atmospheric research community. As a side note, it can be mentioned that already in 1861 Faraday recognized that soot was composed of carbon and that it was produced by incomplete combustion of carbon-containing fuels. Soot is a complex mixture of compounds that are weakly absorbing in the visible spectral region and a highly absorbing black component that is variously called “elemental”, “graphitic” or “black carbon”. Again, literature confirms that the term elemental carbon is used in conjunction with thermal and wet chemical determinations and that the term graphitic carbon suggests the presence of graphite-like micro-crystalline structures in soot[8]. The term black carbon is used to imply that this soot component is primarily responsible for the absorption of visible light[9,10].

Both BC and EC originate from incomplete combustion of carbonaceous fuel and are commonly associated with soot. Again, though both of them somehow refer to the same carbon compounds, their definition is method-specific and resulting data might not be adapted for direct comparison[11,12,13]. Specifically BC is measured by optical techniques, generally using an aethalometer, which quantifies BC on filter samples based on the transmission of light through a sample[13]. EC is measured by thermal techniques, generally using thermal-optical analysis. Differences between both quantities can be explained by effects of the size distribution and mixing state of the aerosol and the presence of other compounds[12]. From the findings in the literature, it was observed that many authors use EC and BC interchangeably although they are actually method-specific. In this project and because of the choice of method and its inherent measured compound EC, EC will be used throughout the rest of this report.

The project was completed with the objective to provide the best possible estimate of the amount of EC, OC and PM_t emitted from selected representative Norwegian wood stoves. The experiments were performed according to the Norwegian standard for enclosed wood stoves. In the project, experimental measurements were carried out on two selected stoves, a) wood stove - old technology and b) wood stove - new technology, in order to arrive at the weighted emission factor for EC, OC and PM_t as grams per kg dry wood consumed. It may also be noted that when firing with wood in Norwegian households, these two stove categories consumes approximately 96 % of all wood combustion according to recent figures from SSB[5].

[7] DeAngelo, Benjamin Ed. (2011) An Assessment of Emissions and Mitigation Options for Black Carbon for the Arctic Council; Technical Report of the Arctic Council Task Force on Short-Lived Climate Forcers. Technical Report. Arctic Council

[8] Rosen, H. and Novakov. T., Raman scattering and the characterization of atmospheric aerosol particles, Nature 266, 708-710, 1977

[9] Yasa, Z. , Amer, N.M., Rosen, H., Hansen, A.D.A and Novakov, T., Photoacoustic investigations of urban aerosol particles, Appl. Opt. 18, 2528-2530, 1979

[10] Rosen, H., Hansen, A.D.A., Dod, R.L., and Novakov T., Soot in urban atmospheres: Determination by an optical absorption technique, Science, 208, 741-744, 1980

[11] Schmid, H., L. Laskus, et al. (2001). "Results of the “carbon conference” international aerosol carbon round robin test stage I." Atmospheric Environment 35(12): 2111-2121

[12] Hitzenberger, R., A. Petzold, et al. (2006). "Intercomparison of thermal and optical measurement methods for elemental carbon and black carbon at an urban location." Environmental Science & Technology 40(20): 6377-6383

[13] Quincey, P., D. Butterfield, et al. (2009). "An evaluation of measurement methods for organic, elemental and black carbon in ambient air monitoring sites." Atmospheric Environment 43(32): 5085-5091

The two selected wood stoves with old and new combustion technology were the old (Jøtul model 3) and new model (Jøtul F3) of the Jøtul 3 series. These stoves were selected based on several arguments enlightened further out in this report.

1.1 Measuring elemental and organic carbon

The method chosen to analyze the two carbonaceous components, EC and OC, was the thermal-optical method using the NIOSH protocol (5040, 1999), which is the most common method used to quantify the bulk carbon/organic content in collected particle matter[14]. Using this method, a filter sample (usually a punch from the sampling filter) is heated and sequentially volatile organics are evolved and oxidized. Eventually graphitic carbon in the sample is oxidized. In each case the carbon in the collected sample is evolved from the particles and detected as CH_4. The result is a measure of EC and OC. As previously mentioned EC and BC are operationally defined by the measurement method applied, although EC and BC are often used interchangeably[14,15,16]. EC is also referred to as light absorbing carbon (LAC) because it is one of the key components of atmospheric aerosols that contribute to positive radiative forcing[17]. Combustion of biomass and diesel are known to be a significant source for this carbon component[1]. Several studies indicate that atmospheric EC is the dominant anthropogenic absorber of incident solar radiation. In addition, it also absorbs thermal infrared radiation when deposited on the ground like in the case of snow and ice where it leads to accelerated melting. When deposited on the ground it changes the surface reflectivity which again ads to increased warming and melting (albedo effect). EC has been found to be a million times stronger absorber of solar radiation than CO_2[18].

1.2 Placing new national emission factors in context

To set the recommended emission factors based on the results from this measurement campaign in perspective, it is important to first look at the history for previously used factors and at the basis of which these national emission factors were established for wood stoves.

- Before 1970-80: Wood stoves were usually produced with only one air inlet, no insulated firebox and no secondary air. Coke stove and cooking stoves, however, could have several air intakes.
- 1970-80: The stove was modernized with larger glass area and used air flushing along the window.
- 1990: New combustion technologies for wood stoves were introduced.
- 1998: New combustion technology introduced and pushed forward because of new regulations that limited the particle emissions from wood stoves to 10 g/kg dry wood and never higher than 20 g/kg at any combustion rate.
- 2001: New emission factors for national emission calculations: Emissions of particulate matter with old technology: 40 g/kg (normal firing) / 33 grams per kilogram (medium firing, applied only for the larger cities). Emissions of particulate matter from clean-burning stoves: 6.2 g/kg.

[14] McMurry, Peter H., Marjorie F. Shepherd, and James S. Vickery. Particulate Matter Science for Policy Makers: A NARSTO Assessment. Cambridge University Press, 2004.
[15] «Summary of Organic and Elemental Carbon/Black Carbon Analysis Methods and Intercomparisons», Watson et al., Aerosol and Air Quality Research, Vol. 5, No.1, pp. 65-102, 2005
[16] Kim, Kyung Hwan. "Characteristics of Atmospheric Elemental Carbon (Char and Soot) in Ultrafine and Fine Particles in a Roadside Environment, Japan." Aerosol and Air Quality Research (2011), http://www.aaqr.org/Doi.php?id=1_AAQR-10-07-OA-0061.
[17] Ramanathan, V., Crutzen, P.J., Kiehl, J.T., Rosenfeld, D. (2001). Atmosphere: Aerosols, Climate, and the Hydrological cycle. Science 294: 2119–2124
[18] Jacobson, M. Z., Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols, Nature, 409, 695-697, 2001

- Efficiency with old technology: around 50 %. Efficiency with new technology: 70 - 80 %[5].

The emission factor used in the SSB/Klif (formerly SFT) emission model before 2000/2001[19] is shown in Table 2 and was 10 g/kg. At that time, one did not distinguish between wood stoves and open fireplaces, nor between traditional and clean-burning fireplaces. Following the introduction of the Norwegian standard requirements for particle emissions in 1998, SSB/Klif introduced new figures in 2001 as shown in Table 3. Here one distinguishes between open fireplace and enclosed stove/fireplace with old and new technology. The figures for enclosed stove/fireplace with old and new technologies are documented by SSB and are partly based on measurements and expert judgments from SINTEF[19].

Table 2. Emission factor for wood combustion used by the SSB/Klif up to 2000/2001[19]

Emission factors used until now by SSB/SFT in the Norwegian particle inventory model. g/kg		
Emission compound	g/kg	Source
PM_{10}	10	Rosland /1987)/Rådet for natur og miljøfag (1986)

Table 3. New emission factors SSB/Klif recommend for the national emission model[19]

Report 2001/36, recommended emission factors for fireplaces in wood stoves. 2000				
	Open fireplace	Enclosed wood stove/fireplace		
		Produced before 1998	Produced in 1998 or later	Unit
PM_{10}	17.3	40	6.2	g/kg

Table 4[20] presents emission factors found in literature from Canada and the United States. Both these countries have standards similar to the Norwegian standard, in the sense that they both use a dilution tunnel. The US standard EPA Method 28 allows particle sampling both from a dilution tunnel (Method 5G - PM Wood Heaters from a Dilution Tunnel) and directly in the stack (Method 5H - PM Wood Heaters from a Stack). When sampled directly in the stack, the flue gas is cooled down so that condensable matter can be collected. As shown in Table 4, the emission factors for tested stoves in Australia is based on collected data from more than 300 models of woodstoves for compliance with AS4013[21]. The average emission factor for all models tested was 3.3 g/kg dry fuel wood (AS4013 tested stoves - laboratory) in Table 4). The reviewers point out that this only represents actual emissions if one can assume that appliances are correctly operated and air-dry firewood is burnt as described in the Australian standard AS4013. The reviewers also generally acknowledged that “real-world” emission factors are higher, possibly by up to a factor of three, because an unknown proportion of households operate their stoves poorly and use wet firewood. This is reflected in what is actually used in the Australian emission inventories (Estimated 'real-world' WH for Australia), which uses estimates of average emission factors because no measurements of emission factors for appliances operating in people's homes have been made. The extrapolated “real-world” emission factor estimates (Estimated 'real-world' WH for Australia) can be seen to be close to measured “real-world” emission factors collected from the United States (AP42 Catalytic (real-world) and AP42 Certified (real-

[19] Utslipp til luft fra vedfyring i Norge Utslippsfaktorer, ildstedsbestand og fyringsvaner, Gisle Haakonsen og Eli Kvingedal 2001/36

[20] Review of literature on residential firewood use, wood-smoke and air toxics, Technical Report No. 4, Environment Australia, June 2002, ISBN 0 6425 4868 4

[21] AS/NZS 4013:1999, Domestic solid fuel burning appliances - Method for determination of flue gas emission, Australian/New Zealand Standards / 01-Jan-1999

world)) in Table 4. Again, it should be emphasized that both United States and Canada perform particle sampling in a dilution tunnel similar to what is described in the Norwegian standard. The US standard requires four categories of burn rates similar to the Norwegian standard while the Australian standard uses three test burns for each of three flow settings (high, medium and low) and includes a conditioning burn for each change of conditions. The Australian standard AS4013 uses a dilution tunnel method with dry hardwood (Norwegian standard uses soft wood) of specified density and size and incorporates measurements at three different airflow settings (low, medium, and high versus the four burn rates described in the Norwegian standard) with specified repetitions and conditioning burns.

The current estimated real-world emission factors for Australia, the United States and Canada are around twice as high as the factors used in Norway for new certified stoves. However, for old stoves the emission factors from these countries are only 0.3 (normal firing) to 0.4 (medium firing) of the current Norwegian emission factors.

Table 4. Emission factors for wood firing[20]

Particulate emission factors for PM_t (g/kg)				
	Wood stove	Range	Open fireplace	Range
AS4013 tested stoves (laboratory)	3.3	0.8 to 5.5		
Australian non-certified wood stoves	11	7 to 15		
Estimated 'real-world' WH for Australia	12.5	9 to 13.6		
DeAngelis et al. 1980	9.1	1 to 28	13	2.4 to 26
Cooper 1980	8.5	1 to 24	9.1	7.2 to 12
AP42 conventional (real-world), U.S. EPA, 1995[19]	15.3		17.3	
U.S. EPA, 1998	18.5			
AP42 Certified (real-world)	9.8	7.3 to 12.9		
AP42 Catalytic (real-world)	10.2	8.1 to 12.1		
Canadian Council of the Ministers of the Environment, Emissions and Projections Task Group (2000)*	13.6			

1.3 Overview of different measuring methods for wood stoves in Europe

Wood heating appliances such as wood stoves, fireplace inserts, fireplaces and boilers have been identified as significant sources for emissions to air. Hence, several countries have introduced emissions requirements for domestic heating with wood. Each stove, which comes on the European market, has to be approved according to the common EU standard EN 13240. This standard sets regulations for safety, efficiency and CO emissions. Some countries have established emission limits for particle emissions and developed measuring methods. The European Committee for Standardization, CEN/TC 295, has for several years worked on a common method for particle measurement. So far the European countries have not yet reached an agreement on one specific method. The two most important measurement methods for particles in Europe are the Norwegian Standard for Enclosed wood heaters using particle sampling in a dilution tunnel and the DIN-plus certification scheme with hot flue gas particle sampling directly in the chimney. The use of these two methods will result in variation in the emission levels, mainly for the total mass of the condensable matter, due to differences in the test procedures as described below.

1.3.1 Norwegian Standard for Enclosed wood heaters NS 3058-1/2, NS 3059

Since 1998, enclosed wood heaters must be approved for sale and use in Norway according to Norwegian standard NS 3058[22]. The stove and fireplaces have to meet the emissions requirements described in NS 3059[23] and shown in Table 5. Denmark also introduced emission limits for wood stoves in 2008 where stoves (brændeovne) must be tested according to either NS3058/59 or DIN-plus certification scheme. The Nordic Swan Ecolabel requires additional testing according to the Norwegian standard NS 3058/59 but with a stricter emission limit of 4 g/kg.

Table 5. Emission limits according to the Norwegian Standard[22]

	Maximum allowable emission for one test (d.b.)	Maximum weighted mean value (d.b.)
Wood heaters	20 g/kg	10 g/kg

NS 3058-1 describes the test facility, fuel and heating patterns. NS 3058-2 gives criteria for the determination of particles sampled in a dilution tunnel. The approval must be performed with four tests at different burn rates (Table 6). The standard divides enclosed wood heaters in two grades; Grade 1 and 2. Grade 1 enfolds stoves and fireplace inserts which can be operated with very low burn rate below 0.8 kg/h. These stoves are in general smaller units. Appliances in Grade 2 achieve the lowest burn rate below 1.25 kg/h but above 0.8 kg/h. Testing at four different burn rates shall reflect real-world firing habits in Norway and take into account that stoves can handle a range of burn rates without compromising particle emissions. NS 3059 describes the final calculation of the four test runs with a specific weighting, depending on the grade and a probable burning pattern.

Table 6. Burn rate categories[22]

Burn rate category [Average burn rate kg/h dry]	1	2	3	4
Grade 1	< 0.80	0.80 – 1.25	1.26 – 1.90	> 1.90
Grade 2	< 1.25	1.25 – 1.90	1.91 – 2.80	> 2.80

The test fuel consists of air dried timbered spruce with moisture content between 16-20 % on the wet basis and weight of 112 ± 11 kg/m^3 of the useable firebox volume. The geometry of the test fuel is shown in Figure 2. The test facility consists of a chimney with a height of about 4.5 m measured from the bottom of the stove to allow testing with natural draft. A dilution tunnel is installed to dilute the exhaust gas with ambient air and cooling the flue gas down close to room temperature. The tests are performed with natural draft (Figure 3). The particle measurement is located in the dilution tunnel and the gas is withdrawn isokinetic with constant volume flow. The filter holder contains two circular 10 cm in diameter plane filters in succession with a porosity of 1 µm.

[22] NORSK STANDARD, NS-3058 (1994), Enclosed wood heaters, Smoke emission
[23] NORSK STANDARD, NS-3059 (1994), Enclosed wood heaters, Smoke emission, Requirements

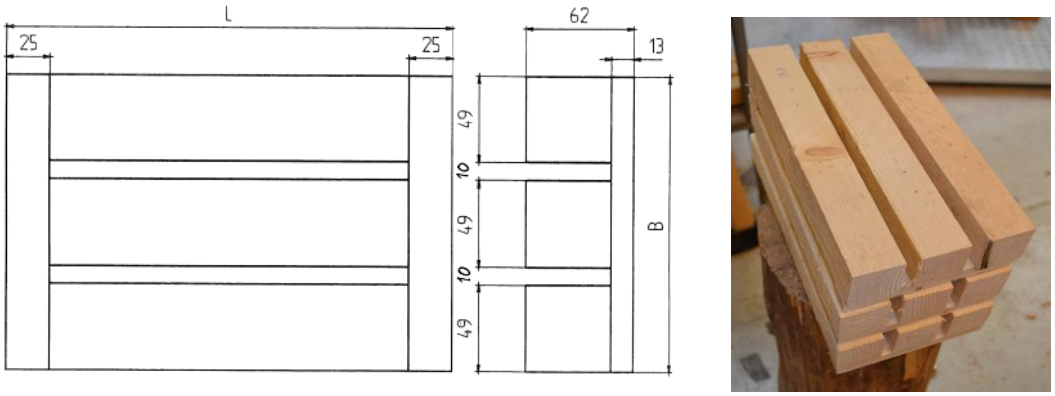


Figure 2. Test fuel geometry according to the Norwegian Standard[22]

The test is performed in a preheated stove, and the emissions are sampled over the whole batch of one fuel load. The requirements are that the pre-test[22] shall last at least one hour with the desired air opening and shall give an amount of charcoal corresponding to 20 to 25 % of the test fuel weight. The average surface temperature shall not differ more than 70 °C from the start to the end of the test, to ensure the stove is in thermal balance. The collected particles are recorded gravimetrically and reported in g/kg dry wood.

1.3.2 EN 13240 – Roomheaters fired by solid fuel

All roomheaters on the European market, including Norway, must be tested according to the standard EN 13240. It combines the basic requirements as with focus on manufacture, construction, safety, performance (efficiency, carbon monoxide emissions), instruction and labelling. It addresses manual feed boilers, stoves and fireplaces inserts fired by solid fuels such as wood logs as well as mineral fuels and peat briquettes. The requirements on CO emissions are 1 vol % and the minimum efficiency is 50 % (see Table 7). EN13240 does not contain requirements for particulate matter emissions. The standard describes the test method and test fuel. The test is performed at nominal heat output with a test fuel defined by the manufacturer with constant forced draught at 12 Pa. In addition to CO emissions, CO_2 levels in the flue gas are recorded. Before the test periods starts, the stove is preheated through an ignition and pre-test period. The following test period consist out of three loadings with a minimum duration of 45 min.

Table 7. Requirements EN 13240 Roomheaters fired by solid fuel

	Limit value
CO	< 1 vol %
Efficiency	> 50 %

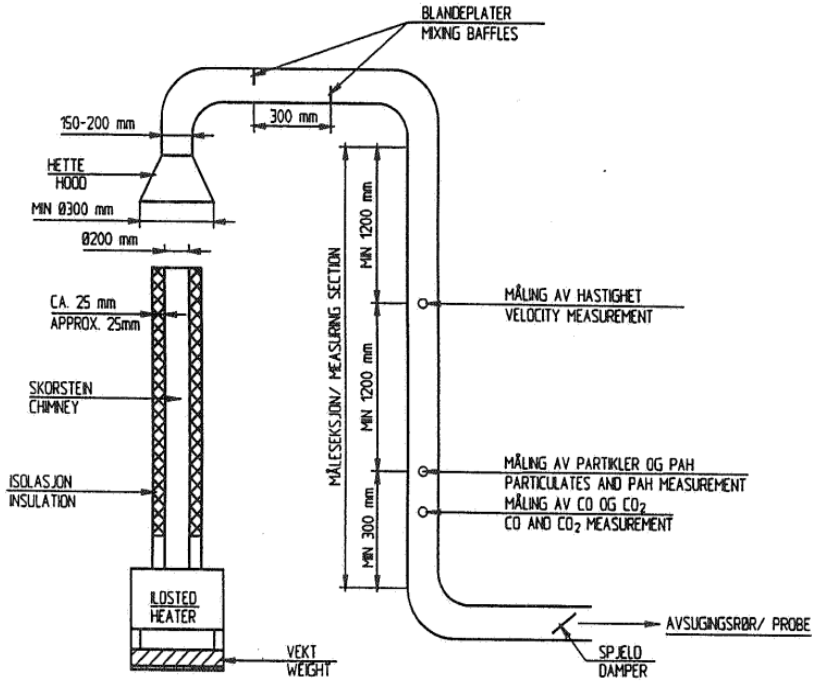


Figure 3. Dilution tunnel with wood heater and chimney (NS 3058)

1.3.3 German method DIN-plus

The German method is based on the certification scheme DIN-plus with stricter requirements than EN 13240 (roomheaters), EN 13229 (inset appliances) and EN 12815 (residential cookers) and includes particle measurement in addition to nitrogen oxides and unburned hydrocarbons. The requirements are shown in Table 8. The particle sampling starts 3 min after the fuel has been added and continues for 30 minutes. A volume of 0.280 Nm^3 is withdrawn in this period. The temperature in the filter is heated up to 70 °C[24]. The tests are performed according to the described test procedure and test set up in the European standards EN 13240, EN 13229 and EN 12815.

Table 8. Requirements on wood stoves according to DIN-plus certification

	Emission and efficiency limits
CO	1500 mg / Nm^3 (corresponds to 0,12 Vol-% at 13 % O2)
NO_x	200 mg / Nm^3
C_nH_m	120 mg / Nm^3
Dust	75 mg / Nm^3
Efficiency	75 %

[24] DINplus certification scheme: Room Heaters (Solid Fuel Stoves) with low-pollution combustion according to DIN EN 13240

1.3.4 Differences in standards and methods

The standards and methods differ in several ways. The most significant differences are which emissions that are measured, test facility, sampling location, sampling temperature, sampling period, heat output and fuel. Table 9 gives an overview about the differences between particles sampling according to NS 3058 and DIN-plus (which includes particle measurements in contrast to EN13240).

Table 9. Overview of the main differences between NS3058 and EN 13240/DIN-plus

	DIN-plus 13240	NS 3058
Location	Chimney	Dilution tunnel
Draught	Forced 12 Pa	natural
Sampling temperature	70°C	35°C
Fuel	Hardwood (logs)	Softwood (profiled timber)
Weight of the test fuel	Acc. to manufacture	112 ± 11 kg/m^3 of the firebox volume
Test condition	Nominal heat output (specified by manufacturer)	4 burn rate categories
Unit	mg/Nm^3	g/kg

Sampling temperature and location influences the kind of particles collected. DIN-plus measurements in the hot undiluted flue gas result in collection of the solid fraction of particles only. However, stoves operated under poor conditions show a high share of condensable particles of organic substances. To collect all particulate matter, the filtration temperature needs to be reduced. By application of NS 3058, dilution of the flue gas with ambient air mimic the natural particle formation from small-scale wood combustion, giving a more close to real-world picture of the total particles released[25].

Sampling particles in the hot undiluted flue gas (DIN-plus) might result in under-estimation of PM due to formation of aerosols of condensable matter in the flue gas when cooling down to ambient temperature. The ratio of particles in the dilution tunnel to particles measured in the chimney depends on the combustion conditions. If the combustion is good, as at nominal conditions meaning almost complete burnout of particle and gaseous flue gas compounds, there may be minor differences between dilution tunnel and the chimney measurements. In general, the dilution tunnel measurements in line with the Norwegian standard produce at least around 2.5 times more PM_t. At unfavorable conditions, the ratio increases up to 10. Then 10 times more PM_t are collected in the dilution tunnel compared to the chimney.[26] The dilution tunnel measurements might on the other hand result in over-estimation of PM_t due to re-evaporation of VOC from the particles by consecutive dilutions with increasing dilution ratio. This may occur when exhaust gas is diluted with ambient air after leaving the chimney[27].

Emission factors according to NS are much higher than emission factors from other European countries using a different measurement method[26]. Differences are primarily due to testing on low load, and applying

[25] Nussbaumer T, Czasch C, Klippel N, Johansson L, Tullin C. Particle emissions from biomass combustion in IEA countries- Survey on measurements and emission factors. International Energy Agency (IEA) Bioenergy Task 32; Swiss Federal Office of Energy; 2008

[26] Nussbaumer, T.; Klippel, N.; Johansson, L. 2008; Survey on measurements and emission factors on particles matter from biomass combustion in IEA countries, 16th European Biomass Conference and Exhibition, 2–6 June 2008, Valencia, Spain – Oral Presentation OA 9.2

[27] Nussbaumer T. Feinstaub-Emmisionsfaktoren von Holzheizungen: Übersicht aus Ländern der Internationalen Energie Agentur – Bioenergy Combustion Task. 10. Holzenergie-Symposium 12.09.2008

a dilution tunnel in which the particles are sampled. The Norwegian standard requires four tests, at four different burn rates. The stoves are tested under less favorable combustion conditions with reduced burn rates lower than 1.25 g/kg. This leads to much higher emissions compared to tests performed only under the combustion condition for which the stove is optimized for, also referred to as nominal load. The dilution tunnel captures condensed particles in addition to solid particles. In conclusion, the choice of measurement method and test procedure have a major influence on the emission factors and can to a large degree explain why different countries report such varying emission factors. Particularly, Norway reports the highest wood stove emission factor in Europe with 1297mg/MJ, which corresponds to an average emission factor of 24 g/kg for old and new stoves. Germany reports an emission factor of 105 mg/MJ for wood heating in households[28].

2 Measurement of PM_t, EC and OC

2.1 Choice of representative wood stoves

To provide emission factors that reflect the total emissions from wood stoves in Norway is not a trivial task. Installed wood stove appliances in Norway can vary from the most modern stoves with state-of-the-art technology for particle emissions reduction and all the way down to the simplest stoves containing none of the particle reducing technologies. SSB, supported by Norwegian Water Resources and Energy Directorate (NVE), The Norwegian Agricultural Authority (SLF) and Klif, perform an annual survey were they ask around 4 000 consumers what type of stove they actually use. The result for 2011 is that the number of households using wood stoves with new and old technology was roughly 50/50.

The selection of representative wood stoves with new and old technology was conducted in collaboration with stove producers (Dovre, Jøtul), NBL and personnel at SINTEF Energy Research. The criteria for the selection were:

- Sales statistics and knowledge of particle emission levels since 1998 for wood stoves with new technology. In corporation with two of the main wood stove producers in Norway, Jøtul and Dovre, we had access to sales statistics to support the selection of a wood stove with new technology. This information is however confidential and cannot be released in this report.
- The selected stove should be that kind of a stove that people typically buy when in need for a robust and easy stove, which they plan to operate frequently. This as opposed to stoves with larger glass area which we assume parts of the consumers mainly buy for pleasure and only use during the coldest periods Stoves that are widely available and have been on the market for a representative number of years.
- The average cost of the stove. It was assumed that the main part of the consumers is only willing to invest in an average cost stove.

Additional reasoning was made for the selection of an old representative stove:

- Households with stoves of the oldest type, i.e. without glass, secondary air and insulated combustion chamber, are more likely to switch to a modern fireplace as opposed to households with stoves of a somewhat newer type, i.e. glass with a certain area with window flushing.
- Stoves of the oldest type are often leaky, have poor efficiency and are often impractical in use.
- The selected wood stove with old technology should not contain any of today's technological solutions but could include an air blown window.

[28] Struschka, M. et al. (2008), " Effiziente Bereitstellung aktueller Emissionsdaten für die Luftreinhaltung", Umweltbundesamt

Based on the above-mentioned criteria, the Jøtul 3 series was selected. As it happens this series is available both without (Jøtul model 3) and with, new combustion technology (Jøtul F3). The new model has been on the market since around 2000-2001. As a side-note and according to sales statistics in North America, the Jøtul 3 series is the best-selling small/medium cast iron wood stove selling up to 20 000 stoves worldwide each year. To our knowledge, no measurement data exists for the old stove type that may relate to the current measurements. However, for the new model a test protocol exists, providing weighted particle emissions of 6.05 g/kg. Figure 4 shows an excerpt from Jøtul's website illustrating the new F3 type.

In the selection of representative stoves, it should be emphasized that there is currently no distinction between old types of stoves. All stoves older than 1998, are considered to be of the old type having an estimated average emission of 40 g/kg assuming normal firing. This figure is based on previous research carried out by SINTEF Energy as depicted to the right in Figure 4[19]. When a representative old stove model was to be selected, the choice fell on a stove that does not have today's new combustion technology but has window air flushing. The selection is based on the assumption that the major consumers of wood, which owns a stove in the category older than 1998, most likely do not use the oldest type of stoves. The assumption is that these stoves are inconvenient to use and have such poor efficiency that they are not used for other purposes than heating during the coldest periods. Households that possess this type of stoves are assumed to be more inclined to switch to the new stoves than households with stoves of the selected type.

Figure 5 provides some illustrative images that show the difference between old and new stoves. Figure 6 exemplifies the main differences between the oldest types (prior to 1970-80) and more modern stoves (1970-80 and up to 1998). Based on these assumptions one should perhaps, in the national emission inventory, distinguish between two types of stoves with old technology by rephrasing/adding some of the questions in the "firing habits" survey referred to earlier.

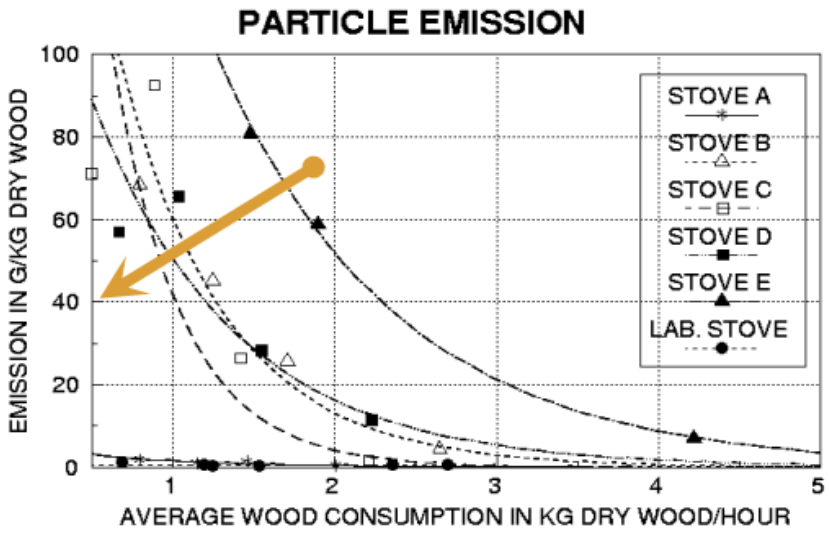


Figure 4. Earlier measurement of different old stove types A-E as well as a laboratory stove. The arrow indicates the current emission factor for old stoves with normal firing. These measurements were the basis for the choice of emission factor (normal firing equal a wood consumption of 1.25 kg/h) of 40 g PM_t/kg for wood stove with old technology in the Norwegian emission inventory

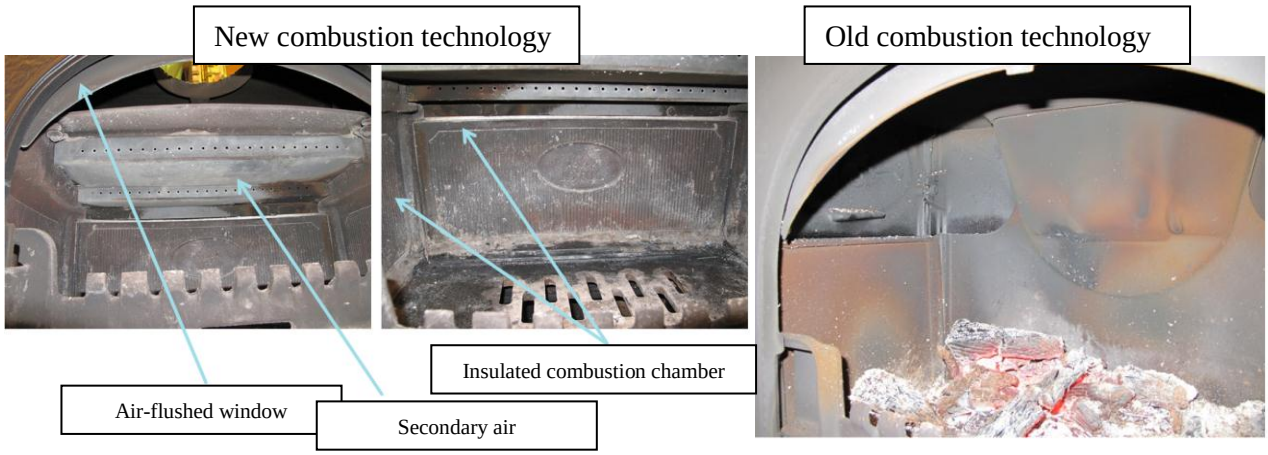


Figure 5. Specific differences between wood stoves with old and new technology

Wood stoves prior to 1970 – 80 (very old):

- no or almost no window, nor window flushing
- no insulation of combustion chamber
- no secondary air





Wood stoves between 1970 – 80 and up to 1998 (old):

- window with window flushing
- no insulation of combustion chamber
- no secondary air





Figure 6 . Categorization of stove types with old technology

2.2 Experimental setup

The experiments were carried out by SINTEF Energy and NBL in their respective laboratories on the two selected Jøtul F3 wood burning stoves, considered to be representative for Norwegian emissions. NBL performered the tests at the stove with old technology while SINTEF Energy tested the stove with new technology. The stove model with old technology was control tested at low burn rate at SINTEF Energy for comparison with experiments performed at NBL. To achieve an acceptable statistical accuracy three repetitive experiments for each of the four required burn rate categories for each stove were performed:

- Stove model with old technology, 3 repetitive experiments at 4 burn rates tested at NBL
- Stove model with new technology, 3 repetitive experiments at 4 burn rates tested at SINTEF Energy

Total number of tests: 2 x 3 x 4 = 24

2.3 Test facility

The wood stove burning test facility installed according to the Norwegian Standard NS 3058 consisted of the stove placed on a scale and connected to an insulated chimney with an interior diameter of 20 cm. The scale enables measurements of the fuel consumption rate. A dilution tunnel is situated above the chimney in which the flue gas leaving the chimney is collected through a hood where ambient air mixes with the flue gas. Particles are sampled in the dilution tunnel isokinetically, i.e. sampled at the same velocity as the fluegas velocity in the dilution tunnel, with two double filter holders (Figure 7). A fan connected to the dilution tunnel outlet controls the dilution ratio.

The main purpose of the experiments was to measure the emission of particles. These were captured isokinetically in the dilution tunnel by a filter using a pump as shown in Figure 7 and Figure 8. The particle filters were installed in a double-particle filter holder as illustrated in Figure 9. In these experiments two double filter holders were used to comply with the selected filtering proceedure for the OC/EC analysis in Finland, as compared to the use of a single filterholder as decsribed in the Norwegian Standard.

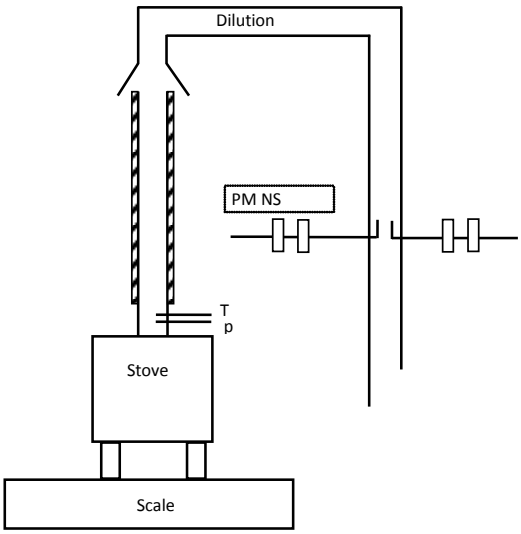


Figure 7. Test facility according NS 3058

The tests were carried out according to NS3058, which is assumed to produce results that are representative for Norwegian emissions. Further layout as it appears in SINTEF Energy's laboratory is shown in Figure 9, with standardized wood test fuel and filter holder.

Figure 8. Illustration of experimental setup according to NS3058/NS3059

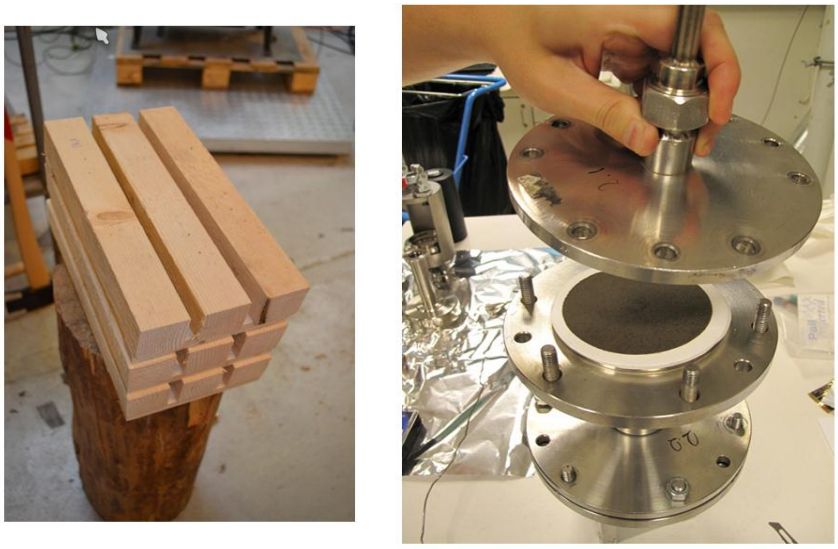


Figure 9. Fuel and filter holder according to NS3058

2.3.1 Test procedure

The experiments were performed using standard preheating to achieve thermal balance of the stove, lasting at least one hour with the same air inlets positions as must be used during the test measurements. The Norwegian standard requires birch as fuel to preheat the stove. The test fuel was loaded when an equivalent weight of 20-25 % of the test fuel charge remained in the stove. During the ignition of the test fuel, the door was slightly open up to 1 minute depending on the burn rate category. The air inlets were completely open in the beginning and set to the desired position after 5 minutes (completely open, 5mm

open, 3mm open, closed; according to burn rate category 4 to 1). Particles were sampled over the total burning cycle, starting when the test fuel was loaded and ending when the test fuel had been consumed.

2.3.2 Filter Handling

The measurement of EC and OC required a second double filter holder with quartz fiber filter as opposed to the Norwegian standard which only requires one sampling line with two glass fiber filters (one for sampling and one for backup). Quartz filters are used because the analysis of EC and OC takes place at high temperatures. The two filter holders were divided into two sampling lines as illustrated in Figure 10. The first sampling line contained two quartz filters (so-called "quartz behind quartz", QBQ). The front quartz filter collects both gaseous OC and particle form OC and EC. The second sampling line contained a PTFE filter and a quartz filter (so-called "quartz behind Teflon", QBT)[29]. Using a PTFE/Teflon filter in the second sampling line is often recommended because it is marginally more inert to absorption of gaseous hydrocarbons. Particulate carbon was quantified by subtracting the particle mass on the back quartz filter (2. line, later 2.2) from the particle mass on the front quartz filter (1. line, later 1.1).

Due to long delivery time for PTFE filters from the manufacturer and the tight project schedule, glass fiber filters had to be used instead of the preferred PTFE filters in the experiments concerning the stove with old combustion technology. A quick literature survey found no specific figures concerning the exact "inertness" of Teflon, quartz and glass fiber filters other than statements saying that Teflon is the most inert and that quartz and glass fiber absorbs marginal amounts of gaseous hydrocarbons. Based on this it was concluded that the application of different filters did not affect the measurements significantly. However, for the experiments on the stove with new combustion technology, PTFE filters were applied. Here, gaseous OC, which was subtracted from the front quartz (1.1) analysis result, was generally 2–7 %. This meant that the OC results, analyzed from particles sampled on glass fiber filters during operation of the stove with old combustion technology, included both particle phase OC and gaseous phase OC. Initial filter analyses showed that the amount of gaseous OC was approximately 2–7 % of the total mass of OC sampled on both the front and back filter.

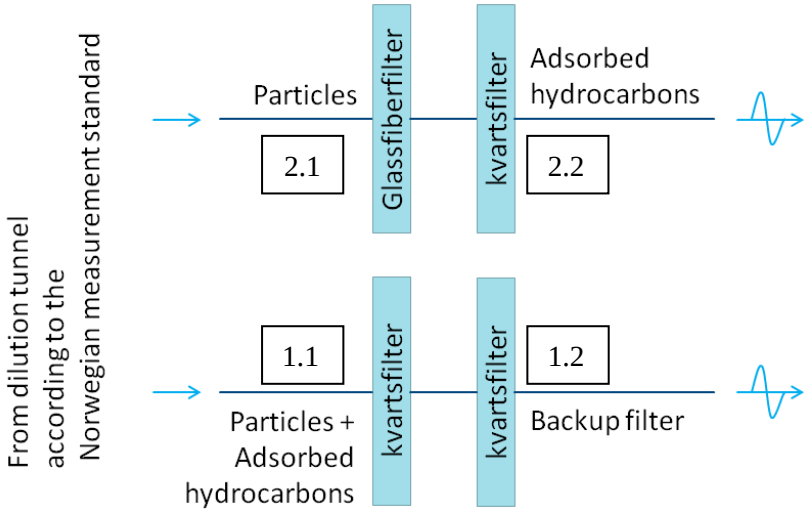


Figure 10. Left: Illustration of two double filter holders for OC and EC analysis for old technology stove

[29] Turpin, B.J., Saxena, P., Andrews, E., 2000. Measuring and simulating particulate organics in the atmosphere: problems and prospects. Atmospheric Environment 34, 2983–3013

Teflon and glass fibre filter were stored 24 hours before and after the test in a desiccator. The quartz fiber filters were purified at 800 °C for 4 hours in order to remove any possible traces of organic material on the filters. This is especially important if low quantities of OC and EC are analyzed. The quartz fiber filter were then stored in acid washed petri dishes in a desiccator for 24 hours before and after the test. After weighing were all quartz fiber filters stored at -18 °C and then shipped to Kuiopo, Finland, in dry ice for analysis. Two filters from each experiment were submitted for analysis, the front filter in the filter holder A and the rear filter in the filter holder B. The intention is to differentiate between the hydrocarbon gases adsorbed in the filter and the particles fraction. For each filter tested, three parts of the filter were analysed, giving a total number of analysis corresponding to 2 x 3 x 4 x 2 x 3 = 144 analysis which were conducted by the University of Eastern Finland (UEF). UEF stored the filters after analysis at -18 °C.

2.4 Description of the OC/EC analysis procedure

The following is a description of the method selected by SINTEF to measure the two carbonaceous components, EC and OC. The analysis of elemental carbon (EC) and organic carbon (OC) were performed with an OC/EC analyzer manufactured by Sunset Laboratory Inc. The analyzer operated with a thermal-optical measurement principle, which Figure 11 shows and the NIOSH protocol 5040 (National Institute for Occupational Safety and Health, 1999) is used. A 1.5 cm^2 piece of the filter was punched from the original quartz filter and the punch was used in the analysis. The sample is pyrolyzed in an oxygenfree helium atmosphere were OC were released at 300, 470, 610 and 865 °C, according to the protocol, allowing the vaporizing of the carbon-containing compounds. The vaporized compounds are the most volatile part of the total carbon. The helium containing OC is first sent to an oxidizer oven where the carbon compounds form CO_2, and then to a methanator to form CH_4. The quantity of carbon corresponding to OC is finally measured using flame ionization detection (FID), which generally delivers more sensitive detection than direct quantification of CO_2[30]. Once the first step is completed, the sample oven is cooled down to 550 °C and 2 % oxygen is added to the helium atmosphere to enable oxidation reactions of EC to CO_2. The flow containing CO_2 is sent to a methanator to form CH_4, which then provides the quantity of carbon corresponding to EC using FID. EC was determined 550, 620, 700, 780, 850 and 865 °C (NIOSH method 5040, 1999). The NIOSH procedure was slightly modified by lengthening of the OC4 step. The change was done since the original protocol has not always been enough to convert all the OC from the sample. Part of the OC are inevitably converted into chars (turns to EC) in an oxygen deficient atmosphere, leading to an ambiguous determination[30]. Correction of pyrolytic conversion of OC to EC was done by laser transmission measurement.

3 Results and Discussion

The results presented below are results from analyzing particulate matter captured on filters during wood stove experiments performed according to the Norwegian standard, on two selected wood stoves, one with new and one with old combustion technology. As discussed in previous chapters the selected method, a thermal – optical method, provides results for the two carbonaceous components, EC and OC. Measurement results for PM_t, OC and EC are in g/kg (grams of PM_t, OC and EC per kilo dry fuel wood consumption).

[30] Watson, J. G., J. C. Chow, et al. (2005). "Summary of Organic and Elemental Carbon/Black Carbon Analysis Methods and Intercomparisons." Aerosol and Air Quality Research Vol. 5(No. 1): pp. 65-102

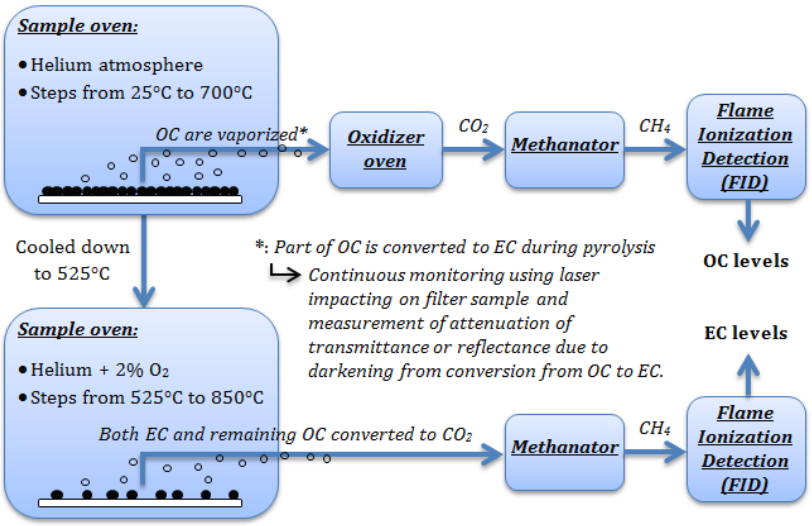


Figure 11. Synaptic of the thermal optical analysis of quartz fiber filters, adapted from description from Sunset Laboratory Inc. 2010[31]

Figure 12 shows some examples of measurement protocols from the current wood stove testing according to NS for new technology stove as well as an image of all four filters, two from each sampling line. As we can see, the front filter in each line collects the main part of the particulate matter. A slight coloring of the back filters, 1.2 and 2.2, is observed. This coloring is mainly due to condensation and adsorption of gaseous hydrocarbons. It can also be seen that the two front filters, 1.1 and 2.1, differ in color. The 1.1 and the 2.1 filters are made from quartz and Teflon material, respectively, which possibly explains the color difference. Sampling for both the double filter holders is done at the same location in the dilution tunnel and should therefore not affect the particle sampling through each sampling line. Normally when sampling particulate matter from wood stove experiments one can observe the variation in filter color depending on the burn rate. Low burn rate often produces brownish colored filters, while high burn rate tends to produce quite black filters.

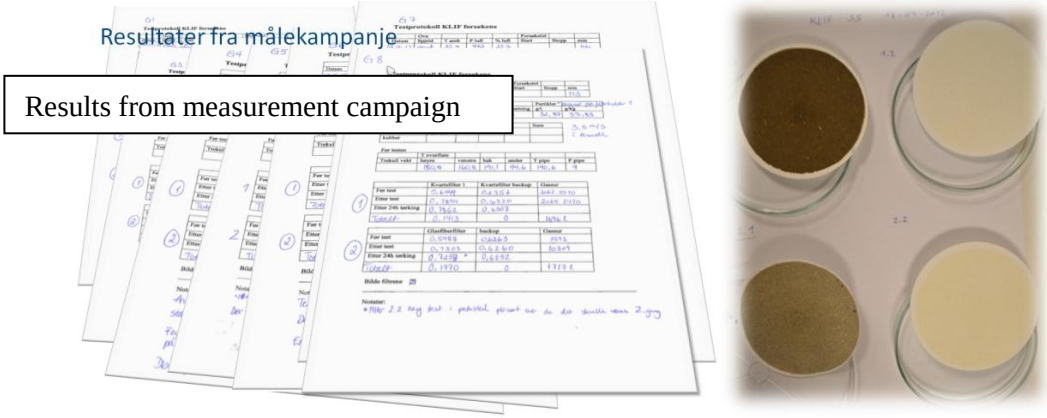


Figure 12. Measurement protocol for some stove experiments according to NS (left) as well as an illustrative image of all four filters from both sampling lines in a new technology stove experiment, first sampling line 1.1 (QBQ) and 1.2 (QBT) (bottom), second sampling line 2.1 (QBQ) and 2.2 (QBT) (top)

[31] Sunset Laboratory. (2010). "Sample Analysis Method for Organic and Elemental Carbon Aerosols." 2012, from http://www.sunlab.com/uploads/assets/product/Sunset%20Lab%20Analysis%20Method.pdf

3.1 PM_t, OC and EC emissions

The following chapter presents the results from particle sampling analysis and the outcome for all experiments including total amount of particle mass and the distribution of organic and elemental carbon in the samples particles. The uncertainties for particle emissions and OC/EC emissions are described including extra tests performed to improve the OC/EC results. Overall, 11 experiments for the stove with old combustion technology and 12 experiments for the stove with new combustion technology are presented in this report. One experiment from the stove with old technology for burn rate category two was not sent to analysis in Finland since three experiments in this burn rate category had already been obtained. For the stove with new combustion technology, one additional sample was analyzed by UEF, giving a total of 24 analyses. However, the results from this additional analysis (S4) is not reported in the following results because the humidity in the wood fuel was judged too high compared to the wood fuel humidity in the remaining experiments.

3.1.1 PM_t emissions

Figure 13 shows values from the filter analysis for PM_t in g/kg, on a dry basis for wood stoves with old and new technology. Both stoves show a clear trend that emission decreases as a power decay function with increasing burn rate (wood consumption per hour) as it can be seen in Figure 13. This is in line with experience from previous measurements performed at SINTEF and NBL. The burn rate is normally an indicator for the combustion quality. Low burn rate (below 1.25 kg/h) occurs when the air inlet valve is almost closed, resulting in poor, smoldering combustion and in general high emission levels due to incomplete combustion. In opposite to this, high burn rate with fully opened air inlet valve results in good combustion conditions with almost complete burnout and low emissions. Still, two tests with same burn rate can result in rather different emission levels. This is explained in more detail below. The stove with old technology emits significantly more particles for very low wood consumption or burn rates (below 1.25 kg/h) than the stove with new combustion technology. Particle emissions are between 30 to 43 g PM_t/kg wood for the old stove. For burn rates higher than 1.9 kg/h, the old stove releases 6-7 g/kg. The lowest emissions detected for this stove was 1.9 g/kg at a burn rate of 5.2 kg/h. The stove with new technology produces low emissions (around 14 g/kg) for the lowest burn rate category (below 1.25 kg/h). However, at a burn rate of around 1.5 kg/h, the stove produced some unexpected high emissions, up to 34 g/kg. An explanation might be that the stove with new technology had been in use for several years and had developed increased leakages due to deterioration of ceilings and gaskets, causing unfavorable combustion condition at this particular burn rate. Burn rates higher than 2 kg/h resulted in emissions below 5 g/kg and down to 1 g/kg for the highest burn rates.

Below each chart for PM_t, OC and EC are shown calculated values for z = (measured value-average value)/standard deviation) where z is a measure of whether a value in a group does not differ significantly from the rest of the values in the group when $-3 > z > 3$. Calculated z-values show that all reported values are well within the range $-3 > z > 3$.

3.1.2 OC and EC emissions

Figure 14 shows values from the filter analysis for OC in g/kg, on a dry basis, for wood stoves with old and new technology. OC emissions show a similar trend as for PM_t, i.e. emissions decrease as a power function with increasing burn rate. Poor combustion conditions at low burn rates results in incomplete combustion and high particle emissions with a major fraction of OC. Good combustion conditions (high burn rates) with almost full burnout of the gases released during the combustion process, results in much lower OC concentrations.

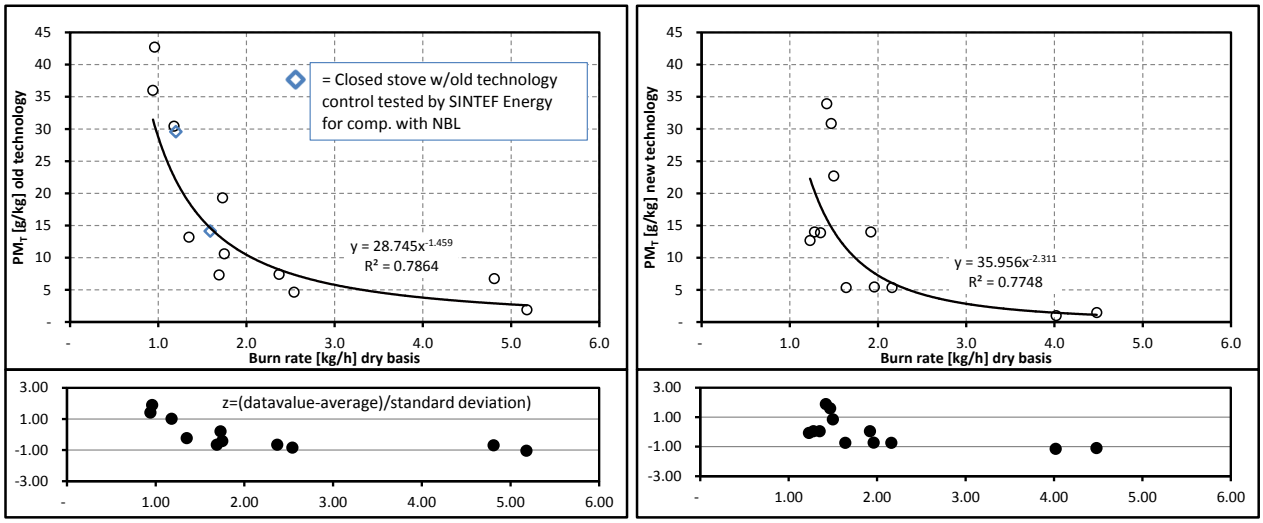


Figure 13. PM_t in [g/kg] vs. dry basis burn rate of wood [kg/h] with associated plots of z= measured value-average value)/standard deviation. Old technology stove to the left. New technology stove to the right

EC emissions (Figure 15) are heavily scattered when plotted against the burn rate, in contrast to the PM_t and OC emission. Both stoves produce rather scattered results, which makes it difficult to conclude on the dependency of the burn rate. However, we do observe that for the old stove the lowest EC emissions (0.3 g EC/kg wood) are obtained when the lowest particle and OC emissions (1.9 g/kg and 0.9 g/kg respectively) occur which is at the highest burn rate (5.2 kg/h). Similar results are obtained for the new stove where emisisons of all particle types are lowest at high burn rates (4.0-4.5 kg/h). The lowest EC emissions (around 0.3 g/kg) are obtained for the tests with the highest burn rate (4-5 kg/h) and lowest PM_t (around 1 g/kg) and OC (around 0.35 g/kg) emissions. This indicates that at very good combustion conditions, with low particle emissions (below 2 g/kg) and OC emissions (below 0.7 g/kg), we can expect EC emissions to be low as well. However more measurements are required in order to prove a clear dependence between combustion conditions and EC emissions. EC emissions over all burn rates were measured between 0.3 and 1.6 g/kg.

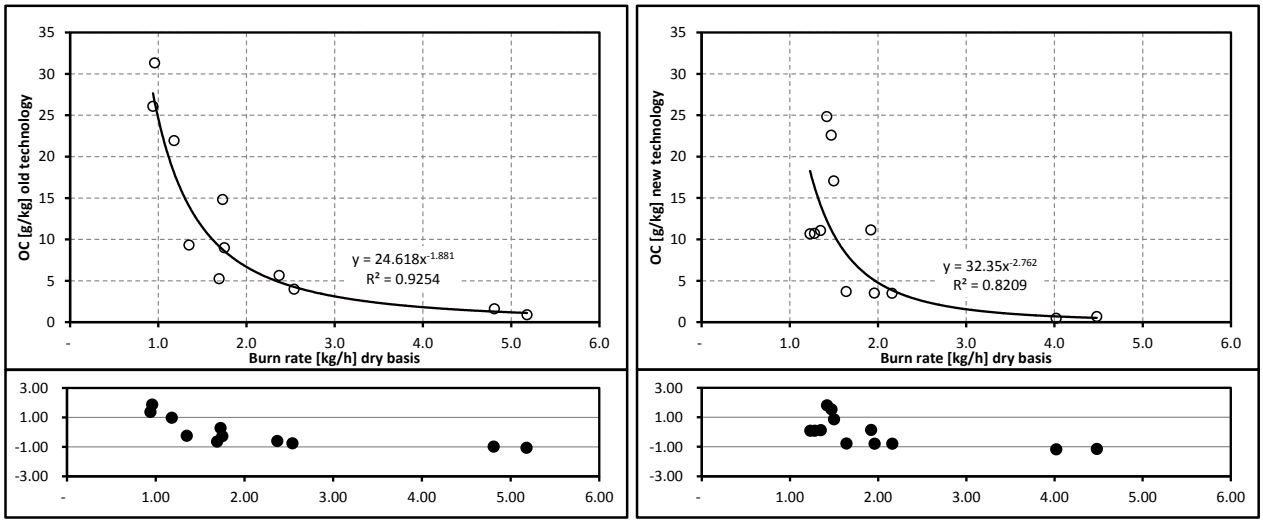


Figure 14. OC in [g/kg] vs. dry basis burn rate of wood [kg/h] with associated plots of z= measured value-average value)/standard deviation. Old technology stove to the left. New technology stove to the right

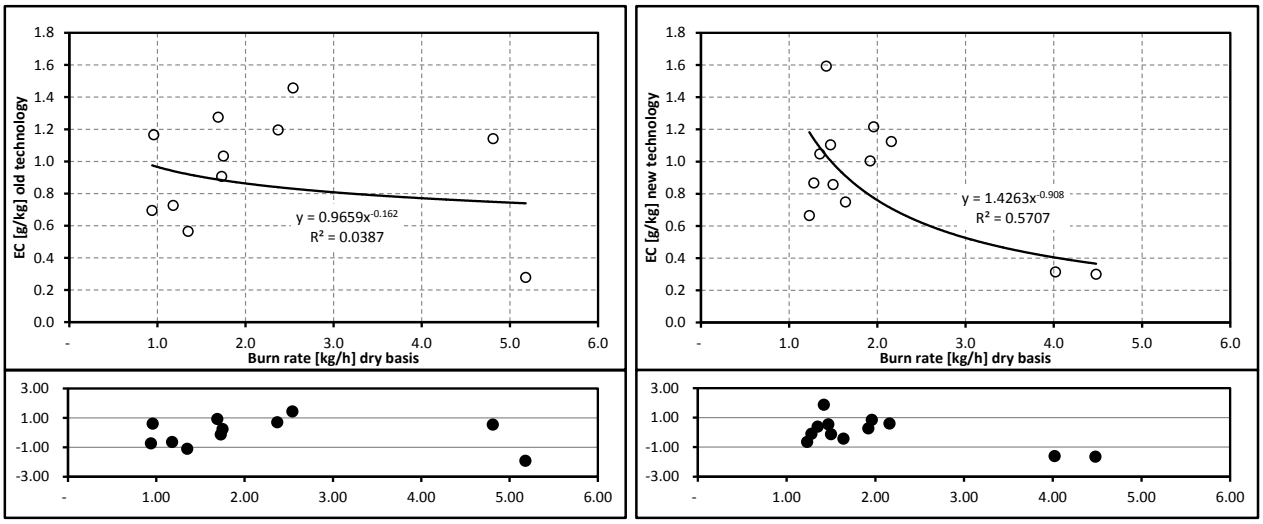


Figure 15. EC in [g/kg] vs. dry basis burn rate of wood [kg/h] with associated plots of z= measured value-average value)/standard deviation. Old technology stove to the left. New technology stove to the right

EC and OC vs. PM_t are shown in Figure 16 highlighting the constant behavior of EC as opposed to the linear increase in OC as the total particle emissions increase, seemingly independent of old or new technology. Increasing PM_t emissions are a result of incomplete combustion, which again produces more unburned hydrocarbons, resulting in increased mass of OC. When the overall particle load is small the share of EC increases due to a lower fraction of OC. Figure 17 shows the EC/OC ratio versus burn rate and PM_t. The EC/OC ratio increases with higher burn rate (Figure 17, left) which corresponds to the smaller fraction of OC emission released with better burnout. The EC/OC ratio decreases with increasing particle emissions (Figure 17, right) for both new and old technology. This is because the mass of unburnt OC in the total particle mass increases.

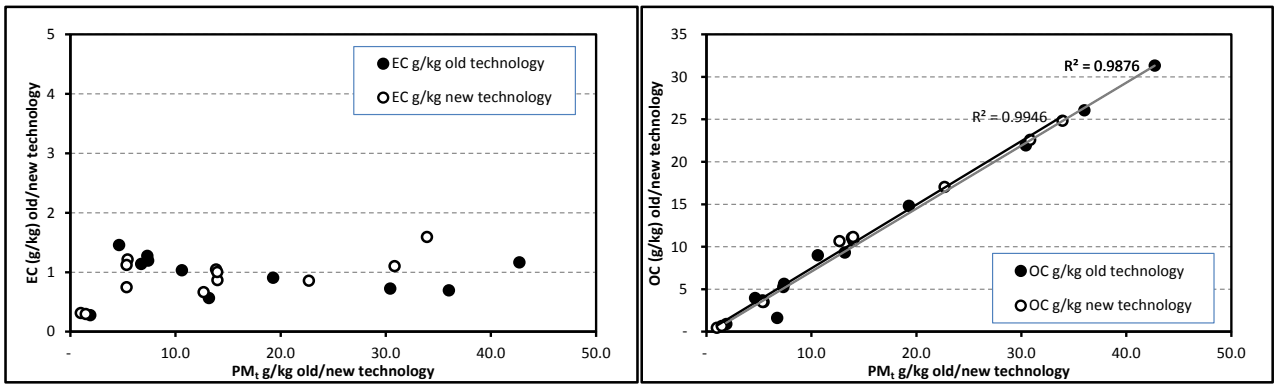


Figure 16. EC (left) and OC (right) vs. PM_t for stoves with old and new technology

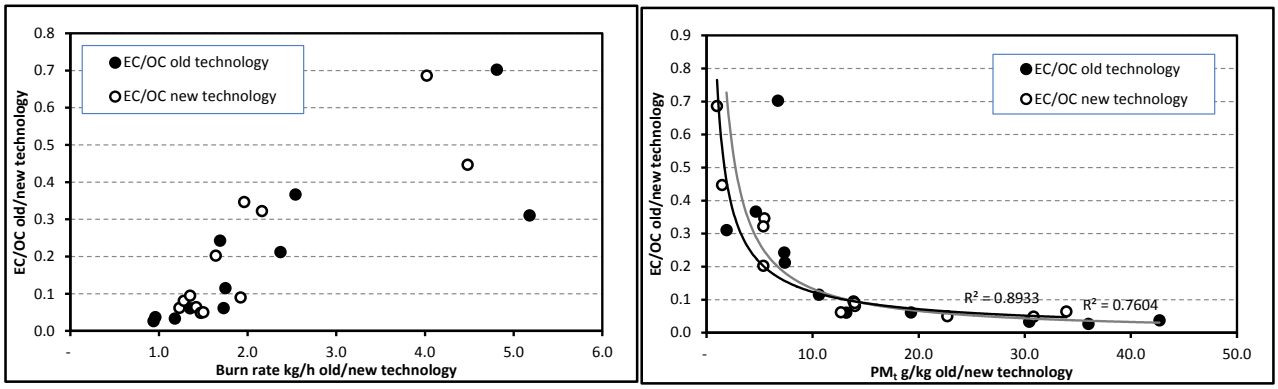


Figure 17. Left: ratio of EC/OC for old and new technology vs. burn rate. Right: ratio of EC/OC for old and new technology vs. PM_t

3.1.3 Calculation of weighted values to obtain emission factors (g/kg)

The Norwegian Standard NS3059 describes the weighing of the four burn rate categories. Depending on the burn rate, the probability is calculated from a cumulative Gaussian distribution with a mean value of 1.6 and a standard deviation of 0.5 for a grade 2 stove. In the current work, both the tested wood stoves were grade 2 stoves, as most stoves on the Norwegian market are. Weighted values, i.e. emission factors for PM_t, OC and EC, are obtained by calculating the arithmetic mean values for each of the three compounds from three repetitive experiments in each burn rate category and then weighing them according to the Norwegian standard as shown in the example in Table 10 for PM_t for each of the four burn rate categories. Normal distributed burn rates from NS are shown in Table 11. Note that the median has a fuel consumption of 1.6 kg/h weighted according to the NS. For normal firing, the median is estimated as equal or lower than 1.25 kg/h.

Table 10. Example of weighing the average discharge of PM_t, Wood stove – old/new technology, Medium firing = 1.6 kg/h as median

Wood stove – old technology	Calculation of weighted average			
	Lowest	Next lowest	Next highest	Highest
Average wood consumption, kg/h	1.03	1.63	2.46	5.00
Average emissions (g/kg)	36.37	12.60	6.02	4.32
Weighted value class 2	Ew (g/kg)	**17.38**		

Wood stove – new technology	Calculation of weighted average			
	Lowest	Next lowest	Next highest	Highest
Average wood consumption, kg/h	1.23	1.44	2.01	4.25
Average emissions (g/kg)	12.67	20.11	8.26	1.23
Weighted value class 2	Ew (g/kg)	**12.18**		

Normal firing involves low fuel consumption. For stoves in grade 1 the consumption is less than 1.15 kg/h. For grade 2 stoves the mean consumptions is 1.25 kg/h. In the Norwegian standard the emissions are weighted from a user experience curve that indicates how often wood is fired at a given burn rate. The median of the cumulative distribution is 1.6 kg/h for grade 2 stoves. 1.6 kg/h is assumed representative for households with a medium firing pattern, i.e. without night firing. By shifting the median down to 1.25 kg/h, one can weigh the measurement results from this test campaign by the related Gaussian distribution, and get a good indication of the emission factors for normal firing, i.e. with night firing. In the Norwegian PM emissions inventory, medium firing is only assumed to occur in four larger cities, namely Oslo, Bergen, Trondheim and Drammen.

Table 11. Cumulative normal distribution as specified in the Norwegian standard

Tabell 2: Kumulativ normalfordeling for klasse 1 og 2
Table 2: Cumulative Gaussian distribution for grades 1 and 2

Midlere brenselforbruk i kg/h *Mean burn rate in kg/h*	P_i for klasse 1 P_i *for grade 1*	P_i for klasse 2 P_i *for grade 2*
0,1	0,0179	
0,2	0,0287	
0,3	0,0446	
0,4	0,0668	
0,5	0,0968	
0,6	0,1357	
0,7	0,1841	
0,8	0,2420	0,0548
0,9	0,3085	0,0808
1,0	0,3821	0,1151
1,1	0,4602	0,1587
1,2	0,5398	0,2119
1,3	0,6179	0,2743
1,4	0,6915	0,3446
1,5	0,7580	0,4207
1,6	0,8159	0,5000

Median

Table 12. Weighing the measurement results with a shifted median equivalent to normal firing, Wood stove – old/new technology, Normal firing = 1.25 kg/h as median

Wood stove – old technology	Calculation of weighted average			
	Lowest	Next lowest	Next highest	Highest
Average wood consumption, kg/h	1.03	1.63	2.46	5.00
Average emissions (g/kg)	36.37	12.60	6.02	4.32
Weighted value class 2	Ew (g/kg)	**22.71**		

Wood stove – new technology	Calculation of weighted average			
	Lowest	Next lowest	Next highest	Highest
Average wood consumption, kg/h	1.23	1.44	2.01	4.25
Average emissions (g/kg)	12.67	20.11	8.26	1.23
Weighted value class 2	Ew (g/kg)	**13.39**		

3.1.4 Weighted PM_t, OC and EC emission factors

The weighted results from all tests for both stoves are shown in Table 13. The results for the new stove show rather high emissions compared to some of the best stoves available today. When we compare the measured emission factors in this project to the emission factors for wood stoves with new and old technology currently applied by SSB/Klif in the national emission inventory, we see that the new PM_t factor for an old stove is almost half of the current emission factor. For stoves with new technology, the factor is almost 2 times higher than the current emission factor. The result is that the PM_t emission factors for stoves with old and new combustion technology do not differ significantly whereas the current PM_t emission factors for old and new stoves do differ significantly. Further, we see that the PM_t emission factor for the new technology stove is higher than the emission limit for stove approval according to NS (10 g PM_t /kg wood, Table 5).

Part of the explanation for this is possibly that the old stove was brand-new straight from the factory, while the new stove was a used laboratory stove which had served in several occasions over a period of about five years. Brand-new stoves tend to be more airtight than stoves which have been used for some time. The stove with old technology showed a leakage of 15 m^3/h tested at 25 Pa while the stove with new technology had a leakage of 22.5 m^3/h. During type testing at NBL the leakage was measured to 19 m^3/h for the stove with new technology. Leakages in new stoves have higher consequences for particle formation than leakages in older stoves without secondary air supply. Leakage means that air is introduced into the stove in wrong places, and not at the secondary air inlet area where it is supposed to mix with hot flue gases and burnout the remaining particle matter. Air leaking into the primary combustion chamber in the wrong places might actually lead to increased emissions compared to a brand-new “air-tight” stove. Here leakages cool down parts of the combustion zone and prevent particle burnout. It is difficult to judge what the specific variation of these factors might have had on the current results. Further studies are needed if such effects are to be quantified in more detail. On the other hand, experiences from wood stove testing

has shown that, depending on the quality of each specific stove type and each stove specific technical solution themselves, normal use over several years might lead to increased air leakage with the inherent result of higher particle emissions. The stove with new technology performs well for very low burn rates but emits quite high emissions for burn rates around 1.5-1.6 kg/h which is the most used operation mode according to the calculation in NS 3059 (Figure 13, right panel). This very atypical behavior, might be a property of the selected stove, and possibly related to what is mentioned above regarding air leakage. Thus, one main result from this project is that stoves which have been in use for some time emits more particulates than brand new stoves. This means that our results for the new technology stove may be viewed as more representative for real life Norwegian emissions from wood burning.

The weighted emissions for EC showed as emission factors in Table 13, turned out to be rather indifferent of burn rate as already observed in Figure 15. Another observation is that the EC emission factors are only slightly affected when going from old to new combustion technology.

Emission factors for OC showed in Table 13, reveals a stronger link to burn rate compared to EC. The weighted values indicate that the stove with old combustion technology will emit more OC at lower burn rate than the stove with new combustion technology.

Table 13. Weighted PM_t, OC and EC emission factors

Medium firing (without nightfiring)= 1.6 kg/h as median			
Emission factor / **Stove type**	[g PM_t/kg wood]	[g EC/kg wood]	[g OC/kg wood]
Wood stove – old technology	17.4	1.01	12.89
Wood stove – new technology	12.2	0.90	9.26

Normal firing (with night firing) = 1.25 kg/h as median			
Emission factor / **Stove type**	[g PM_t/kg wood]	[g EC/kg wood]	[g OC/kg wood]
Wood stove – old technology	22.7	0.96	16.74
Wood stove – new technology	13.4	0.86	10.47

The Jøtul F3 has been type approved for the Norwegian market, i.e. the stove emitted less than 10 g/kg PM_t for maximum weighted mean value when it was approval tested. Explanations for the higher emission factor in this project other than air leakage could be that the Norwegian standard has some degree of freedom on how to perform a test. It could be that the differences in the standardized fuel wood could cause the variations and the results observed in this test campaign. During the tests the fuel wood variables

such as moisture, wood type and size, were attempted to be kept as constant as possible. Another possible explanation is that during type approval tests, when a stove in one test obtains the required limit below 20 g/kg for one burn rate category but not in another test, the test higher than 20 g/kg is normally excluded from the final weighted factor. In this work even tests that exceeded the emission limit described by the Norwegian standard, were included in the calculation of the proposed emission factors. The reasoning for not omitting any of the tests that exceeded the emission limits was the project's intention of obtaining close to "real world" emission factors for Norwegian dwellings.

Batch combustion of wood is a complex process which is influenced by many factors. Slight changes such as variations during the preheating of the stove, operations performed when allowing the test fuel to ignite, fuel size, shape and moisture content are known to significantly affect emission levels, particularly at low burn rates. However, it is also important to note that different stoves behave in different ways. Experience show that some stoves are very sensitive to moisture content while others are not.

Much effort was put in by NBL and SINTEF Energy Research to ensure that both stove preheating and testing were performed in line with predefined procedures for the preheating, using equal amounts of fuel wood and as well, close to constant moisture content. After preheating the stove, the initiation of each test starts by a periode of controlled ignition of the newly laid in standardized fuel wood. This means that the stove operator should attempt to ignite the fire wood in such a way that the wood will burn steadily until it reaches the charcoal phase. The stove operator usually achieves this through experience and by varying the time and the opening of the main front door of the stove. However, it is difficult to keep this door open in exactly the same wayfor each test. Hence, it might be that in one test the fuel ignites better than in another and therefore burns better with significantly lower emissions.

Another factor that affects the combustion is how the fuel is placed inside the combustion chamber. Also the charcoal bed that remains from the preheating might change from test to test in such a way that it affects the remaining combustion cycle all the way to the charcoal phase. During combustion some of the fuel wood will collapse randomly against either side of the stove walls which sometimes can result in an immediate change in burn rate. All these factors mentioned are parameters that affect the total particle emissions but are hard to fully control, when attempting to perform repeated tests. In 6 of the 12 experiment where the air inlet was closed, the burn rate varied from 1.23 kg/h to 1.5 kg/h. Three tests with similar burn rates of 1.42, 1.47 and 1.5 kg/h resulted in very different emissions levels such as 25.7, 23.3, and 17.2 g/kg. For 1.23, 1.28 and 1.35 kg/h the emissions were similar with 9.6, 10.6 and 10.5 g/kg, respectively. Hence it is extremely challenging to reproduce a burn rate with the same emissions.

3.1.5 Uncertainties in the PM_t results

Previous observations at NBL report variations, including instrument accuracy, at around 10 % for particle measurements when trying to repeat two wood stove experiments with the same initial conditions. The variation in the current test results should be analyzed only for experiments with close to identical burn rates. When comparing emissions at close to the same burn rate, it was found that the variation of particle emissions for the current experiments were between 5 and 20 %.

Another inaccuracy is the losses from the filter during handling. In addition it was noticed that quartz filters were much more brittle and thereby inherent to mass loss during handling after sampling than teflon filters or glass, or both.

Experience also show that wood stove experiments have an inherent tendency to be quite hard to reproduce. The different factors affecting particle emissions have already been elaborated in previous chapters and are mainly related to:

- Uncontrollable variation in fuel properties, mainly moisture, as well as how the wood loads behave during the combustion test cycle.
- Operator dependency, meaning that although tests are performed according to the Norwegian standard, some degrees of freedom do exist which could influence the test results.

During the course of the experimental campaign, SINTEF Energy performed two control experiments to validate the tests performed by NBL on the stove with old combustion technology. Due to the beforehand coordination between the stove operators, a quite acceptable agreement between the results from the two laboratories was found as illustrated by the blue diamonds in Figure 13. As experience show some variation in results from wood stove testing depend on the operator due to a certain operating freedom in the initial part of the test cycle, both operators were instructed to operate the stove as similar as possible.

Earlier experience from wood stove experiments has shown that particle emissions can vary significantly between tests even when repeated with equal initial variables. In practice, it is not possible to repeat the experiments and achieve exactly the same results as previously discussed. Deviation in the results caused by slight variations in moisture, wood load behavior and composition, are also difficult to quantify and have not been considered in the current work. The wood log moisture levels were kept as close to constant as possible and were always within the limits given by NS.

3.1.6 Uncertainties related to the EC/OC analysis

The main source of uncertainty for the current particle analysis is related to a very high accumulation of particle mass on most of the filters. This particle overload resulted in Flame Ionization Detector (FID) over-range. The FID, which measures the concentration of vaporized carbon during the analysis, went over-range during the OC1 step (see Appendix C), when the most volatile fraction of OC is released from the filter. When the FID surpasses its measuring range, the instrument software automatically writes “OFFSCALE!!!” to the resulting data file as illustrated in Table 14.

The effect of over-ranged FID was evaluated. To improve the accuracy of the original results a few approaches were completed such as tests with smaller punch sizes, tests to confirm the EC distribution over the filter surface, tests with extended OC4 step and finally recalculation of the pyrolyzed carbon and the effect on the EC and OC results. The individual analyses are described later in this report in detail. When FID over-range was present (both FID1 and FID2), the analyzer did not give any value for uncertainty indicating that the uncertainty increased significantly in such cases. It is not advisable to use the original data of OC and TC when FID over-range was present because not all of the OC and TC were analyzed. It was estimated that in the original analysis, OC was underestimated by 15-42 % when the OC concentration on the filter was more than 500 µg/cm^2.

The filter-overloading problem was solved to some extent when smaller filter punch sizes were used. New values were obtained by re-analyzing with smaller punch sizes and use these values to correct the originally obtained values. Figure 18 illustrates which results are within the range (three data points encircled by solid red line), partly over-ranged (ten data points encircled by dotted green line) and over-ranged compared to the FID detection range of the analyzer.

Table 14. Data printout to illustrate FID over-range

Sunset Laboratory OCEC Results															
Date Calculated: 06-21-2012															
Sample ID	OC(ug/sq cm)	OC unc	EC(ug/sq cm)	EC unc	CC(ug/sq cm)	CC unc	TC(ug/sq cm)	TC unc	EC/TC ratio	Date	Time	CalConst	Punch Are	FID1	FID2
instrblanco	0.826946	0.2413473	5.56E-03	0.2002779	0	-	0.8325034	0.3416252	6.68E-03	6/21/2012	8:21:11 AM	22.22	1.5	ok	ok
glucose	40.82651	2.241326	0	0.2	0	-	40.82651	2.341326	0	6/21/2012	8:44:38 AM	22.22	1	ok	ok
G81.1etua	824.9348	2.00E+09	49.09945	2.00E+09	0	-	874.0342	2.00E+09	5.62E-02	6/21/2012	9:06:48 AM	22.22	1.5	OFFSCALE!!!	OFFSCALE
G81.1etub	805.6997	2.00E+09	22.31993	2.00E+09	0	-	828.0197	2.00E+09	0.0269558	6/21/2012	9:28:30 AM	22.22	1.5	OFFSCALE!!!	OFFSCALE
G81.1etuc	763.4625	2.00E+09	18.4798	2.00E+09	0	-	781.9423	2.00E+09	2.36E-02	6/21/2012	9:50:26 AM	22.22	1.5	OFFSCALE!!!	OFFSCALE
	798.03	***2000000000.00***	***29.97***	***2000000000.00***			***828.00***	***2000000000.00***	***0.04***						
G82.2taka	13.94692	0.8973461	0.5479943	0.2273997	0	-	14.49492	1.024746	3.78E-02	6/21/2012	10:12:20 AM	22.22	1.5	ok	ok
	1142.6														
	1128.69	**ug/sq cm**	**29.97**	**ug/sq cm**			**828.00**	**ug/sq cm**							

When the experiments were prepared, UEF wrote a guideline in which it was described a procedure for particle collection in order to ensure proper samples for the OC/EC analysis. Maximum values for total mass, EC and OC in µg/cm^2 were given. SINTEF indicated that the total mass most likely would exceed the limits of the analyzer. However, at that point in the project it was not possible to work with an alternative method that would still comply with the Norwegian standard. The manufacturer of the analyzer has given a measuring range for OC and EC; 5 to 400 µg/cm^2 for OC and 1 to 15 µg/cm^2 for EC. These values were exceeded especially with respect to OC.

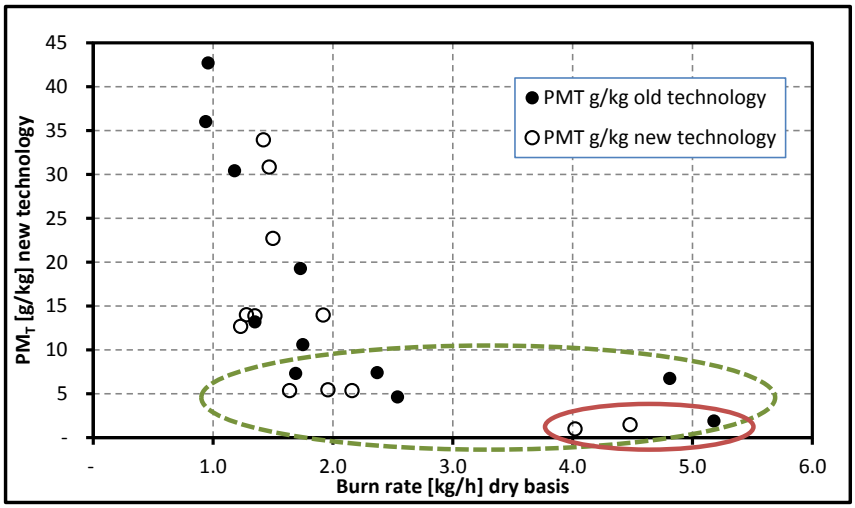


Figure 18. Total results from particle analysis for stoves with new and old technology, grouped by particle load on the filter. Red line (3 samples) = FID within range, Dashed green line (10 samples) = FID partly over-ranged, remaining values = FID over-range

A second source of uncertainty was related to possible internal leakage in the filter sample holder through or around the front filter to the back filter. The particle analysis indicated in some cases when comparing results for filters 1.2 and 2.2 possible internal leakage possibly due to filter deterioration caused by overloaded filters. However, with the current emission levels, the amount was found to be negligible and had no influence on the total particle emissions.

A third source of uncertainty, which is present in all of the analysis results, is the possibility of uneven distribution of large particles on the filter surface. Uneven distribution of particles on the filter area causes problems in chemical analysis such as OC/EC analysis, where only a small part of the total filter area is used. To reduce the uncertainty caused by uneven distribution, three samples from different parts of the filter area were analyzed for each filter as part of the agreed analyzing procedure. To quantify the effect of

uneven distribution, a few additional analyzes were performed. The procedure consisted of analyzing three punches taken at the same distance from the filter center on a few selected filters. The EC results deviated with maximum 5 %, OC results with maximum 3 % and TC results with maximum 3 %. This is less than the uncertainty stated by the analysis program, which was 5 - 6 % for OC and 5.5 - 7 % for EC.

Additional analyses carried out to verify the results

Tests with smaller punch size

A limited number of additional tests were carried out with a smaller filter punch size. Instead of 1.5 cm^2 punch as required by NIOSH, punch sizes of 0.5 cm^2 and 0.25 cm^2 were used. Because the analyzer was not designed for filter sizes this small, the smaller punches were placed on top of a 1.5 cm^2 piece of clean quartz filter. Not all samples were tested with this method but samples for this extra test were selected representing both small and large values of EC and OC from the original analysis. In total 15 extra analyses with smaller punch sizes were performed. The results are presented in Figure 19 and Figure 20. With smaller punch sizes, the total carbon content on the sample was reduced compared to the original punch size and actually enabled normal operation of the FID. The results from these extra tests clearly show that when OC values in the original analysis were less than 400 µg/cm^2, which is the limit value provided by Sunset Laboratory Inc., the original values and the values from smaller punch size agreed well. However, for OC values outside the detection limit, the original and the extra test values were significantly different. The higher the OC value, the more it was underestimated in the original analysis with standard punch size. Based on the new results with smaller punch size a mathematical correlation was developed to correct the OC values that were originally higher than 500 µg/cm^2. As can be seen in Figure 19, the corrected OC values are considerably higher. In contrast to the OC values, the EC values that are presented in Figure 20 show that the original analysis and the analysis with smaller punch sizes did not correlate. Some of the values with smaller punch size were lower than the original ones, some correlated well but none of the new values were higher than the original. There might be two possible explanations for this; 1) the smaller punch size has an effect on the transmission measurement (and split time) or 2) EC is not distributed uniformly on the filter area due to large particles.

Analyses to validate the EC results

Since EC values from the original analyses and from smaller punch size differed in some samples, a few additional analyses were performed in order to ensure that this variation was not due to non-uniform distribution of large EC particles on the filter area. Three filters were re-analyzed because they contained relatively small amounts of EC and OC and variation was seen in EC results between the original analyses and the analyses from the smaller filter punches. Three pieces of each filter with original punch size 1.5 cm^2 were taken from different parts of each filter. No samples were taken from the very center part of the filter because visibly larger particles were present at the center. The original results showed larger EC value in the center part. Large particles had to be excluded from this additional analyzes because it was not possible to take multiple samples in the middle of the filter area, and large particles are very likely to cause variation in measured EC values. However, the center part of the filter, containing visible larger particles, is taken into account in the overall results. In this analysis, pieces were taken using the same distance from the center of the filter as the original analyses, to ensure reproducibility.

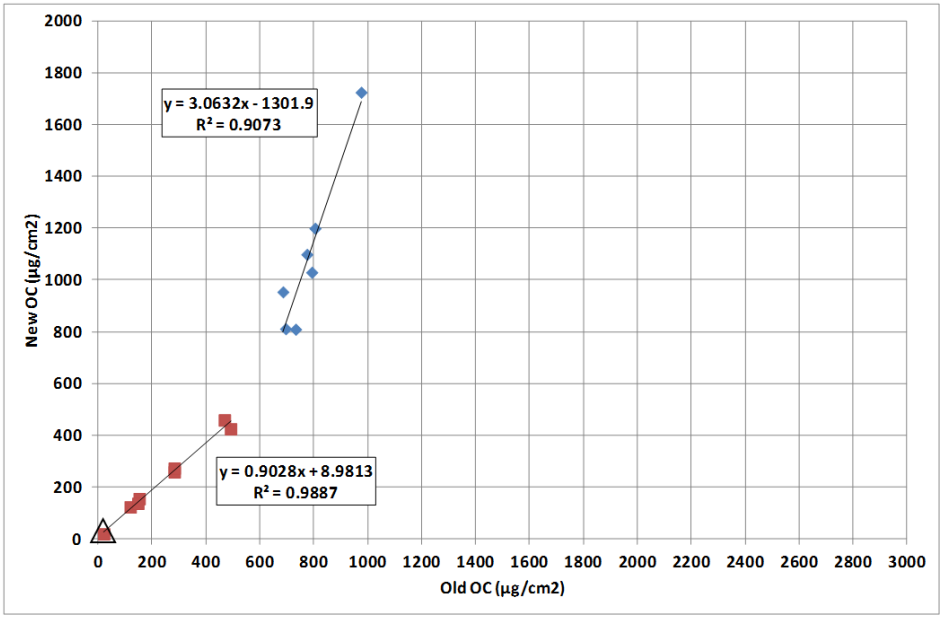


Figure 19. Figure highlights the result from the extra analysis where smaller punch sizes were used. Red boxes highlight that below 500 µg/cm^2 of OC, the "original" and the "new" results are well in line. Blue diamonds show that when the initial OC exceeded 600 µg/cm^2, the "original" and the "new" values vary significantly. According to this finding, "original" OC values that were higher than 500 µg/cm^2 were corrected using the equation "new" = [3.0632*(original)]-1301.9. Samples with a triangle are within FID range

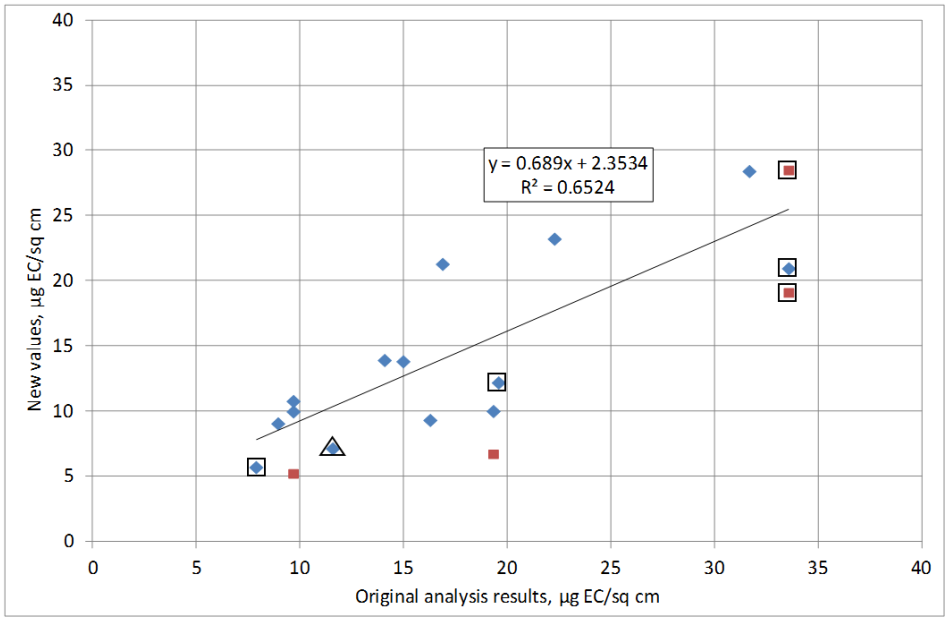


Figure 20. Original EC values (µg/cm^2) plotted against the results from the extra tests. Blue diamonds are data points from "smaller punch size" tests and red boxes from "longer OC4 step" test. "Partly over-ranged samples" and "within range samples", are marked with square and triangle, respectively, in the figure

The results from these additional analyses show two things. First, when the very center of the filter is not considered, the particles were evenly distributed on the filter area. The variation between the three

samples was maximum 5 % for EC and maximum 3.5 % for OC. This indicate that the particles were evenly distributed, and the original analysis is reliable. Second, since the differences in EC results most likely were not caused by the uneven distribution of the particle, it was concluded that the EC results for the test with smaller punch sizes more likely was caused by errors in the transmission measurements so that the split time was incorrectly determined. This indicates that the analysis from the small punch is not reliable for EC. Split time can affected both EC and OC values. Since the OC was the dominating component, a slight change in the split time affected the EC value considerable, whereas the effect on OC value remained insignificant. In conclusion, the EC values from the original analysis should be used in the final results. The split time defines the EC that has been pyrolytically (PC) formed at high temperatures during the OC phase. The PC value is added to the OC value to get the corrected OC, and PC is subtracted from the EC to get the corrected EC value. This is a so-called optical correction, which is usually made automatically in the analysis program. The split times used in our analysis are shown in Appendix C.

Additional analyses with extended OC4 step

Additional analyses were carried out in order to check whether all OC was extracted from the sample during the OC phase of the analysis. There has been some evidence previously that in some cases the so-called OC4 step may be too short. Test samples were selected among the same samples that were already analyzed with smaller punch size. It was thus possible to compare the extended OC4 analyses and the original analysis with each other. The tests were made with a 0.5 cm^2 punch size in order to avoid FID over-ranging, to achieve better OC accuracy. Results from punch sizes this small, was demonstrated above to be affected by incorrect split time determination. This affects the determination of PC and affects particularly the EC result. Results are presented in Figure 20 and Figure 21. For EC, no correlation was found with extended OC4 step and therefore no changes were made to the original EC values. The extended OC4 step did not affect the OC result. Some variation in the measured values for OC can be observed in Figure 21, but it is not significant.

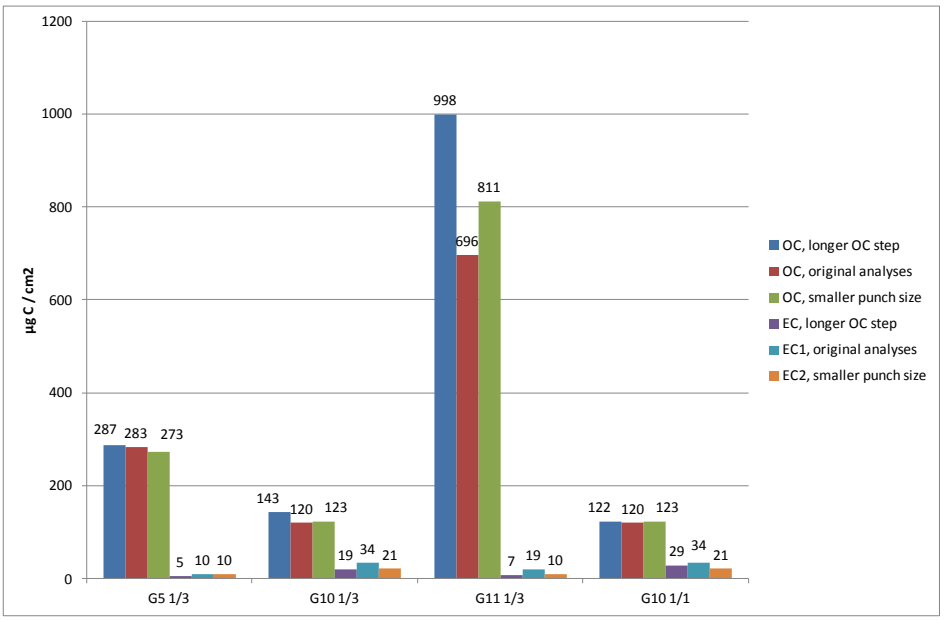


Figure 21. Results of OC and EC presented to highlight the differences between the extra tests and the original analysis. Sample G10 was considered as "partly over-ranged". G5, G10, G11: Name of experiment. 1/1 means that the punch sizes was 1.5 cm^2. 1/3 means that the punch size was 0.5 cm^2. The numbers above the bars shows the results for EC and OC in µgC/cm^2

Effect of recalculated pyrolyzed carbon on the EC and OC results

From the results we observe that there are some variations in the PC to OC ratio for the samples that were analyzed. Variation in PC to OC ratio is normal but there was evidence that the ratio could be too low in overloaded samples. To evaluate the extent of the potential error, the PC values were recalculated using the following assumption: average PC/OC ratio was calculated from three samples (G6, S2 and S3). These samples were chosen because they were within and partly over-ranged samples. While S2 and S3 are regarded as good measurements (within range), G6 is a partly over-range measurement. For the remaining samples, the original PC values were recalculated using the obtained PC/OC ratio. Recalculated OC and EC for are presented in Figure 22 to Figure 24, respectively. “partly over-ranged samples” and “within range samples” are marked with square and triangle, respectively, in the figures to illustrate which results that are within range, partly over-ranged and over-ranged compared to the FID range of the analyzer as illustrated in Figure 18.

The changes in the OC values (Figure 23) are rather small due to large content of OC compared to EC and PC. The recalculation changed the values of EC more significantly. Figure 22 shows that in some cases the recalculated EC is less than the original result, indicating that the recalculated PC was lower than the original PC value (for example G6, G7, G8, G11 and G12).

Particulate total carbon, TC, is the sum of OC and EC and it represents the carbon content of the sample. Other compounds are also captured on the filters as shown in Figure 24. There will for instance be other organic material (OM) than OC. In the literature, a factor 1.1-1.4 depending on the source is often use to convert between OC and OM[1]. Particles may also contain some inorganic species, which are for example K_2SO_4, KCl, K_2CO_3, or similar as well as oxygen and hydrogen. Some metals may also be present. At poor combustion condition, such as at low burn rates, inorganic species represent only a small share, because of large amounts of carbonaceous compounds (EC, OC and OM) which represent almost all of the PM. As we can see from the Figure 24, the share of “other” varies between 10 – 60 % of PMT. There is no clear correlation for any of the two stoves, between burn rate and the amount of other species formed.

Summary and conclusion for the OC/EC analysis

As previously explained, the main source of uncertainty for the current particle analysis was related to a very high accumulation of particle mass on most of the filters, which again resulted over-ranged FID signals. Figure 18 illustrates which results that are within range, partly over-ranged and over-ranged compared to the FID range of the analyzer.

The Sunset laboratory Inc. OC/EC analyzer calculates the appurtenant uncertainties based on the measured values and how well these fall within the FID range. For the three samples that were within FID range, the uncertainties for stoves with new and old technology and medium firing, are; OC = 5-6 %, EC = 5.5-7 % and TC < 2 %. Uncertainties were lowest for low TC values, less than 30 µg/cm^2 and then increased for higher TC values. For samples within range and partly over-range, for stoves with new and old technology and medium firing, the uncertainties are; OC = 5–6 %, EC = 5.5–7 % and TC = 5–10 %.

The use of smaller filter size and to correct OC and TC values accordingly, was seen as the only possibility to obtain reliable OC and TC values in overloaded samples where the analyzer FID was over-ranged. By comparing the results for not overloaded filters in the original tests and in the smaller punch size test, it was possible to say that when a smaller filter punch was used, the uncertainty was 7–21 % for OC and 2–15 % for TC. The increased uncertainty is assumed to be related to inaccuracies which occurs during filter cutting, as this was done by hand.

The purpose of the PC correction was to evaluate the possible uncertainties originating from the determination of split time and pyrolyzed carbon in overloaded samples. For EC, uncertainty differs between the new technology stove and the old technology stove. In the old stove, the uncertainty are 35 %, but in the new stove, the differences are higher, typically 50–80 %.

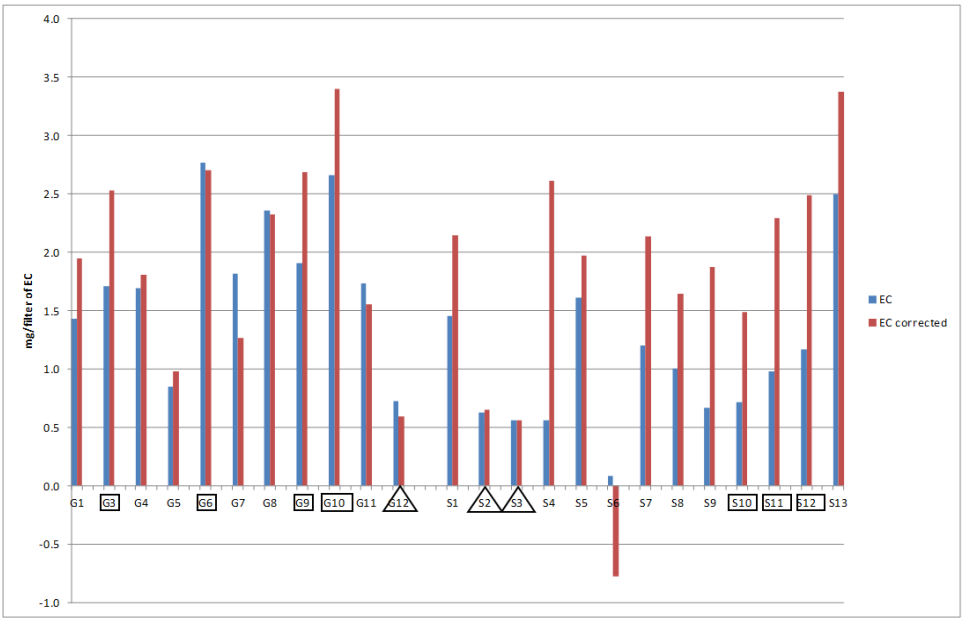


Figure 22. Original EC values and recalculated EC values. Recalculation was based on the correction in the PC value. "Partly over-ranged samples" and "within range samples" are marked with square and triangle, respectively, in the figure. The other measurements were over-ranged compared to the FID range of the analyzer

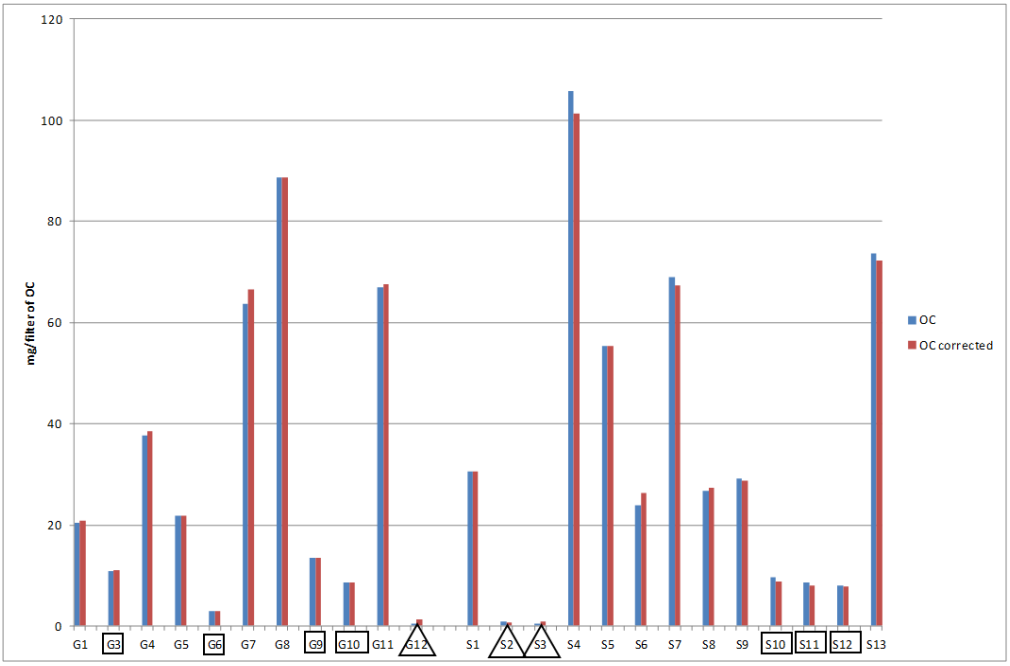


Figure 23. Figure presents the OC values, which are corrected due to the FID over-range (results from smaller filter pieces) and "corrected OC" which were based on the PC correction. "Partly over-ranged samples" and "within range samples" are marked with square and triangle, respectively, in the figure

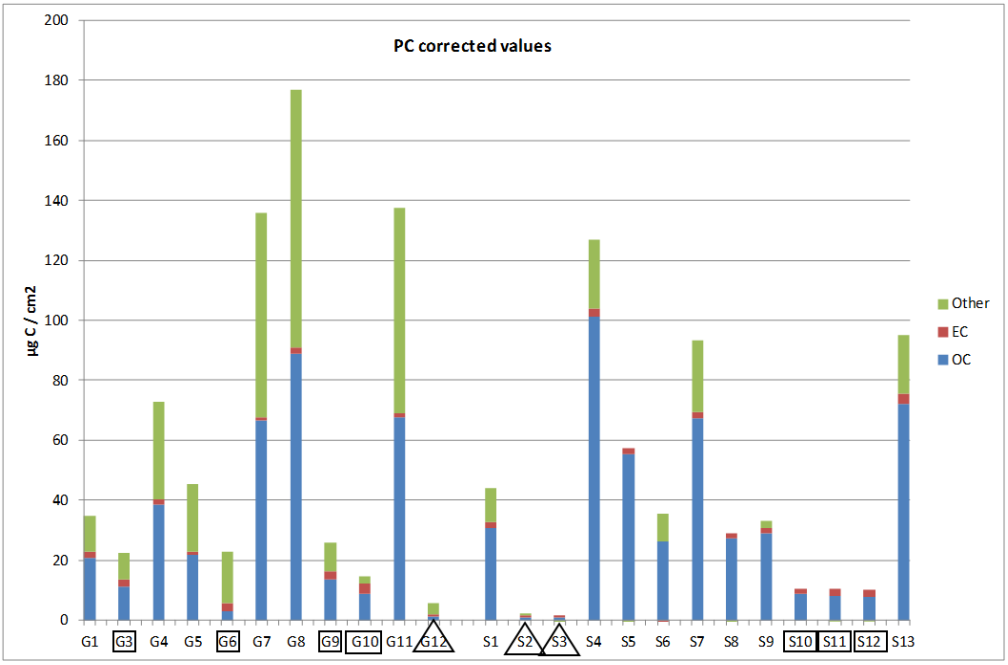


Figure 24. EC and OC in different combustion tests after the PC correction. "Other" represents the fraction of weighed PM, which was not analyzed in carbon analysis. It contains particle mass other than carbon, and it is affected by the uncertainties of weighing and OC/EC analysis. "Partly over-ranged samples" and "within range samples", are marked with square and triangle, respectively, in the figure

The final emission factors are listed in Table 15 given as best estimates for all the 24 considered experiments. Here the EC values are based on the corrected PC values whereas the OC values have been corrected based on smaller filter punches. The final uncertainties for the best estimated emission factors for stoves with old combustion technology are; OC = 14 %, EC = 45 % and TC = 10 % whereas for stoves with new combustion technology values are; OC = 14 %, EC = 27 % and TC = 10 %.

In order to guarantee low enough mass on the filter to ensure more accurate EC and OC analysis, several measures can be implemented: 1) increasing the dilution ratio for filter collection, 2) shortening of the collection time by collecting multiple filter samples during the combustion experiment or 3) increasing the filter area. Conversely, each of these measures has some drawbacks independent from any test standard. Increasing the dilution ratio will change the aerosol properties and higher dilution will cause changes in the particle concentration. The Norwegian dilution tunnel does not allow high enough dilution ratio to reduce the mass low enough. Additional part flow dilution must then be applied. Part flow dilution can cause unpredictable mass loss in the dilution unit as it happened when using an ejector dilutor for particle size measurement. Another problem with part flow dilution is that clogging of the dilution unit changes the dilution ratio over the sampling period, which can give a significant error when recalculating particle emissions. Shortening of the collection time with multiple filters would have ended up in increased need of working hours for filter handling and analyzing, by a factor of two or more. In addition, it is difficult to identify the correct time for the filter change and probably two filters are not enough. Increasing the filter area requires such large filters that reliable filtration is difficult to achieve.

The best possible option for a more accurate EC measurements is an additional particle sampling line in the hot flue gas, which decreases the total mass on the filter significant. The high mass load in the dilution is caused by organic particles, which condensed during dilution. Since EC does not change trough dilution and

is part of solid particles, it can be sampled directly in the chimney. Sampling just solid particle will result in very low particle mass on the filter. This will decrease the uncertainty for the EC measurement down to acceptable levels.

Based on the previous discussions related to uncertainties in the current setup the following can be concluded:

- TC values are usable in all 24 samples, when the correction achieved from smaller punch size tests are used for samples containing more than 500 µg/cm^2 of TC.
- For EC, for the 10 samples containing the least mass (FID partly over-ranged), the original values without corrections should be used.
- For overloaded samples (FID over-ranged), the uncertainty increases significantly.
- For OC, correction with smaller punch size increases the uncertainty by about 7 % and variation from PC correction by maximum 10 %.

A final uncertainty for all 24 samples is achieved by using a weighted calculation for all experiments the same way as particle emissions are weighted based on the Norwegian standard. Final uncertainties for all 24 samples are then calculated to:

- Uncertainty EC old technology all samples 27 % weighted
- Uncertainty EC new technology all samples 45 % weighted

Table 15 presents the emission factors obtained in the project for stoves with old and new combustion technology, calculated according to NS 3059 for both normal and medium firing. This table shows the original weighted emissions as emission factors (first column), OC corrected values with smaller filter punches (second column), best estimate including the EC correction with PC/OC ratio (third column) as well as partly over-ranged and within range emission factors (fourth and fifth column respectively). It should again be pointed out that the main reason for the high uncertainties in the results from the current work, is due to the lack of available instruments for measuring EC and OC in the high particle load resulting from sampling in a dilution tunnel as required by the Norwegian standard. The final corrected results from this project, with appurtenant uncertainties below, are found in the column named “Best estimate. 24 samples”. Selecting only the 10 samples (representing moderate and high burn rate) with lower uncertainty burn rate do not represent the total Norwegian heating pattern including firing at low burn rate.

3.2 Particle emission vs. ambient particle concentration

New knowledge regarding particles from biomass combustion shows that the particle concentration changes with dilution when particles encounter the atmosphere after the chimney outlet as Figure 25 shows[32]. These measurements showed that particle emissions increase with increasing dilution (see illustrative red line in Figure 25). When the exhaust gas is diluted, it forms primary organic aerosols in the air. With increasing dilution, when the flue gas leaves the chimney and meets ambient air, some of these condensed particles evaporate again. In the air, part of the emissions from wood burning, like unburnt hydrocarbons, reacts with O_3 and NO_x under the influence of sunlight to form secondary aerosols. This means the particle concentration in the ambient air might be quite different from the concentration measured in the dilution tunnel.

[32] Nussbaumer, T.; Klippel, N.; Johansson, L. 2008; Survey on measurements and emission factors on particles matter from biomass combustion in IEA countries, 16th European Biomass Conference and Exhibition, 2–6 June 2008, Valencia, Spain – Oral Presentation OA 9.2

Table 15. Emission factors (g/kg) with related uncertainties (± %) obtained in the project

	EMISSION FACTORS OBTAINED IN the "BLACKout" project (g component/kg wood consumed)																			
Stove technology and burning practice	**Original 24 samples.**				**24 samples. OC corrected values based on smaller filter punches. EC not corrected.**				**Best estimate. 24 samples. EC corrected values based on corrected PC values. OC corrected based on smaller filter punches.**				**10 samples (Uncorrected).**				**3 samples (Uncorrected).**			
	PM	**EC**	**OC**	**TC[1]**	**PM**	**EC**	**OC**	**TC**	**PM**	**EC**	**OC**	**TC**	**PM**	**EC**	**OC**	**TC**	**PM**	**EC**	**OC**	**TC**
New technology stove (<1998) with normal firing	**13.4**	**0.62**	**10.1**	**10.7**	**13.4**	**0.62**	**10.47**	**11.09**	**13.4**	**0.86**	**10.47**	**11.33**	**Data not available[b]**							
Uncertainty (%)[2]	*6.5*	*50-80[4]*	*15-42[5]*	*15-42[5]*	*6.5*	*50-80[4]*	*7-21[3]*	*2-15[b]*	*6.5*	*45[4]*	*14[3]*	*10[b]*								
New technology stove (<1998), medium firing (applied in large cities only)	**12.2**	**0.58**	**9.2**	**9.8**	**12.2**	**0.58**	**9.26**	**9.84**	**12.2**	**0.9**	**9.26**	**10.16**	**2.2**	**0.47**	**1.42**	**1.89**	**0.6**	**0.15**	**0.28**	**0.43**
Uncertainty (%)[2]	*6.5*	*50-80[4]*	*15-42[5]*	*15-42[5]*	*6.5*	*50-80[4]*	*7-21[3]*	*2-15[b]*	*6.5*	*45[4]*	*14[3]*	*10[b]*	*10*	*5.5-7[b]*	*5-6[b]*	*5-10[b]*	*25*	*5.5-7[b]*	*5-6[b]*	*<2[b]*
Old technology stove (<1998) with normal firing	**22.7**	**0.89**	**16.5**	**17.4**	**22.7**	**0.89**	**16.74**	**17.6**	**22.7**	**0.96**	**16.74**	**17.7**	**Data not available[a]**							
Uncertainty (%)[2]	*5*	*35[4]*	*15-42[5]*	*15-42[5]*	*5*	*35[4]*	*7-21[3]*	*2-15[b]*	*5*	*27[4]*	*14[3]*	*10[b]*								
Old technology stove (>1998), medium firing (applied in large cities only)	**17.4**	**0.88**	**12.7**	**13.6**	**17.4**	**0.88**	**12.89**	**13.8**	**17.4**	**1.01**	**12.89**	**13.9**	**3.7**	**0.78**	**2.89**	**3.67**	**0.5**	**0.07**	**0.22**	**0.29**
Uncertainty (%)[2]	6.5	*35[4]*	*15-42[5]*	*15-42[5]*	6.5	*35[4]*	*7-21[3]*	*2-15[c]*	*6.5*	*27[4]*	*14[3]*	*10[b]*	10	*5.5-7[b]*	*5-6[b]*	*5-10[c]*	25	*5.5-7[b]*	*5-6[b]*	*<2[b]*
Burn rates covered (kg/h)	**0-5.2**	**0-5.2**	**0-5.2**	**0-5.2**	**0-5.2**	**0-5.2**	**0-5.2**	**0-5.2**	**0-5.2**	**0-5.2**	**0-5.2**	**0-5.2**	**1.6-5.2**	**1.6-5.2**	**1.6-5.2**	**1.6-5.2**	**4-5.2**	**4-5.2**	**4-5.2**	**4-5.2**

[1] TC is the sum of EC and OC

[2] All uncertainty estimates are based on expert judgment, if not otherwise specified.
PM: Uncertainties occur when filters are handled and are related to material loss. The less particle matter that is captured, the larger the uncertainties become. The uncertainties have been given in the interval 5-25 %, were 5 % is for the highest particle loads and 25 % is for the smallest loads.

[3] Uncertainty was estimated by comparing results from normal punch size and smaller punch size. It includes uncertainty of the analysis.

[4] Uncertainties estimated based on the results from the original 24 samples and PC corrected values. However, they are also affected by the use of small punch size and uncertainty of the analysis. Uncertainties for all samples are weighted according to the Norwegian standard.

[5] Uncertainty is estimation. Analyses were affected by overloaded filter.

[a] Values for night firing are estimated. Measured values are weighted for a median of 1.6 kg/h while nigh firing are weighted for a median of 1.25 kg/h. All the 10 samples have a burning rate above 1.5 kg/h, thus it is not possible to estimate emission factors.
[b] Uncertainties are given by the Sunset laboratory analyzer

3.3 Results from NBL approval tests of stoves for the Norwegian market

To set the selected stove with new technology in perspective vis-à-vis type approval data from NBL, the Jøtul F3 with new combustion technology , is compared to measured data from NBL from 1998 and up to today as illustrated in Figure 26. The Jøtul F3 has a weighted particle emission of 6.05 g/kg (obtained from confidential NBL test protocol). The measurement data shown in figure 26 represents most of the stoves NBL has tested and approved for the Norwegian market. Data for stoves with old technology is not available for comparison. The Jøtul F3 weighted emission figure (horizontal red line in figure 26), shows that emissions from this stove is representative for emissions from new wood stoves which have been approved for the Norwegian market.

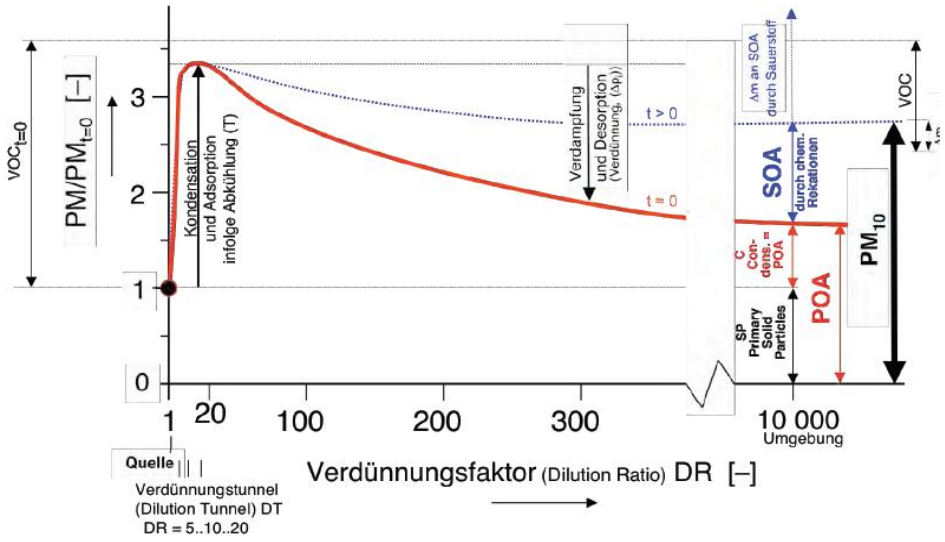


Figure 25. Effects of dilution of particles from wood burning[32]

The data shown in Figure 26 originates from work performed by SINTEF in 2012[33]. The objective of this work was to review the environmental and energetic performance history for wood stoves, with special focus on the last 15 years, and to evaluate the further improvement potential for wood stoves. Emissions were measured according to the Norwegian standard as described in the test procedure, both for the fuel size and moisture. The fuel used in Norwegian households can vary considerably. The size of the wood loads will affect emissions just as varying humidity will. Quite dry wood can result in significantly lower emissions compared to high moisture content, which results in much higher particle emissions.

The introduction of the Norwegian wood stove-testing standard, NS 3058/3059, in 1998 introduced an emission limit for particles of 10 g/kg dry wood for new wood stoves. From 1998, staged combustion, with both primary and secondary air addition, was introduced and has since completely dominated the Norwegian wood stove market. These wood stoves also have the potential to perform energetically much better than old types of wood stoves, due to better combustion air control, reducing the overall excess air ratio. However, during the last 15 years, continuous improvements have resulted in wood stoves with much reduced particle emission levels. Reduction in emissions of particles are approaching 80 % compared to the 10 g/kg dry fuel emission limit, i.e. between 1-2 g PM_t/kg. This work is part of the Stable Wood project (New solutions and technologies for heating of buildings with low heating demand: Stable heat release and distribution from batch combustion of wood), led by SINTEF Energy Research and financed by the Research Council of Norway and four industry partners.

For comparison with the current results, a weighted emission factor was calculated based on all available tests from NBL. In Table 16, we see that this calculated emission factor becomes 4.7 g/kg. However, it is not believed that the calculated weighted emission factor of 4.7 g/kg is currently representative for a wood burning stove with new technology used in Norwegian households. This is based on previous assumptions when representative wood stoves were selected for testing in the current project. In the future, however, emission factors down to 1-2 g/kg might be obtainable for the best stoves on the market today, assuming proper regular leakage maintenance, use of proper firewood and stove operation according to the producer's manual.

[33] Environmental and Energetic Performance History and Further Improvement Potential for Wood Stoves, 20th European Biomass Conference and Exhibition, 978-88-89407-54-7, 2012

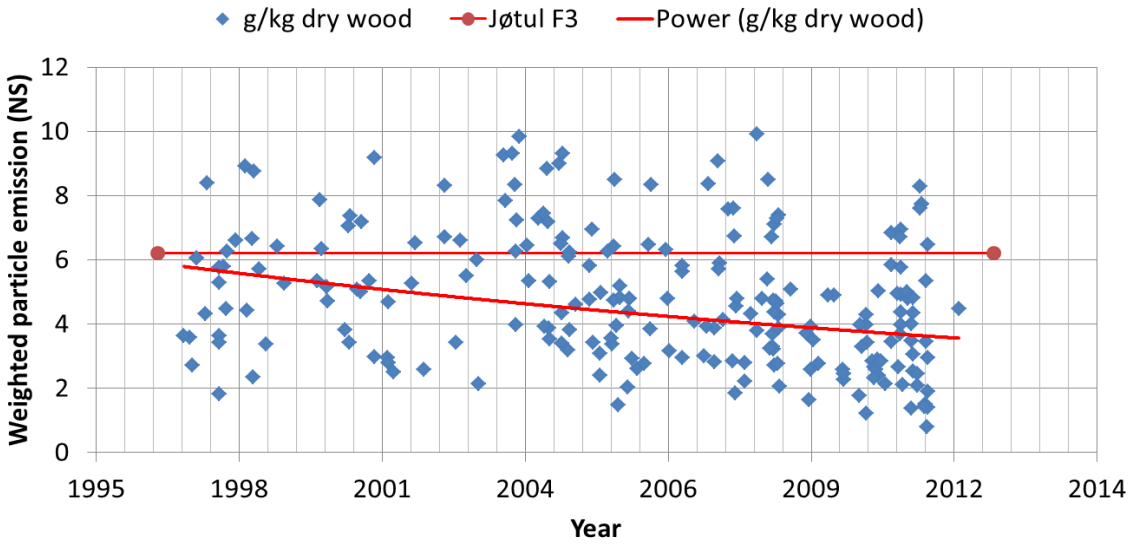


Figure 26. Development of particle emissions from 1998 to the present[33]

Table 16. Calculation of weighted emission of PM_t g/kg on dry basis for all tests at NBL

	Calculation of weighted average			
	Lowest	Next lowest	Next highest	Highest
Average wood consumption, kg/h	1.26	1.51	2.19	2.76
Average emissions (g/kg)	7.04	4.36	3.51	3.41
Weighted value class 2	Ew (g/kg)	**4.69**		

3.4 Particle size distribution of emissions from wood burning

During the test campaign, stove experiments that would provide the particle distribution for the four load categories described in NS were attempted. The selected setup proved unfortunately to be of such a nature that the mass balance of the particles could not be closed. Only around 50 % of the particle mass was collected using an impactor when compared to the mass of particles collected in the parallel stream. An impactor is a particle-measuring tool used to segregate particles by size. So-called cascade impactors use the principle of inertial separation to size segregate particle samples from a particle laden gas stream. The mass of each size fraction is determined gravimetrically. It is difficult to identify why the experiments with the impactor failed, but a dilution unit was required and can cause particle losses due to deposition in the dilution unit. A possible future setup should make use of an impactor with an area large enough to avoid dilution even at low burn rates. There is little literature available looking on particle mass size distribution depending on the burn rate. Previous work done by SINTEF reveals that PM10 and PM2.5 on the average will constitute about 98 % and 94 % of the particulate emissions[34] as shown in Figure 27 (left panel) for a stove with an afterburner. The size distribution for a stove without afterburner gives a fraction of 90 % of all particles smaller than 2.5 µm, and 95 % below 10 µm (Figure 27 right panel). By application of these

[34] Project Report Claudia Schön, SINTEF Energy Research and Norwegian University of Science and Technology Trondheim, 22nd April 2003

results, both PM10 and PM2.5 can be estimated from the measured amount of PM_t in the current study, by simply multiplying PM_t with 0.96 and 0.92, respectively. Particles below 1 µm varied depending on the burn rate. For poor combustion condition with a burn rate around 1 kg/h the fraction of particles below 1 µm was 50 %. The total share of PM1 particles increased with higher burn rate up to 70 and 90% for the stove without and with afterburner respectively.

The estimation of the occurrence of EC and OC in the different particle size classes is difficult without actual measurement data in accordance with the Norwegian standard. A study accomplished by Geagauf[35] concluded that EC and OC are unevenly distributed for all particles size classes, illustrated in Figure 28. The highest fraction of EC was found in particles larger than 9 µm but most OC occurred in particles below 2.5 µm. However, the test was performed for a wood chip burner with very low particles emissions of 1.45 g/kg sampled in the hot flue gas. It cannot be confirmed that these results can be applied for Norwegian wood stoves.

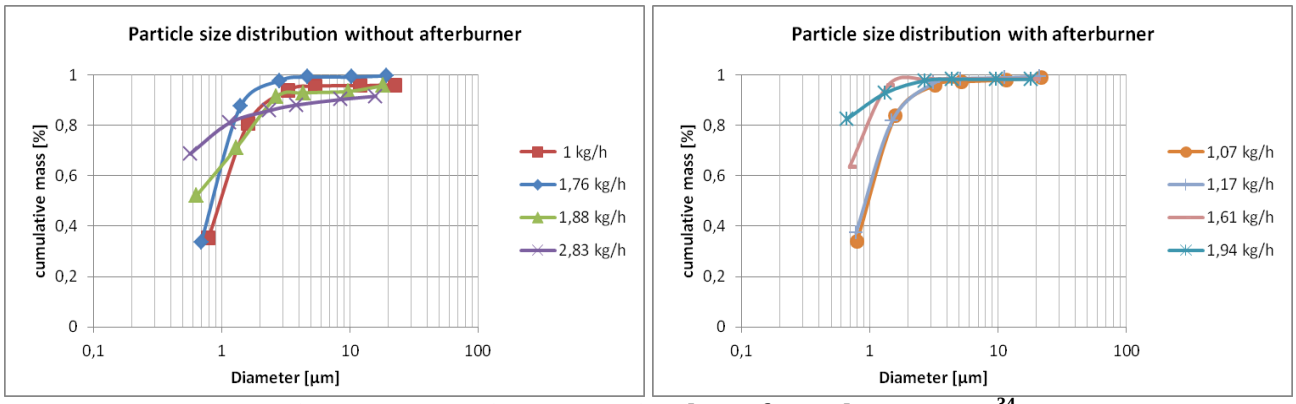


Figure 27. Experiments previously performed at SINTEF[34]

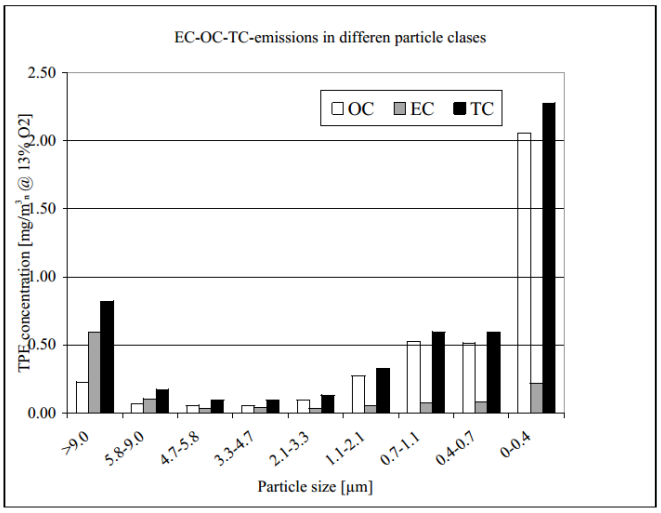


Figure 28. Distribution of EC, OC and TC for a wood chip burner sampled in the hot flue gas[35]

[35] Geagauf, C.; Schmid, M.; Pierre, G.; Elemental and Organic Carbon in Flue Gas Particles of Various Wood Combustion Systems, 2005, Ökozentrum Langenbruck

4 Conclusion

New emission factors for EC, OC and PM_t, obtained by experimental tests on two selected wood stoves employing new and old combustion technology, are proposed. The measured concentrations of EC and OC in PM_t samples obtained from these stoves are appliance specific and cannot be applied directly to other stove types. The figures relate strictly to Norwegian emissions resulting from wood burning.

The emission factors obtained in this project are closely linked to the experimental conditions constrained by the Norwegian wood stove-firing standard. Direct comparison between emissions results from the current project with those obtained from similar projects should be made with caution. Measurements made according to the Norwegian standard provide emission figures which are directly linked to the measurement method. The use of a different measurement method would result in different values. The Norwegian standard for wood stoves has been developed with the aim of reflecting typical real-world's household stove use in Norway. This is taken into account by testing stoves at low burn rates, and by diluting the flue gas before particulate matter is sampled. SINTEF recommends that direct comparisons can only be made with combustion practice in countries, which employ exactly the same standards as in Norway.

In the case of new, less energy-demanding houses, testing at low burn rates will become even more important if wood stove manufacturers fail to develop new stoves better adapted to the requirements of modern housing. The term "new stoves" refers to those which are able to operate at relatively low nominal burn rates, producing between 1 and 2kW (or less) of heat, and which still meet stipulated particle emission limits. If today's somewhat large stoves continue to be the only models available on the market, and thus continue to be installed in low-energy houses, the householder will seek to achieve very low burn rates avoid uncomfortably high temperatures by closing off much of the air inlet to the stove. The results of the use of such "over-dimensioned" stoves, operated under conditions far below their nominal effect, include higher particle emissions resulting from poor combustion efficiency. Particle emissions increase exponentially with decreases in burn rate.

The main achieved objectives of this project are as follows:

- Emission factors for PM_t, EC and OC have been calculated from wood-burning stove experiments performed at the respective laboratories at NBL and SINTEF Energy
- Filters were analysed at UEF using a thermal-optical method
- Statistics obtained from NBL compared with the current results have been used to put the results from stoves using new and state-of-the-art technology in perspective

The conclusions and recommendations from this project are:

- Total PM_t emissions can be significantly reduced by avoiding firing at low burn rate with throttled air inlet valve.
- The major fraction of particle emissions is organic matter, OC.
- The results indicate that a reduction in the total amount of particles leads to a clear reduction in OC.
- The present filter analysis did not provide a satisfying correlation of EC as a function of PM_t at moderate reductions in the total amount of particles.

- High burn rates (> 4 kg/g), under very good combustion conditions, resulted in very low particle emissions (less than 2 g/kg), and very low EC and OC emissions
- Wood-burning stoves employing old combustion technology should be categorized separately based on their year of manufacture, i.e. 1940 to 1970-80, and 1970-80 to 1998
- Data should be acquired on the number of stoves currently in use and installed with only one air damper and no window (very old stoves)
- It has not been possible to correlate measured EC emission factors with BC. This report addresses only EC measurements, and information about the relationship between EC and BC is scarce.
- Previous work performed by SINTEF suggests that PM10 constitutes 96% of PM_t, and PM2.5, 92%.
- The content of EC/OC for different PM size fractions (PM_{10}, $PM_{2.5}$, PM_1) should be further investigated, together with the relationship between EC and BC
- Measurements of the PM size distribution should be further investigated. This can be carried out using an appropriate impactor

To set the selected stove with new technology in perspective vis-à-vis type approval data from NBL, the Jøtul F3 with new combustion technology , is compared to measured data from NBL from 1998 and up to today. Emission factors obtained by weighting the data obtained from NBL are considered to be too low and unrepresentative of true Norwegian emissions. The reason for this lies in an assessment of the number of stoves in use today in relation to the number of fireplaces sold during the last 12-15 years, compared to the stoves selected for the current project. A further issue is that the tests carried out at NBL were performed on brand new stoves, and that the weighted emissions values are based on only a single test at each of the four burn rates stipulated by the Norwegian test protocol. On this basis, it is highly unlikely that the calculated weighted emission factor of 4.7 g/kg is representative of today's wood-burning stoves employing state-of-the-art technology installed in Norwegian households. In the future, however, emission factors as low as 1-2 g/kg might be achievable for the best stoves currently on the market, contingent on proper leakage maintenance, use of proper firewood, and stove operation in compliance with the manufacturer's manual.

Based on the results of this project, new emission factors and uncertainty windows are proposed for the factors PM_t, EC and OC for both normal and medium firing (see Table 15 and Table 17). The emission factors obtained during this project reflect real-world particulate emissions from Norwegian households. It is recommended that emission factors for stoves manufactured from 1940 to 1970-80 be maintained at 40 g/kg (normal firing) and 33 g/kg (medium firing), respectively. In terms of the accuracy of the PM emission inventories, we are left with the challenge of finding satisfactory estimates of the number of very old, old, and new stoves currently in use. However, based on the criteria used to select representative Norwegian stoves, it is likely that the greater part of the wood consumption in pre-1998 stoves takes place in old stoves manufactured in the period 1970-80 to 1998.

One other important outcome of this project is the observation that stoves that have been in use for several years emit more particulates than brand new stoves. This means that our results obtained from state-of-the-art technology stoves can be regarded as more representative of real-life Norwegian wood combustion emissions. However, this does not mean that the impact in terms of reductions in particle emissions of replacing old and very old stoves with new and cleaner technologies is less important than before. The objective of work presented in this report was to provide a sound estimate of what actually is emitted from Norwegian households at the present day. This is why SINTEF selected a stove employing state-of-the-art technology that had already been in use for several years (introduced to the market as

early as in 2001), but did not inherit current, highly optimized combustion technology. Some of the best stoves currently on the market can operate with a weighted particle emission concentration of between 1-2 g/kg. Assuming that the end-user operates these stoves in compliance with the manufacturer's manual, using dry wood, and ensuring that the stove is checked regularly for leakages, the replacement of old and very old stoves by those employing modern combustion technology, could substantially (factor of ~ 10) reduce the PM_t emission factor by a factor of 10. Based on the selection criteria for representative stoves in Norway, it is likely that the greater part of wood consumption in pre-1998 stoves takes place in old stoves manufactured in the period 1970-80 to 1998.

It is also recommended that some kind of inspectorate body, perhaps involving chimney sweeps, should be assigned the responsibility of carrying out stove leakage checks. Alternatively, regulations might be introduced with the aim of ensuring that stoves sold on the Norwegian market can be used for a stipulated number of years with a minimum leakage guarantee.

Compared to the current emission factors used in the Norwegian particle emission inventory, the new PM_t emission factors proposed in this project are more in-line with those factors employed in countries, such as the USA, Australia, Canada, where similar test standards are applied.

Table 17 shows that EC emission factors decrease only marginally when we compare old with new combustion technologies. The reason for this may be related on the one hand to measurement uncertainties and on the other to the relatively similar results for PM_t obtained for both selected stove types. However, it is important to bear in mind that the EC factor is not always reduced significantly when changing from an old to a new stove type.

4.1 Further work

It is recommended that improved sampling methods for EC and OC emissions be developed. The content of EC/OC for different PM size fractions (PM10, PM2.5, PM1) should be further investigated, together with the relationship between EC and BC. In addition, the measurements of the PM size distribution should be examined by carrying out measurements using an appropriate particle impactor.

On the health-side, the PM2.5 share of total particles is also an important factor. In the human body, the nose filters very large particles, larger than 10 microns. Particles between 2.5 and 10 microns accumulate in the upper respiratory tract and large airways. PM2.5 particles, in contrast, can make it into terminal bronchioles and alveoli, the smallest passages deep in the lungs.

The measurement method according to NS3058/59 should reflect Norwegian firing practice and provide emissions data that are truly representative for Norway. It is also important to identify whether wood stove firing practices have changed since the standard was introduced in 1998. We recommend that a survey be carried out to determine whether the actual firing practices incorporated in Norwegian building standards applying to new housing have changed considerably over the last decade, and whether energy demand in housing has been reduced. Heat pumps have been installed in many houses. Responses to the following questions would be useful in this respect; Does better insulated housing combined with heat pumps result in increased levels of wood burning with lower heat output? Is the lower heat output achieved because of air inlet damper throttling, or shorter firing periods?

Table 17. Proposed emission factors based on measurements of enclosed stoves using old and state-of-the-art technologies. The values are specific to this project and refer to a glass fibre filter complying with Norwegian standards. Emission factors for both normal- and night firing operation are based on measured emissions which are also weighted in accordance with two distinct wood consumption trends.

Medium firing = 1.6 kg/h as median			
Emission factor / Stove type	[g PM_t/kg wood]	[g EC/kg wood]	[g OC/kg wood]
Wood stove – "very" old technology	33		
Wood stove – old technology	17.4	1.01	12.89
Wood stove – new technology	12.2	0.90	9.26

Normal firing = 1.25 kg/h as median			
Emission factor / Stove type	[g PM_t/kg wood]	[g EC/kg wood]	[g OC/kg wood]
Wood stove – "very" old technology	40		
Wood stove – old technology	22.7	0.96	16.74
Wood stove – new technology	13.4	0.86	10.47

Other important factors influencing emissions are the properties of the fuel. What kind of wood does the householder use in terms of log size and moisture content? The Norwegian standard currently stipulates a single standardised fuel source (spruce). For this reason, comparisons are needed between the Norwegian standard and the actual fuel sources used.

In this study, two stove types were tested, both manufactured by Jøtul. However, it remains unclear as to how stove design specifically influences particle emissions. Different designs should be tested to compare results.

The experiments carried out during this project were as largely idealized in the sense that they were carried out under controlled laboratory conditions. Fuel type and moisture content were strictly controlled. This means that particle emissions values are most probably lower than those obtained from stoves used in an average household. One possible means of achieving more realistic emissions factors for the Norwegian emission inventory is to carry out on-site investigations. Such projects could be implemented in two phases; (1) planning, and (2) the on-site measurement process.

Step 1 should involve the preparation, together with SSB, SINTEF and Klif, of a detailed questionnaire designed to determine (1) what types of stoves are installed in Norwegian households?, (2) how and when they are used?, and (3) what type of wood is burned? The investigation should also encompass selected representative regions within Norway (Northern, Central and Southern), and a distinction made between urban and rural settings. For example, one urban and one rural setting could be selected for each region. The survey results can then be used to classify Norwegian stoves in use, and will form the basis for the selection of households in which the measurements can be taken. During Step 1, we recommend collaboration with organisations such as CICERO in order to determine where on the chimney outlet structure emissions should be measured (i.e. at which dilution level). Laboratory experiments should then be carried out using the same dilution levels in order to simulate emissions from the chimneys. If possible, selected experiments could be carried out in so-called climate rooms with the aim of obtaining a better picture of atmospheric chemistry. This will enable us to find out how atmospheric residence times affect factors such as particle size, composition etc.

Step 2 comprises the actual process of obtaining measurements from the selected households. Measurements should be taken in households with stoves in each of the predetermined stove categories, and repeated over time. Particle filter measurement should be sufficient. Analysis should be performed to obtain PM_t, EC and OC values. After the analysis of particulate matter obtained on-site, one stove from each of the selected categories should be tested at SINTEF's laboratory using a weighted firing pattern simulating that used in the relevant households. The particulate matter obtained should be analysed for PM_t/EC/OC as a control. The measurement campaign will provide values for PM_t, EC and OC, and size distributions for each category of stove. The inherent uncertainty in the results will depend on how well the stove categorisation is carried out, and how many stoves are tested.

The results from the current project fail to demonstrate a correlation between EC and combustion conditions. Given the relatively large uncertainties linked to the EC values, it is at present unclear if this lack of correlation is characteristic of Norwegian wood stoves in general, or if the result is stove-specific. Future work should focus on testing for the existence, or not, of a correlation between combustion conditions and EC emissions.

Fuel type presents another interesting variable, and in future work it might be interesting to include investigations of variation resulting from selected wood types.

It is important in connection with all future measurements of EC and OC emissions from wood stoves to address the problem encountered by this project related to filter particle overload during the NS-compliant measurement and analysis of EC and OC using state-of-the-art instruments.

Annex A: Customer's assignment

12. BILAG

Bilag 1 Kundens beskrivelse av oppdraget

Fullstendig beskrivelse av leveransen for prosjekt nr 4011051

Avtalen punkt 1.1 Avtalens omfang

Klima- og forurensningsdirektoratets behov for resultatene

Klima- og forurensningsdirektoratet (Klif) ønsker å få gjennomført målinger av partikkelutslipp fra vedfyring i norske husholdninger for å kunne etablere spesifikke utslippsfaktorer for utslipp til luft av «black carbon» (BC/EC) fra denne kilden. Benevningen «Black carbon» og «elemental carbon» (EC) benyttes om hverandre og benevningen er avhengig av hvilken metode som blir benyttet for å analysere filterprøvene. Metoden som er valgt i dette prosjektet tilsier at det er «elemental carbon» som skal måles. I tillegg skal utslippsfaktor for organisk karbon (OC) bestemmes. Utslipp av begge komponenter skal relateres til utslippet av total mengde partikler (TSP). I tillegg skal begge komponenter, om mulig, relateres til utslippet av PM10 og/eller PM2,5 basert på data fra litteraturen. Utslippsfaktoren skal angis per enhet innfyrt mengde (kg) ved. Dette skal anvendes av Klif blant annet til å utvikle et norsk utslippsregnskap for EC, og eventuelt også oppdatere utslippsregnskapet for TSP, PM10 og PM2,5. Utslipp av EC fra vedfyring antas å være et vesentlig bidrag til det nasjonale utslippet av EC. Arbeidet vurderes også å kunne bidra til utvikling av bedre utslippsregnskap for EC i andre land, fordi dataene vil bidra til å øke den generelle forståelsen for mekanismene som ligger til grunn for dannelse av EC fra vedfyring.

Tallmaterialet som finnes for Norge for utslipp av EC er per i dag beregnet på grunnlag av utslippsfaktorer fra litteraturen. Det finnes svært få målinger av EC-utslipp fra vedfyring i husholdningssektoren globalt. De målingene som foreligger er ikke gjort i henhold til Norsk Standard for måling av utslipp av partikler fra vedfyring (NS: NS3058 og NS3059). Partikkelmålingene som danner grunnlaget for utslippsfaktorer av partikler (TSP, PM_{10}, $PM_{2,5}$) i det norske regnskapet er gjort i henhold til Norsk Standard (NS: NS3058 og NS3059). Vi vet at fyringsvaner som Norsk Standard for typegodkjenning av vedovner representerer, gir høyere utslippsfaktorer enn standarden mange andre europeiske land bruker. Dette gjør det vanskelig å sammenlikne norske utslipp fra vedfyring med utslipp i andre land. Således er det også problematisk å anvende forhold mellom EC og PM som er etablert i andre land for å bestemme utslipp av EC fra vedfyring i Norge. Klif ønsker at oppdragstaker anbefaler hvordan norske utslipp av partikler kan/bør sammenliknes med utslipp fra ulike andre land (for eksempel europeiske land, USA og Canada), gitt ulike standarder for målinger. Herunder hvordan land som benytter en annen målestandard best kan anvende resultatene fra dette prosjektet.

Klima- og forurensningsdirektoratets krav til Oppdraget

Oppdragstaker skal gjennom nye målinger og analyser av utslipp fra vedfyring:

- Foreslå utslippsfaktorer for EC, OC, total mengde partikler (TSP), og om mulig $PM_{2,5}$, PM_{10} (basert på data fra litteraturen), for vedfyring i lukket vedovn med henholdsvis gammel og ny teknologi[1]. Utslippsfaktorene skal angis per enhet innfyrt mengde (kg) ved. Resultatene skal være representative for vedovnstyper brukt i Norge, og resultatene skal baseres på måleresultater og analyser, samt oppdragstakers faglige vurderinger.
- Forslag til utslippsfaktorer for TSP, og eventuelt $PM_{2.5}$, PM_{10} (basert på data fra litteraturen), som eventuelt skal erstatte dagens faktorer i det nasjonale utslippsregnskapet, skal bygge på måleresultater fra ovner i bruk i Norge. Måledata fra dette prosjektet og typegodkjenningsdata tilgjengelig hos NBL skal benyttes i vurderingene.
- Målingene som foretas for bestemmelse av utslippsfaktorer skal utføres i henhold til NS og i et stort nok antall til å kunne gi statistiske holdbare verdier for lukkede vedovner både med gammel og ny teknologi som er representative for norske husholdninger.
- Oppdragstaker skal beskrive hvordan prøvematerialet best kan ivaretas og lagres for å være tilgjengelig for eventuelt fremtidige re-analyser.
  Dersom filtermaterialet som er igjen etter oppdragets prøvetakinger er av en slik art at Oppdragstaker mener det ikke vil kunne gjenbrukes og/eller en hensiktsmessig oppbevaringsmetode vanskelig kan identifiseres, skal Kunden umiddelbart varsles. Oppdragstaker må kunne begrunne sin vurdering. Vurderingen tas inn i sluttrapporten.

Oppdragstaker skal vurdere resultatene med henblikk på:

- Sammenligning av utslipp fra vedfyring slik det måles i mange andre land (for eksempel europeiske land, USA og Canada) med Norsk standard (dvs. sammenligning av utslippsfaktorer, hvorfor NS gir forskjellig resultat fra standarden mange andre land bruker, og hvordan norske utslipp best kan sammenlignes med utslipp fra andre land).
- Hvordan land som benytter en annen målestandard best kan anvende resultatene fra dette prosjektet.
- Hvordan måleoppsettet kan influere på resultatet, spesielt forholdet mellom hva som måles, og mengden partikler som slippes ut i lufta.
- Forholdet mellom OC og EC utslipp.
- Usikkerhet i resultatene, herunder hvilke faktorer som er av betydning for utslippsfaktorene, og i hvilken retning utslippet endres for eksempel ved endret fuktighet, treslag, last, etc.

Sluttresultatet av Oppdraget

Oppdragstaker skal beskrive resultatene i en rapport der metodikk og resultater, samt vurderinger som liste ovenfor er inkludert. Rapporten skal skrives på engelsk med et fyldig, frittstående norsk sammendrag.

Oppdraget skal påbegynnes så fort som mulig etter kontraktsinngåelse. Oppdraget skal være avsluttet innen 28. september 2012.

[1] Dvs. ovner bygget henholdsvis før og etter 1998, da Norsk Standard trådte i kraft.

Annex B: The consultant's description of the project assignment

Bilag 2 Konsulentens spesifikasjon av Oppdraget

Konsulentens spesifikasjon av Oppdraget:

1 Bakgrunn

Prosjektforslaget er utarbeidet med bakgrunn i KLIF's uttrykte ønske (ref.: Åpen anbudskonkurranse etter forskriftens del I og III, for anskaffelse av utslippsfaktorer fra vedfyring i Norge, Saksnr. 4011051) om å få tallfestet Norges bidrag til utslipp av elementært karbon (EC = Elemental Carbon/BC =Black Carbon) spesielt fra vedfyring. Grunnen til at KLIF er interessert i dette er bl.a. Arktisk Råds ministermøte i mai hvor man ble enige om sammenhengen mellom sotutslipp og issmelting i arktiske strøk. Rådet anbefalte medlemslandene store kutt i sotutslippene. De åtte utenriksministerne i landene som danner Arktisk Råd; Canada, Danmark/Grønland/Færøyene, Finland, Island, Norge, Sverige, Russland og USA skrev under på å anerkjenne nødvendigheten av store kutt i klimagassutslipp for å bekjempe klimaendringene. Erklæringen inneholder en oppfordring til alle land i Arktis om å implementere anbefalinger til redusert utslipp av BC.

Tallmaterialet som finnes for Norge for utslipp av EC er per i dag kun et anslag. Det finnes ikke målinger som kan bekrefte størrelsen på utslippene. Når i tillegg tallene viser at Norge ligger godt over andre skandinaviske land og land som inngår i Arktisk råds medlemsmasse, som det er naturlig å sammenligne med, er det viktig at man snarest får opp et godt nok estimat på hva bidraget egentlig er. Den mest naturlige framgangsmåten er å utføre eksperiment i et stort nok antall til å kunne gi statistiske holdbare verdier for et antall representative vedovner.

Når det gjelder vedfyring i Norge viser dagens tall at vedforbruket i husholdningene økte med 15 prosent fra 2009 til 2010[1]. Nesten to tredeler av svevestøvutslippet i Norge kommer fra vedfyring. Det ble brent i overkant av 1,5 millioner tonn ved i norske boliger i 2010, en økning på 15 prosent fra 2009. I tillegg ble det brent i overkant av 250 000 tonn ved i fritidsboliger i 2010, en økning på 23 prosent fra året før. Ved benyttet i fritidsboliger utgjorde 14 prosent av det totale norske vedforbruket i 2010. Sammenlignet med 2009 har det vært en økning i mengde ved brent i alle ildstedstyper. Foreløpige tall viser at økningen var størst for ovner med ny teknologi, hvor det i 2010 ble brent over 100 000 tonn, eller 19 prosent mer enn i 2009. I 2010 hadde 46 prosent av husholdningene som fyrer med ved ovner med ny teknologi (ovner produsert etter 1998). Antall nye ovner har økt med over 50 prosent siden 2005, og 48 prosent av veden ble brent i ovner med ny teknologi i 2010. Tallene for 2010 (se Tabell 1-1) viser at vedforbruket i boliger er 4%, 48 % og 48 % for hhv. Peis, lukket ovn med gammel teknologi og lukket ovn med ny teknologi.

Tabell 1-1: Tall fra SSB[1]

Vedforbruk i boliger, energiinnhold og svevestøvutslipp[1] (PM_{10}) fra vedfyring fordelt på ildstedstype. 2010. Tonn og TWh

	Enhet	I alt	Peis	Lukket ovn, gammel teknologi	Lukket ovn, ny teknologi
Vedforbruk i boliger	Tonn	1 530 843	56 753	737 820	736 271
Teoretisk energiinnhold	TWh	7,15	0,27	3,45	3,44
Nyttiggjort energi	TWh	4,00	0,04	1,38	2,58
Svevestøvutslipp (PM_{10})	Tonn	28 457	805	23 908	3 743

[1] Sintef har anbefalt faktoren 40 g/kg brukt for gamle lukkede ovner, med unntak av fyring i Oslo der de anbefaler 33 g/kg som følge av mindre nattefyring. Denne faktoren er også benyttet for Bergen, Trondheim og Drammen.

[1] http://www.ssb.no/magasinet/miljo/art-2011-06-17-01.html

I en rapport fra Arktisk råd konkluderes det med at hovedkilden til utslipp av EC som rammer arktiske strøk stammer fra vedfyring og kjeler som opereres i nærliggende land.

> ***Domestic Heating.*** Wood stoves and boilers have emerged as a leading target for BC mitigation strategies because they represent a major source of BC emissions in the Arctic. Wood burning also produces emissions of methane and ozone precursors. Although some countries do regulate particle emissions from these stoves and boilers, control measures may not always capture BC emissions. Although planned stove replacement campaigns and particle emissions controls may reduce BC emissions in some areas, without new measures, overall emissions from this sector are projected to remain steady or increase by 2030. New technologies may enable highly effective mitigation measures to improve both health and climate. The following measures offer potential for reductions of BC emissions in the Domestic sector: [2]

2 Målsetting

Med bakgrunn i de innledningsvis nevnte forholdene foreslås det å gjennomføre et prosjekt med den målsetting å gi et best mulig estimat på mengden EC, OC og total mengde partikler som slippes ut fra norske vedovner, et estimat i den forstand at forsøkene utføres iht. Norsk Standard. Forskjell mellom reelle utslipp og resultat fra fyring iht. NS er måten det fyres på, dvs. mer kontrollert. Gjennom prosjektet vil man foreta eksperimentelle målinger på to representative vedovner; A) Lukket ovn - gammel teknologi og B) Lukket ovn – ny teknologi, med den hensikt å få fram en utslippsfaktor for EC, OC og total mengde partikler som gram per kg innfyrt brensel. I norske boliger står disse to ovnstypene for 96 % av all vedforbrenning.

Ovnstype	Utslippsfaktor [g EC/kg ved]	Utslippsfaktor [g OC/kg ved]	Utslippsfaktor [gPM/kg ved]
Lukket ovn - gammel teknologi	X	X	X
Lukket ovn – ny teknologi	X	X	X

Hovedmål

- Fastslå utslippsfaktorer for EC, OC og total mengde partikler for vedfyring i de to mest representative vedovnstypene i Norge.

Delmål

- Innlede samarbeid med Finsk partner med tanke på internasjonal standardisering av måle- og analysemetode for EC/OC for land som er medlem i Arktisk råd

[2] An Assessment of Emissions and Mitigation Options for Black Carbon for the Arctic Council (May 2011)

3 Leveranser

Arbeidet er planlagt utført primo mai til ut september måned 2012. Det er planlagt en foreløpig rapport ultimo juni 2012. Endelig rapport blir levert ultimo september 2012.

	Task Name	Resource Names	Start	Finish
1.2.5	**Reports and dissemination**		**Mon 18.06.12**	**Fri 28.09.12**
1.2.5.2	Deliver preliminary report	SINTEF Energi AS;NBL;UEF	Fri 29.06.12	Fri 29.06.12
1.2.5.4	Deliver final report	SINTEF Energi AS;NBL;UEF	Fri 28.09.12	Fri 28.09.12

4 Arbeidsbeskrivelse

Under følger planlagte oppgaver som skal gjennomføres ila prosjektets gang. Oppgavene er kommentert under hvor dette er nødvendig.

	Task Name	Resource Names
1	**"BlackOUT" Project leader - SINTEF**	**SINTEF Energi AS**
1.1	Project coordination	SINTEF Energi AS
1.2	Planning and organization of test campaign and analyses	SINTEF Energi AS
1.3	SINTEF visit at UEF	SINTEF Energi AS
1.4	**Test campaign stove type new/old - SINTEF**	**SINTEF Energi AS**
1.4.1	SINTEF initiation	SINTEF Energi AS
1.4.2	SINTEF test campaign 8 tests	SINTEF Energi AS
1.5	**Test campaign stovetype new/old - NBL**	**NBL**
1.5.1	NBL initiation	NBL
1.5.2	NBL test campaign 16 tests	NBL
1.6	**Filter analyses 2x3x4x2x3- UEF**	**UEF**
1.6.1	UEF initiation	UEF
1.6.2	UEF analyses	UEF
1.7	**Reports and dissemination**	
1.7.1	Reporting	SINTEF Energi AS,NBL,UEF
1.7.2	Deliver preliminary report	SINTEF Energi AS,NBL,UEF
1.7.3	Reporting	SINTEF Energi AS,NBL,UEF
1.7.4	Deliver final report	SINTEF Energi AS,NBL,UEF

Kommentarer til ovennevnte oppgaver:

- SINTEF/NBL utfører testene i sine respektive laboratorium på to utvalgte ovnstyper som er representative for Norge. Ovnene velges ut av SINTEF/NBL.
- Filter oppbevares ved -18 °C.
- SINTEF vil utføre 8 tester:
  - 4 tester ovnstype A – Lukket m/gammel teknologi
  - 4 tester ovnstype B – Lukket m/ny teknologi
- NBL vil utføre 16 tester:
  - 8 tester ovnstype A – Lukket m/gammel teknologi

  - 8 tester ovnstype B – Lukket m/ny teknologi
- Testene utføres iht. Norsk Standard, med den hensikt at målingene skal gjenspeile norske utslipp. For verifisering av ovnstype sammenstilles målingene med data som SINTEF NBL har tilgjengelig ifm tidligere typegodkjenning av utvalgt ovner. Sammenstilles med tanke på å representere «mest brukte» ovnstyper siste dekade.
- UEF utfører analyser basert på termisk-optisk metode[2]. Alle filter sendes til UEF - Finland for analyse. Pakkes i tørris under forsendelse.
  - Fra hvert forsøk tas det ut 2 filtre for analyse
  - Fra hvert filter testes 3 deler av filteret
  - Totalt antall analyser: 2 x 3 x 4 x 2 x 3 = 144
- En foreløpig rapport for framkomne resultater leveres ultimo juni 2012. Utslippsfaktorer for både EC, OC og total mengde partikler skal være av en slik kvalitet at de kan benyttes av SSB som offisielle tall for Norge.

Følgende utstyr må kjøpes inn som en del av prosjektet:

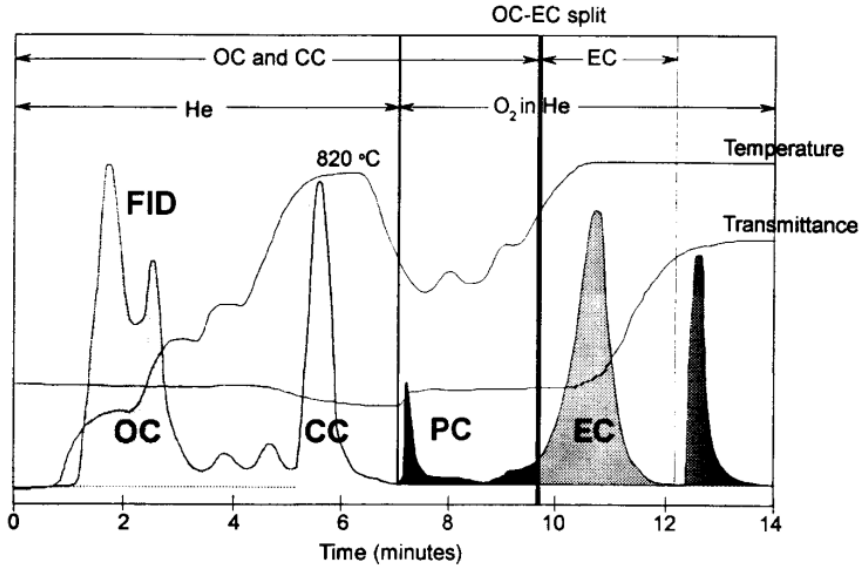
- 2 stk vedovner for gjennomføring av tester.
- 1 stk fryser for oppbevaring av filtere.

Dersom resterende filtermateriale etter gjennomførte analyser er av en slik beskaffenhet at de kan lagres for fremtidig bruk og kunden ønsker dette vil denne fryseren være nødvendig for oppbevaring. Fryseren vil være KLIF's eiendom og KLIF vil være ansvarlig for denne. Det betyr at om fryseren havarerer er dette ikke SINTEF's ansvar. Dersom et slikt havari oppdages tidsnok til at lagret filtermateriale ikke blir ødelagt, vil det bli innkjøpt ny fryser som KLIF må bekoste. KLIF må også påregne årlige lagringskostader (areal, strøm).

[2] http://www.borenv.net/BER/pdfs/ber14/ber14-255.pdf

Annex C: Representative thermograms from EC/OC analyzes

Explanations for thermograms



Example thermogram for sample containing rock dust (carbonate source) and diesel exhaust. Three traces correspond to temperature, filter transmittance and detector (FID) response. Peaks correspond to organic (OC), carbonate (CC), pyrolytic (PC) and elemental (EC) carbon. (Source: Aerosol Science and Technology Monitoring Occupational Exposures to Diesel Exhaust 227 2513 October 1996)

Three thermograms have been supplied in this annex as exemplification. All examples were taken from the front filter 1-1. The first two thermograms are for stoves with old combustion technology (G12 and G3) while the third thermogram represents new combustion technology (S7). G12 was an experiment within the FID range of the instrument, while G3 was a partly overloaded experiment. S7 was an experiment with high particle load on the filter, thus the FID off-scale indication in the figure. The colored curves on the plot are explained with color codes. A vertical black line indicates the split time.

1.1 Front quartz filter, includes both gaseous and particle form organic carbon + particle form elemental carbon. Etu=front; a, b, c were taken from different parts of the filter.
1.2 Backup filter, behind 1.1.

2.2 Quartz filter behind the PTFE filter, contains gaseous organic carbon.

References

Turpin, B.J., Saxena, P., Andrews, E., 2000. Measuring and simulating particulate organics in the atmosphere: problems and prospects. Atmospheric Environment 34, 2983–3013.

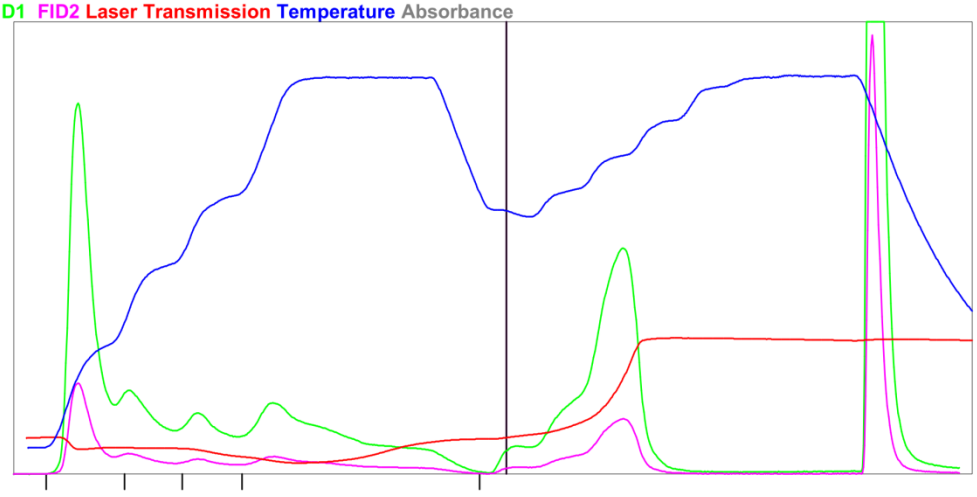
Sample ID: G12 1.1etub
Analysis Date/Time 6/25/2012 1:40:52 PM

Organic C =	**14.97 +-0.95 ug/sq cm**
Carbonate C =	**0.00 +- ug/sq cm**
Elemental C =	**8.05 +-0.60 ug/sq cm**
Total C =	**23.02 +-1.45 ug/sq cm**
EC/TC ratio =	**0.350**

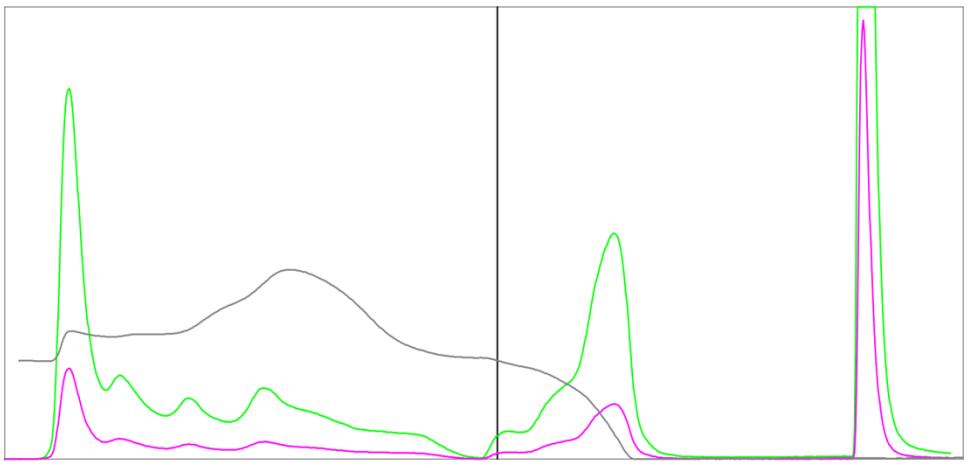
FID: FID:OK FID2:OK DL= 10 Punch Area, sq cm = 1.5
Calibration area Used = 218942.0 Calibration Constant = 22.22
FID2 Calibration area = 53513.0
Laser correction factor = 0.99
Split time Used = 453 seconds Split time Calculated = 453 seconds
Pk1= 6.40 Pk2= 2.02 Pk3= 1.66 Pk4= 4.81

FID GRAPHIC SCALE= 10

FID1 FID2 Laser Transmission Temperature Absorbance



Inital absorbance = 1.299 Absorbance at StartPyrolize = 1.344
Absorbtion Coefficient of original elemental C = 16.1
Absorbance plotted from 0 to 6



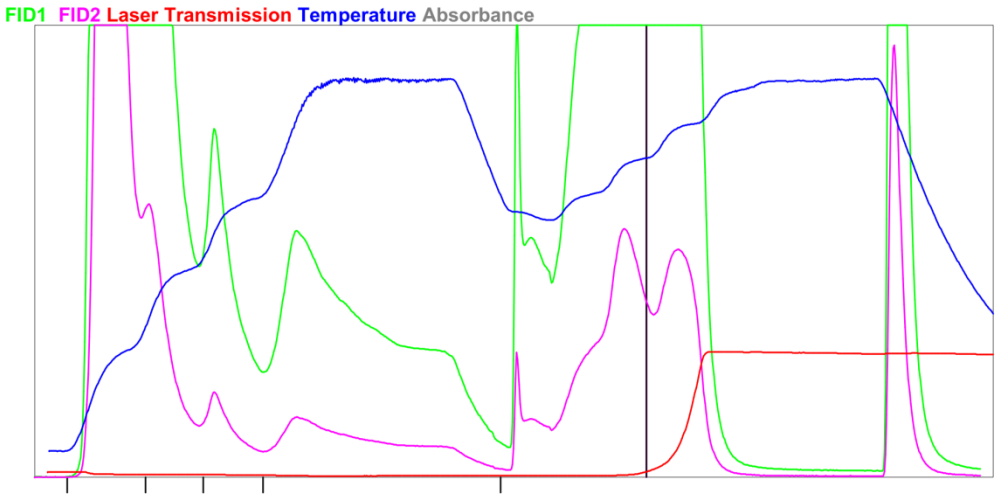
OC/EC Analysis Program (c) Sunset Laboratory, Inc. Analyst - virpi

Sample ID: G3 1.1etua
Analysis Date/Time 6/26/2012 1:29:01 PM

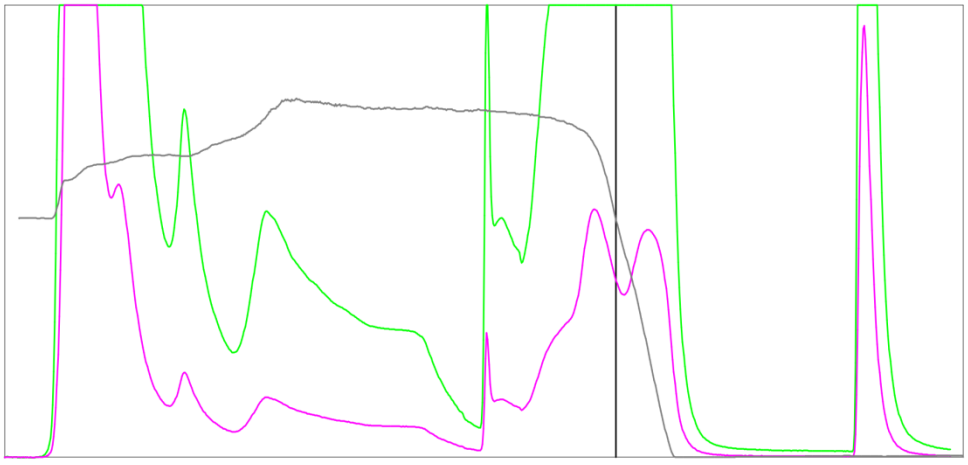
Organic C = 156.57 +-8.03 ug/sq cm
Carbonate C = 0.00 +- ug/sq cm
Elemental C = 25.74 +-1.49 ug/sq cm
Total C = 182.31 +-9.42 ug/sq cm
EC/TC ratio = 0.141

FID: FID1 OFFSCALE!!! FID2:OK DL= 10 Punch Area, sq cm = 1.5
Calibration area Used = 59329.0 Calibration Constant = 22.22
FID2 Calibration area = 59329.0
Laser correction factor = 0.99
Split time Used = 562 seconds Split time Calculated = 562 seconds
Pk1= 79.72 Pk2= 16.78 Pk3= 6.52 Pk4= 17.86

FID GRAPHIC SCALE= 10



Inital absorbance = 3.169 Absorbance at StartPyrolize = 4.604
Absorbtion Coefficient of original elemental C = 12.3
Absorbance plotted from 0 to 6



OC/EC Analysis Program (c) Sunset Laboratory, Inc. Analyst - virpi

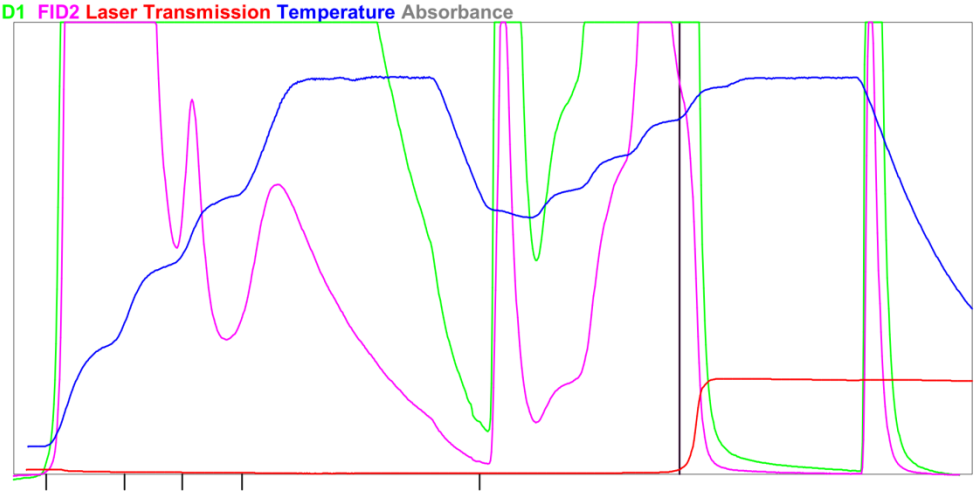
Sample ID: S7 1.1etu c
Analysis Date/Time 8/23/2012 2:11:08 PM

Organic C =	**791.95 +-2000000000.00 ug/sq cm**
Carbonate C =	**0.00 +- ug/sq cm**
Elemental C =	**15.97 +-2000000000.00 ug/sq cm**
Total C =	**807.93 +-2000000000.00 ug/sq cm**
EC/TC ratio =	**0.020**

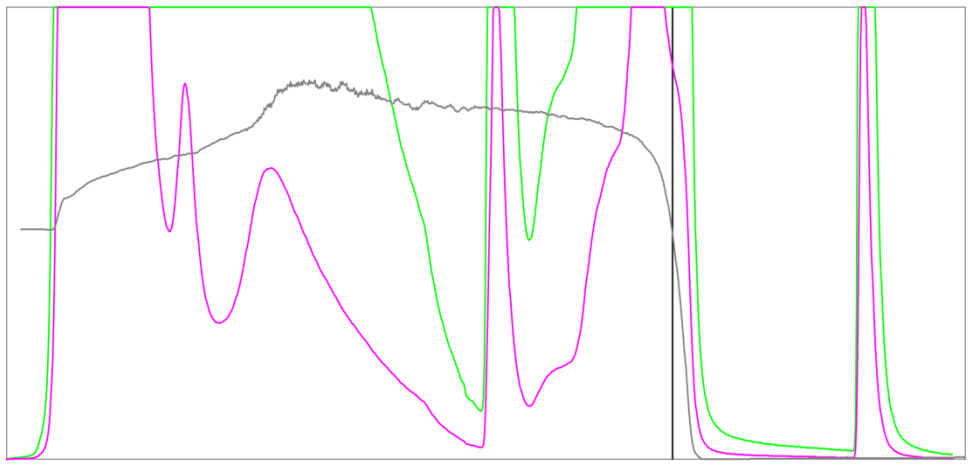
FID: FID1 OFFSCALE!!! FID2 OFFSCALE!!! DL= 10 Punch Area, sq cm = 1.5
Calibration area Used = 57328.0 Calibration Constant = 22.22
FID2 Calibration area = 57328.0
Laser correction factor = 1.01
Split time Used = 612 seconds Split time Calculated = 612 seconds
Pk1= 429.55 Pk2= 146.55 Pk3= 28.78 Pk4= 75.79

FID GRAPHIC SCALE= 10

FID1 FID2 Laser Transmission Temperature Absorbance



Inital absorbance = 3.051 Absorbance at StartPyrolize = 4.673
Absorbtion Coefficient of original elemental C = 19.1
Absorbance plotted from 0 to 6



OC/EC Analysis Program (c) Sunset Laboratory, Inc. Analyst - virpi

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