
PAH measurements in air and moss around selected industrial sites in Norway 2015

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Summary

On request from the Norwegian Environment Agency a pilot study of atmospheric deposition of PAH around industrial enterprises in Norway has been carried out. The participation was voluntary and 10 industries located at 10 different sites financed their own participation. The survey is based on analysis of samples of naturally growing moss collected around the enterprises during the summer of 2015. In addition, passive air samplers for collection of volatile PAH were placed around 6 of the participating enterprises. Generally, the PAH level determined in moss collected around industrial sites were considerably higher than the PAH level found in moss collected at background sites. The levels of PAHs found in the air samples was low and often at the same level as found at the closest background site, for all out of two sites, i.e. Sunndal and Kristiansand. There is no clear indication that the industry is the only source to the levels of PAHs in moss. Hence, results from this pilot study, illustrates that moss and air samples together provide a more comprehensive information regarding the spatial distribution of PAH around the industrial sites.

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1 Introduction

It was early discovered that terrestrial moss samples has the ability to be used for monitoring of atmospheric deposition of pollutants. In Norway, nationwide atmospheric deposition surveys for heavy metals has been conducted at regular intervals since 1977 (Steinnes, Berg, & Uggerud, 2011; Steinnes, Uggerud, & Pfaffhuber, 2012).

Sampling of moss is included in the state program for monitoring pollution, and is additionally part of an international survey where moss is sampled in several European countries (Harmens et al., 2015). Coordination of the joint sampling is carried out by ICP Vegetation (ICP Vegetation, 2016) which is part of the Convention on Long-range Transboundary Air Pollution (CLRTAP) under the United Nations Economic Commission for Europe (UNECE). In Norway moss sampling is conducted by sampling the terrestrial moss, *Hylocomium Splendens*, which is shown to successfully sample deposition of trace metals. Studies have shown clear relations between bulk deposition and findings in moss (Berg, Royset, & Steinnes, 1995).

Within the European network on monitoring of environmental pollutants it has been discussed whether moss also can be utilized for sampling other types of contaminants such as e.g. persistent organic pollutants (POPs) and polycyclic aromatic hydrocarbons (PAHs) (Harmens, Foan, Simon, & Mills, 2013). It has earlier been discovered that environmental samples may well serve as passive samplers of organic contaminants. Already in the early 1980 it was discovered that moss and lichen successfully sampled chlorinated pesticides and PAH (e.g. Foan, Domercq, Bermejo, Santamaria, & Simon, 2015; Migaszewski, Galuszka, Crock, Lamothe, & Dolegowska, 2009; Thomas & Herrmann, 1980; Thomas, Ruhling, & Simon, 1984). Based on the findings from the moss survey in 2010 (Steinnes & Schlabach, 2012) and in 2015 (Schlabach, Steinnes, & Uggerud, 2016) and on the request from the Norwegian Environment Agency (Miljødirektoratet) it was decided to carry out a pilot study close to some industrial sites in Norway. The participation was voluntary and the partaking enterprises financed their own participation. Within the Norwegian ferroalloys industry (FeSi/Si), different projects concerning PAH are in progress, where the main objective is to improve measurement methodology to be able to reduce emissions of PAHs. The FeSi/Si enterprises have a collaboration project on improving the measurement technique by measuring PAH in dust fractions. The manganese industry will have the same approach in their work. Improvement of measurement technique is also a topic in the projects ENSENSE, that are led by the Eyde network and in SFI Metal production.

A total of 10 industries participated in the industrial moss survey 2015 survey (see Figure 1 and Table 1).

Eramet Porsgrunn, Porsgrunn
Elkem Carbon, Kristiansand S
Eramet Kvinesdal, Kvinesdal
Eramet Sauda, Sauda
Elkem AS Bjølvfossen, Ålvik
Hydro Aluminium Sunndal, Sunndal
Wacker Chemicals, Hemne
Elkem Thamshavn, Orkanger
Alcoa Mosjøen, Mosjøen
Glencore Manganese, Mo i Rana

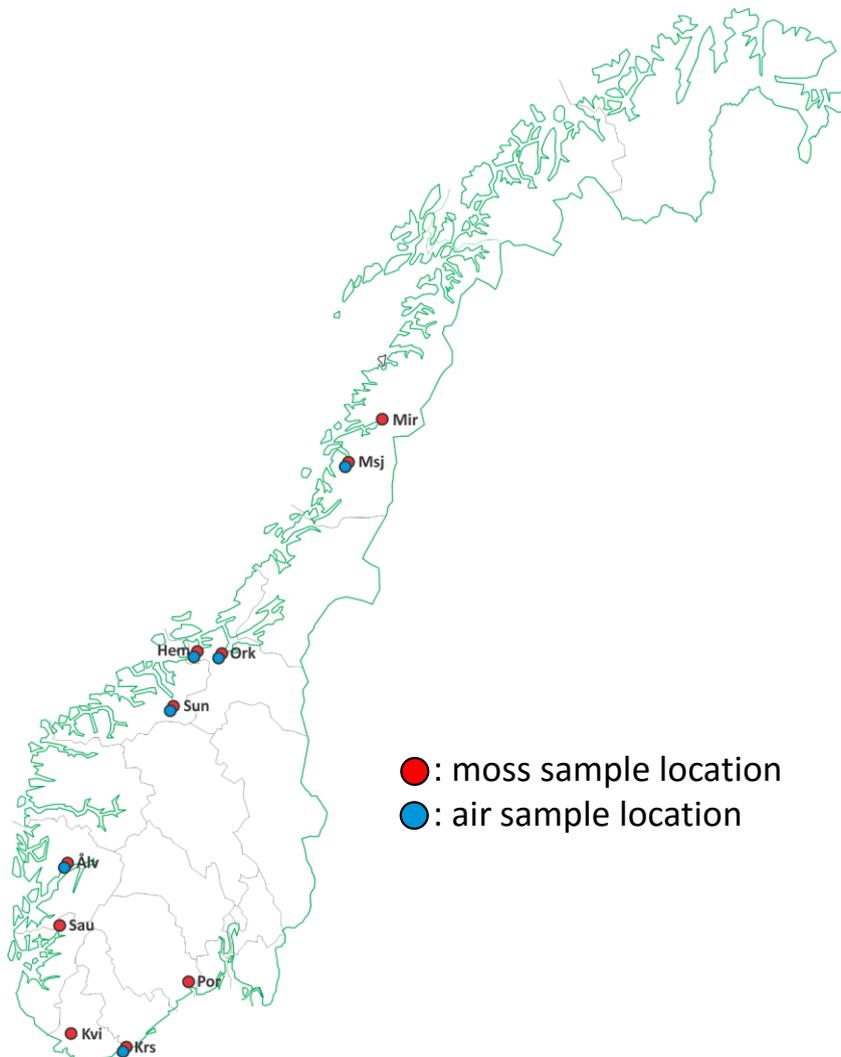


Figure 1: Map showing both moss and air sample locations across Norway. Porsgrunn = Por, Kristiansand = Krs, Kvinesdal = Kvi, Sauda = Sau, Ålvik = Ålv, Sunndal = Sun, Hemne = Hem, Orkanger = Ork, Mosjøen = Msj, Mo i Rana = Mir

The industrial sites encompassed in this study, which is mainly metallurgical industry, is believed to emit PAHs during industrial processes involving anode production; 1) Söderberg anode or 2) pre-bake anode, which emits PAHs (e.g. Hopf, Carreon, & Talaska, 2009; Næs, 1998; Rachwal, Magieral, & Wawer, 2015; Sanderson, Kelly, & Farant, 2005). Consequently, it was decided to carry out a pilot study on monitoring PAHs by using moss. Here the objective was to evaluate possible geographical differences in the deposition pattern of PAHs close to the industrial locations.

Additionally, not only the deposition pattern is vital to monitor, but it is also important to assess the concentration of PAHs in the surrounding air with respect to the industrial locations. Traditionally, air sampling is carried out by use of active air samplers (AAS), where both particles and the more gaseous compounds within organic contaminants are sampled. The high cost, need of electricity and trained field personnel, limits their spatial coverage. In the current study we used passive air samplers (PAS). Over the last decade, PAS has become increasingly popular and has proven to be a useful complementary tool to AAS (Halse et al., 2011; Jaward, Farrar, Harner, Sweetman, & Jones, 2004; Shoeib & Harner, 2002). In order to increase the knowledge regarding the spatial pattern of PAHs around the industrial sites, the current study utilizes both PAS alongside moss samples collected around selected industrial sites. PAS will sample the more gaseous PAH compounds in air, while moss act as a sampler for the deposited PAHs which are more in the particle phase. Hence, the current study provides a complementary measuring technique in order to provide an overall picture of the PAH concentration close to the industrial locations.

In the present study, moss (*Hylocomium Splendens*) was sampled at a number of industrial localities (n=10) in Norway in late summer 2015 (see Table 1). In addition, 5 PAS was co-deployed close to 6 different industrial locations (all together 30 PAS), see Table 1. In order to provide as much as possible a truthful image of the PAH pattern in air with respect to the industry, the PAS was deployed at a certain distance from roads and buildings.

Moreover, an important object of the current study was to assess whether the industry is a potential source to emission of PAHs. Hence, in order to put the results in a wider context concerning the air samples, we have included results of PAHs from a passive air sampling campaign which were conducted in 2006 at background sites across Europe (Halse et al., 2011) and in Norway (Halse, Schlabach, Sweetman, Jones, & Breivik, 2012). The findings from the current campaign will be compared and contrasted with the results from the latter, *i.e.* Norwegian background sites. Regarding the moss samples, the results are contrasted to the closest background values, obtained in the National moss survey, 2015. Please find more information in Table A 3. The background sites is carefully selected to be located far away from any potential local source. Consequently, the background samples were collected away from industry, roads, settlement to mention a few (Halse et al., 2011; Schlabach et al., 2016).

Table 1: Type of samples collected at each location

ID	Location	PAH Moss	PAH Air
Por	Porsgrunn	x	
Krs	Kristiansand	x*	x
Kvi	Kvinesdal	x	
Sau	Sauda	x	
Ålv	Ålvik	x	x
Sun	Sunndal	x	x
Hem	Hemne	x	x
Ork	Orkanger	x	x
Msj	Mosjøen	x	x
MiR	Mo i Rana	x	

*No moss was found at this location

1.1 Selected PAHs

A group of 16 PAHs, defined as US EPA PAH priority list, were selected for analysis. Some of them are suspected carcinogenic including benzo[a]pyrene, benzo[b]fluoranthene and indeno[1,2,3-cd]pyrene (Bojes & Pope, 2007). Others are frequently detected in the environment and includes naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benz[a]anthracene, chrysene, benzo[k]fluoranthene, dibenzo[ah]anthracene and benzo[ghi]perylene. Regarding the figures presenting the results, all 16 PAHs has been included when discussing the moss samples, while a selection of 8 PAHs, *i.e.* fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benz[a]anthracene, chrysene and benzo[a]pyrene, has been the focus when presenting the results for the air samples. This is because they are 1) more frequently detected in the PAS and 2) available for comparison from similar studies.

2 Experimental

2.1 Sampling and sample transport

2.1.1 Moss (*Hylocomium splendens*)

Moss (*Hylocomium Splendens*) samples were collected during the period from May to August 2015, around participating/selected industries in Norway. The location of the sampling sites were selected in order to best characterize the local deposition pattern with respect to topography and dominant wind directions relative to the location of industrial site. In most cases, the moss samples were collected at 1-10 km distance from the industrial site, but for some sites the fjord landscape only allowed sampling where practically possible. The coordinates for each site were recorded by GPS, see Table A 1 and Figure 1 for participating industries and location, respectively.

More information regarding the sampling is given in a previous report (Schlabach et al., 2016), and only a brief introduction is given here. All together 10 moss samples were collected, by bare hand pre-cleaned with wet moss (Spaghnum moss) from the same site. 1 litre of moss was collected in order to cover a representative area, i.e 50x50 meter close to the industrial site. The moss sample collected at Hemne was collected at four different locations, where each individual site again covered an area of 50x50 meter. Samples from all four sites were pooled and represents four sub-samples (10, 8, 3, 4). The samples were sampled directly in to a pre-cleaned glassware and stored at -20°C until sample treatment and analysis.

2.1.2 Air samples (PUF-PAS)

Air samples were collected by use of PAS, and consist of a pre-cleaned polyurethane foam (PUF) disk located between two stainless steel metal domes (Figure 2). PUF is excellent as a sampling medium for semi-volatile organic compounds such as PAHs. The PUF disk is located between two metal domes, in a so-called “flying saucer” design (Wilford, Harner, Zhu, Shoeib, & Jones, 2004). The metal domes protects the sampling media from precipitation, wind and shields against possible photo degradation by sunlight (Tuduri, Harner, Blanchard, et al., 2006). The air is allowed to flow over the sampling media between the gaps, and the organic contaminants may accumulate into the PUF-disk by simple diffusion (Shoeib & Harner, 2002).

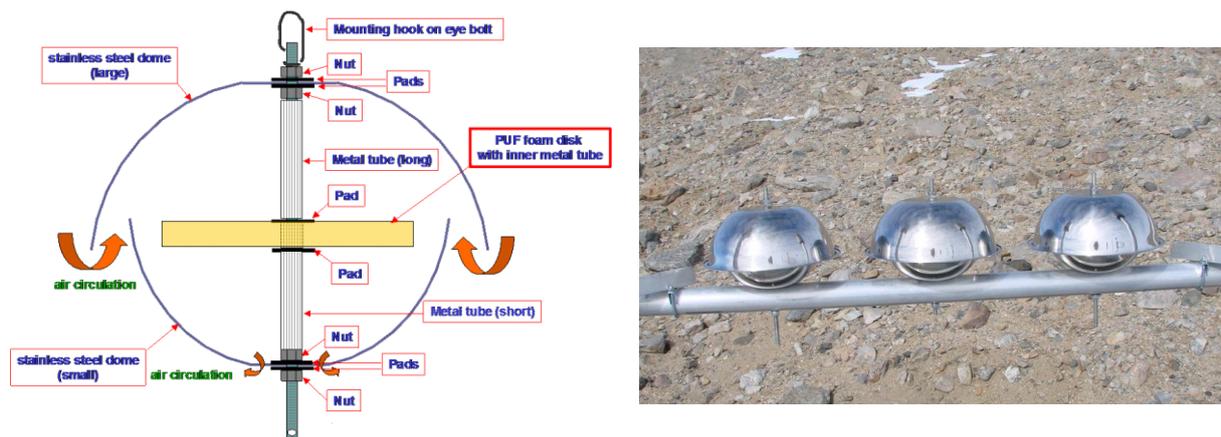


Figure 2: PAS and the flying saucer-design, and PAS deployed in the Antarctic (Photo: Jan Henrik Wasseng)

PAS samplers (n=5) were deployed at 6 industrial sites for one month during summer/autumn 2015 (see Table A 1). The location of the individual PAS was carefully chosen to represent a transect downwind from the industrial site. Data from the closest meteorological station were used in order to deploy the PAS in the prevailing wind direction.

2.2 Sample preparation and clean-up

The moss samples in the current study was prepared according to the same procedure as in the moss nationwide survey for POPs (Schlabach et al., 2016) and only a brief introduction is given here. It should be kept in mind that the current study includes PAHs primarily, and some modifications to the method were introduced. The moss samples were dried in an oven at 25 °C, and 4-5 g dried moss were transferred to an extraction sleeve and added a mixture of deuterium labelled PAHs as an internal standard (2.2.1).

For determination of the PAHs, the moss were soxhlet extracted with ~250 mL cyclohexane for approximately 10 hours. The volume of the extracts was reduced to 0.5 mL and further cleaned by using a liquid-liquid extraction method followed by silica liquid column chromatography (Schlabach et al., 2016).

Concerning the air samples, all the PUF-disk (deployed samples, field and method blank) were added a mixture of deuterium labelled PAHs as an internal standard (2.2.1) and soxhlet extracted using cyclohexane for approximately 10 hours. The volumes of the extracts were reduced to 0.5 mL and the extracts were further cleaned by utilizing silica liquid column chromatography.

The volumes of all extracts, both for moss and air samples, were reduced to approximately 0.5 mL and further concentrated to ~100 μ L by using a gentle stream of nitrogen. Finally the extracts were added a mixture of deuterium labelled compounds as recovery standard.

2.2.1 Instrumental analyses

In order to monitor the recovery rates after extraction and clean-up, internal standards were added to each sample prior to extraction. The standard mixture consisted of a mixture of deuterium labelled PAH congeners (2-methylnaphtalene- d10, acenaphtene- d10, anthracene- d10, pyrene- d10, benz[a]anthracene- d12 and benz[e]pyrene- d12, benz[ghi]perylene- d12). In order to quantify the recovery of the internal standards, a recovery standard consisting of deuterated PAHs (biphenyl-d10, fluorantene-d10 and perylene-d12) was added as a final step prior to analysis. All standards were purchased from LGC, formerly Promochem AB (Borås, Sweden). Identification and quantification of the PAHs was carried out by GC/LRMS on an Agilent 6890N gas chromatograph coupled to an Agilent 5973 mass spectrometer in an electron impact (EI) mode. 1 μ L of the sample was injected by an auto sampler on the split/splitless injection port in splitless mode with helium as a carrier gas. The flow rate was ~1 mL/min.

2.3 Uncertainties

The analytical procedure was monitored using NS/EN ISO/IEC 17025 accredited routines for quality assurance and quality control. In addition a dilution of a PAH mixture containing 16 PAHs (NE 1378) was analysed during each run. More information on uncertainties regarding sampling and sample handling together with the study design of the moss samples is found elsewhere (Schlabach et al., 2016).

In order to assess uncertainties during deployment and/or sampling in field from e.g. transport, storage or general handling of the samples, field blanks were included along with the deployed samples. Field blanks were included for the air samples only, and consist of PUF-disks transported out in field with the samples, but not deployed. These blanks were brought back to the laboratory and stored cold (-20 °C) until sample treatment and analysis. Additionally, in order to monitor sample treatment and clean-up procedures, method blanks were included. In contrast to the field blanks, method blanks were stored at NILU during the entire sampling period. Both field and method blanks consisted of pre-cleaned PUF-disks and were extracted and analysed in the same way as the exposed samples. Method blank for the moss samples consisted of an empty extraction sleeve prepared along with the moss samples.

2.3.1 Uncertainty in the chemical analysis

Several factors may introduce uncertainties in the chemical analyses. During sample treatment, *i.e.* extraction and clean-up, loss of sample may occur. In order to compensate for possible loss during sample treatment, a mixture of deuterium labelled internal standard was used in combination with a recovery standard. Still, the accuracy of the standards used and instrumental parameters, in addition to potential interference of other compounds together with possible contamination, have the potential to increase the uncertainty in the chemical analysis. However, the use of certified reference material, instrumental control standards and involvement in a number of inter-laboratory exercises, help to control the uncertainty and to assure sufficient quality of the analysis. Field blanks were used in order to detect possible contamination during transport and deployment, while the method blank monitored sorbents and solvents used during the sample treatment. To examine the extent of the uncertainties, different approaches may be applied, *i.e.* performance of both inter- and intra-laboratory exercises together with a critical step-by-step evaluation of all analytical steps (except sampling). Both approaches were carried out during establishment of the analytical method and method validation, which resulted in a similar estimate for errors in the chemical analysis, in the range of 29-37 % for all PAHs.

2.3.2 Uncertainty in the PAS method

In contrast to active air sampling (AAS), passive air sampling is more uncertain when it comes to temporal trends, hence passive air sampling is more suitable for spatial mapping of environmental contaminants. In passive air sampling, the volume is not measured, but is calculated. Calculation is mainly based on the physical and chemical parameters of the individual compounds, which are site specific and dependent on meteorological conditions (Gouin, Harner, Blanchard, & Mackay, 2005; Harner et al., 2006; Klanova, Eupr, Kohoutek, & Harner, 2008).

Theoretically, the uptake during sampling is believed to be linear which means that there is a direct relationship between days deployed in field and compounds sampled, and it is possible to use this relationship in order to calculate volume of the air sampled. For the current study, concentrations are presented as the accumulated amount of PAHs per sampler during the sampling period. The samplers are deployed over a longer time period (*i.e.* 1-3 months) and the accumulated compounds may be influenced by wind speed effects (Tuduri, Harner, & Hung, 2006), temperature (Klanova et al., 2008), sun light intensity (Bartkow et al., 2006) and other possible artefacts caused by unintentional particle-phase sampling of PAHs (e.g. Klanova et al., 2008). All these artefacts may alter the uptake rate and deviation from the linear uptake stage and several studies has been conducted in order to address this issue (e.g. Chaemfa et al., 2008; Gouin et al., 2005; Moeckel et al., 2009).

2.4 Sources of PAHs

There are primary and secondary sources of PAHs. Primary sources are a result of 1) production, use and disposal of PAH intentionally used, or 2) PAH unintentionally formed due to incomplete combustion processes of organic materials. Hence there are many current sources of formation and emission of PAHs (Lohmann, Northcott, & Jones, 2000; Ravindra, Sokhi, & Van Grieken, 2008). Thus, both natural sources, e.g. forest fires (Choi, 2014), and anthropogenic sources such as domestic heating from burning of wood and coal (de Gennaro

et al., 2016; Guerreiro, Horalek, de Leeuw, & Couvidat, 2016) or road traffic (Liu et al., 2015) are potential sources for emitting PAHs. However, the major emissions of PAHs into the atmosphere are from industrial activities, mainly metallurgical industries such as aluminium production (Miljødirektoratet, 2015). There are historically two types of aluminium smelter technology: 1) pre-bake anode cell and 2) Söderberg anode cell; for both types anodes are consumed during production of aluminium. Emission of PAHs is most probably due to combustion processes of the anodes in the electrolytic cell during the alumina reduction processes (Hopf et al., 2009; Sanderson et al., 2005). The Söderberg technology has to a large extent been replaced by a pre-bake technology which is believed to cause less emissions of PAH. Yet, the pre-bake anode technology emits considerable amount of PAHs (Hopf et al., 2009). Secondary sources are when PAHs are re-emitted from environmental reservoirs, e.g. soils, water bodies or stock piles, which have been contaminated in the past e.g. from the formerly mentioned sources. Which PAHs that are re-emitted is dependent on the physical-chemical properties of the PAH in question combined with meteorological parameters.

3 Source identification of PAH emissions

There are many current sources to emission of PAHs. The resulting emission depends on the combustion conditions, such as the temperature and what is consumed. Specific PAHs however have a potential to be used as markers to identify type of source or processes releasing the PAHs. Both the 1) concentration profile, 2) diagnostic ratio, and 3) principal component analysis (PCA) may be used as source identification of PAHs. A review by Ravindra and co-workers (2008) has identified a number of PAHs that may be used for identification of specific source categories. They proposed source origins for individual as well as groups of PAHs. Specific studies suggested that chrysene and benzo[k]fluorantene were emitted from coal combustion (Khalili, Scheff, & Holsen, 1995) and that pyrene, fluoranthene and phenanthrene originated from incineration, but also from oil combustion (Harrison, Smith, & Luhana, 1996), and that benzo[a]pyrene is a suitable indicator for PAH emission from metallurgical/aluminium industry (Sanderson et al., 2005).

Further, by using a diagnostic ratio based on comparing ratios of PAHs that are frequently found together, one may distinguish between contributions from e.g. traffic and other sources of combustion (Ravindra et al., 2008). A study by Motelay-Massei and co-workers identified ratios based on PAHs in order to identify combustion sources of PAHs, e.g. fluoranthene/pyrene. Values >1 indicated combustion sources of organic material, while <1 indicated coal combustion (Motelay-Massei et al., 2007). Furthermore Wang et al., (2004) proposed ratios based on deposited PAHs; a phenanthrene/antracene ratio > 15 and a fluoranthene/pyrene ratio < 1 indicating emission from crude oil sources (fossil fuel), and a ratio phenanthrene/antracene < 10 and fluoranthene/pyrene >1 indicating combustion of organic material other than fossil fuel. Factor analysis (PCA) may also be utilized in order to identify emission sources to PAHs (Ravindra et al., 2008), here factors are associated to a source characterized with the most signifying PAH.

Heavier PAHs such as benzo[ghi]perylene, indeno [1,2,3-cd]pyrene) together with benzo[a]pyrene and coronene may be emitted from petroleum related sources, e.g. used tires (Sadiktsis, Bergvall, Johansson, & Westerholm, 2012). Lighter PAH (2-4 ring PAHs), such as fluorene, fluoranthene and pyrene, but also acenaphylene, are more abundant in emissions from industrial activity (Kaya et al., 2012; Odabasi et al., 2009). Furthermore, predominate PAHs in wood smoke are acenaphtylene, naphthalene, anthracene, phenanthrene, benzo[a]pyrene, and benzo[e]pyrene (Khalili et al., 1995), while the following PAHs; naphthalene, acenaphtylene, fluorene, phenanthrene, pyrene and acenaphtene are dominating in emissions from traffic (Bari, Baumbach, Kuch, & Scheffknecht, 2009; Khalili et al., 1995). Naphtalene, acenaphtylene, fluorene, and phenanthrene dominate in emission from coke oven (Khalili et al., 1995).

3.1.1 Transport potential of PAHs

Many PAHs are prone to long range atmospheric transport (LRAT), which means they can be deposited in regions far away from any point source (Halsall, Sweetman, Barrie, & Jones, 2001). The environmental fate is media specific, and relies on removal processes such as biodegradation and half-life of the component in question. PAHs may be easily transported in air, and their transport, deposition and degradation behaviour is dependent on their physicochemical state, e.g. if they appear in the gas phase or are mainly absorbed to particles (Harner & Bidleman, 1998). Meteorological factors such as ambient temperature, humidity and precipitation are also important aspects for the transport potential of POPs (Klanova et al., 2008; Lee & Jones, 1999). The lighter PAHs (2-3 benzene rings) appear solely in the gas phase, and are easily re-emitted from secondary sources as well as prone to LRAT. Heavier PAHs (>5 benzene rings) are more attached to particles, and thereby less mobile and prone to be deposited close to source regions (Wania & Mackay, 1996). Consequently it appears likely that heavier PAHs are found in moss, while the lighter ones are collected by the air sampler. Additionally, removal of PAHs is largely dependent on the seasonal trends. In winter at low temperatures and during rainy seasons, PAHs are generally more likely to be scavenged from the atmosphere due to dry or wet deposition (Ravindra et al., 2008).

4 Results and discussion

4.1 Introductory remarks

Results for the moss samples is presented in Table A 2, while results for the PAS is listed in Table A 4 in Appendix B. All results combined presented per congener is given in Table A 5 in Appendix C.

Regarding the moss and air samples in the current study, the results were corrected for blank values, and the limit of detection (LOD) was established based on the blank values. LOD for the air samples were based on both laboratory and field blanks, while LOD for the moss samples were based on laboratory blanks. Whenever the concentrations fell below the LOD, the values were excluded from further statistical treatment. Naphtalene and acenaphtene, together with dibenzo[ah]anthracene, was often detected below LOD in the air samples (see Table A 4 in Appendix B). Results from both air and moss samples have been compared to the closest background station. The background air samples were collected in 2006 (Halse et al., 2011), while the background moss samples was collected in 2015 and the results for the latter is available in Table A 3.

In order to adequately compare results from the air samples with results from respective background, the latter results were also blank corrected. Air sampling at the industrial locations were carried out for 1 month, while sampling at the background sites lasted for 3 months. In order to have the same length of sampling period, the results from the background sites were divided by 3. As these background PAS were deployed for a longer time period and in the way described in section 2.3.2, the linear sampling stage may have been reached for the lighter PAHs, and results for fluorene, phenanthrene and anthracene may have been underestimated.

Concerning the results from the background stations, we wanted to evaluate whether it is scientifically sound to compare a dataset from 2006 with another data-set from 2015. Consequently we have utilized data from the continuous air monitoring network at Birkenes observatory. The observatory is located in Aust-Agder (58°, 23'N, 8°, 15'E) and is a central measurement site within the European monitoring and evaluation programme (EMEP) under the Convention on Long-range Transboundary Air Pollution (CLRTAP) (UNECE, 2004). Dataset from Birkenes comprised data for the months July and August from 2009 to 2015 for the following eight PAHs: fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benz[a]anthracene, chrysene and benzo[a]pyrene, which were the same as studied in 2006 (Halse et al., 2011).

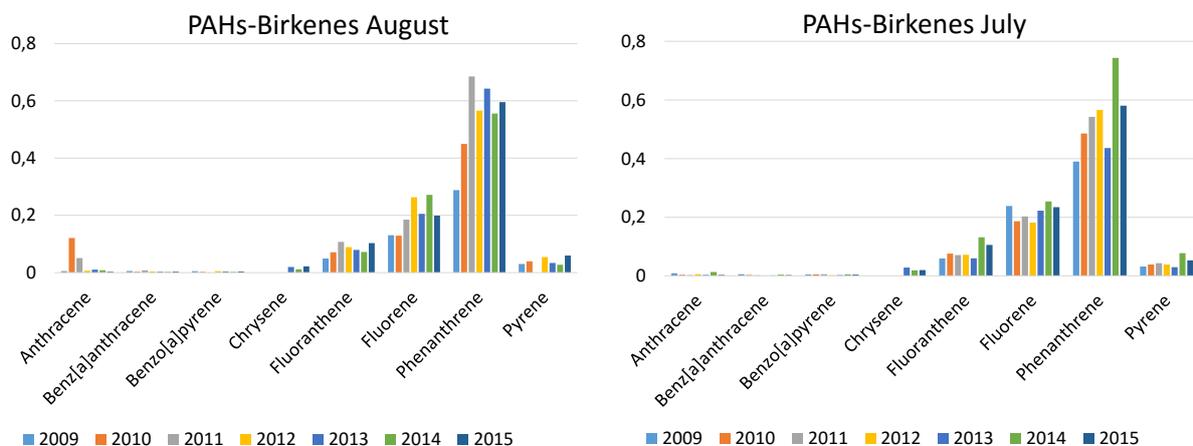


Figure 3: Trends of PAHs in ng/m^3 from active air samples collected at Birkenes from July and August during the period 2009-2015

As Figure 3 displays, there is no clear declining or decreasing trend of PAH at Birkenes from 2009 to 2015. From this we conclude that it seems reasonable to compare a dataset from 2006 with another data-set from 2015. Hence, in the following results from industrial PAS will be compared with background PAS. Additionally, a wind rose from the closest meteorological station, is included in figures 9, 12, 14, 16, 18 and 20. However, the wind rose is representing the dominating wind direction in a larger area, and may not capture local wind conditions potentially affecting the air sampling.

4.2 Air samples (PUF-PAS)

The amounts of PAHs detected in the air samples will be presented separately by localities. Results from the passive air samplers in the figures are presented as ng/sample for eight selected PAHs, namely: Fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benz[a]anthracene, chrysene, and benzo[a]pyrene. Individual amounts for all 16 PAHs are available in Table A 4 (Appendix B). Additionally, as described in section 4.1, results from a background study from 2006 have been included in all figures in order to evaluate the results from the industrial sites in a wider context. Moreover the PAS were deployed along a transect going from each industrial site, for one month during summer of 2015. Figure 4 shows the levels of Σ_8 PAHs from each industry participating in the study. Highest levels of Σ_8 PAHs were found at Sunndal and Kristiansand and in the following section more details will be presented.

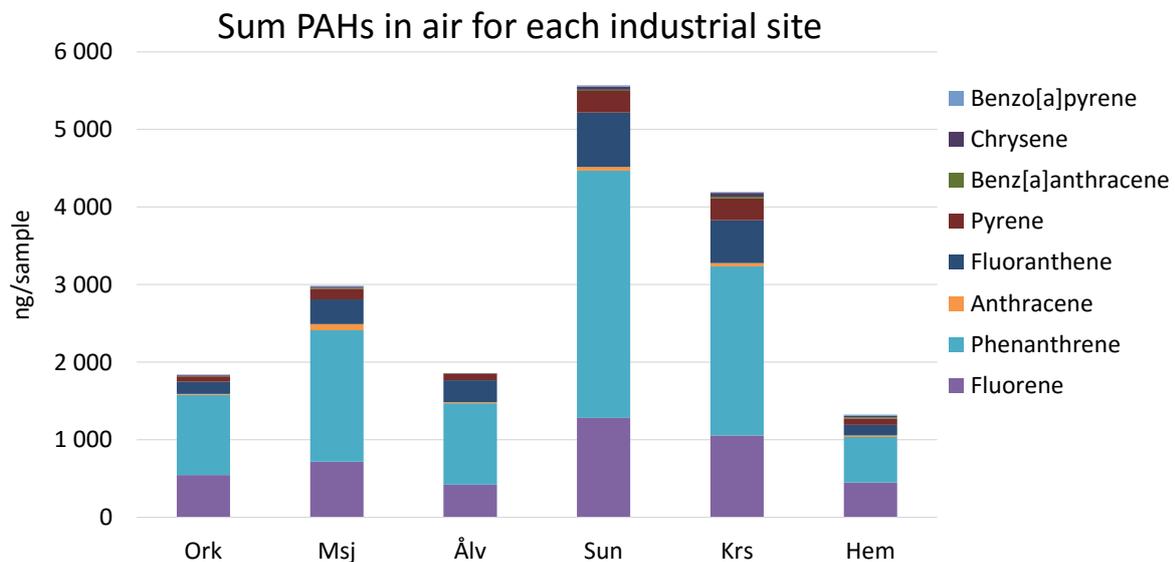


Figure 4: Distribution of the Σ_8 PAHs at the industrial sites; Kristiansand = Krs, Ålvik = Ålv, Sunndal = Sun, Hemne = Hem, Orkanger = Ork, Mosjøen = Msj

4.3 Results discussed by location

Concentrations of individual PAHs (n=16) *i.e.* naphthalene, acenaphene, acenaphthylene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benz[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, indeno[1,2,3-cd]pyrene, dibenzo[ah]anthracene and benzo[ghi]perylene, in moss are presented in Figure 5, and in Appendix B, Table A 2. The sum of 16 PAHs (Σ_{16} PAHs) ranges between 135 ng/g dw (Ålvik) and 2334 ng/g dw (Orkanger). In addition to Orkanger, elevated levels of Σ_{16} PAHs were found at Sunndal (1825 ng/g dw). Lowest concentrations of Σ_{16} PAHs were observed at Ålvik, Kvinesdal, and Sauda, with 135 ng/g dw, 151 ng/g dw and 175 ng/g dw, respectively. The most abundant PAHs detected in the moss samples were benzo[b]fluoranthene, fluoranthene, chrysene, and benzo[a]pyrene, which contributed with 14 %, 13 %, 10 % and 9,6 % to the Σ_{16} PAHs, respectively.

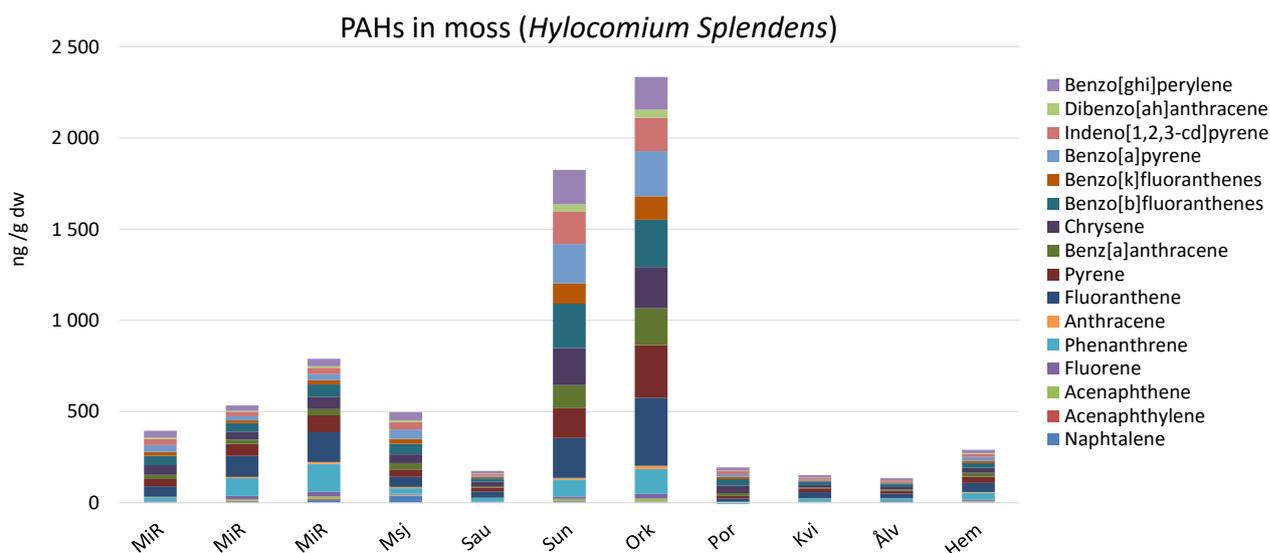


Figure 5: Distribution of 16 PAHs in moss (ng/g dw) for Norwegian industrial sites in 2015; Porsgrunn = Por, Kristiansand = Krs, Kvinesdal = Kvi, Sauda = Sau, Ålvik = Ålv, Sunndal = Sun, Hemne = Hem, Orkanger = Ork, Mosjøen = Msj, Mo i Rana = Mir

Comparison of these results with the moss results from background sites collected during the same time period (Schlabach et al., 2016), clearly reveals that the industrial sites were recognized with considerably higher levels of PAHs. The maximum concentrations at the industrial sites were approximately twenty times higher compared to the highest value from the background sites, which was ~150 ng/g dw (sum 16 PAHs).

When comparing present findings of PAHs in moss with emission data from 2014 (Miljødirektoratet, 2014), it is likely that the higher determined concentrations of PAHs in moss are correlated to the higher emission data from industry (Figure 6), such as observed at Sunndal. Nonetheless it should be noted that Figure 6 only includes sites where moss and air was monitored simultaneously, thus Porsgrunn, Kristiansand, Kvinesdal, Sauda and Mo i Rana, is not included in the figure.

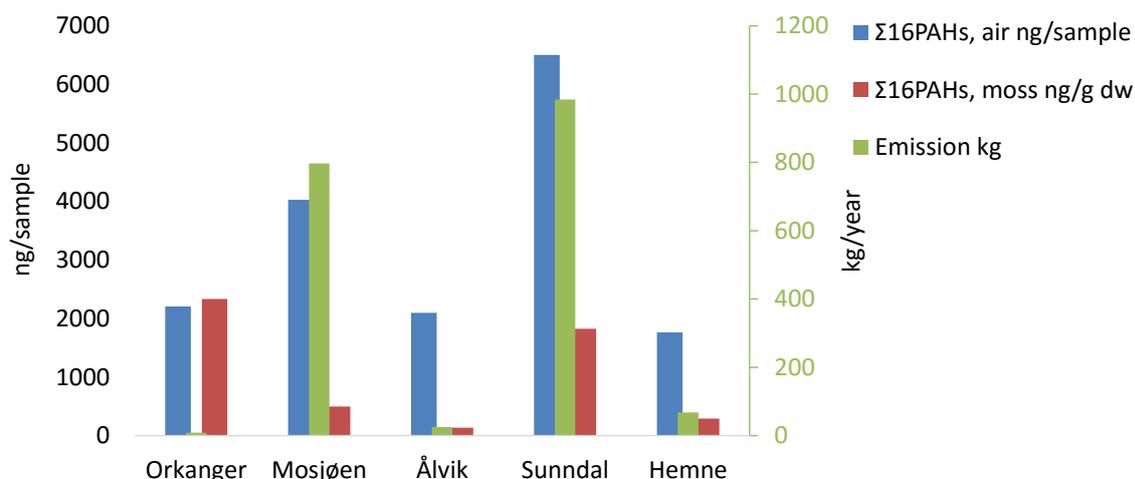


Figure 6: Reported emission (kg/year) of PAHs and measured sum of 16 PAHs in air (ng/sample) and moss (ng/g dw)

As discussed in section 3 there may be several sources to PAHs. In order to evaluate possible contribution from sources other than the industries monitored, ratios between some selected PAHs may be utilized. A phenanthrene/antracene ratio > 15 and fluoranthene/pyrene ratio < 1 indicate emission from crude oil sources, while a phenanthrene/antracene ratio < 10 together with fluoranthene/pyrene > 1 indicates combustion sources of organic material other than fossil fuel, section 3). Hence, the moss samples in this study, the corresponding ratios at some sites, *i.e.* Mosjøen, Orkanger, Porsgrunn and the pooled sample from Hemne (phenanthrene/antracene < 10 and fluoranthene/pyrene > 1) may indicate that combustion other than fossil fuel is a significant source to PAH. Sources that may also contribute to the concentrations of PAHs are industrial processes, e.g. steel industry (Ravindra et al., 2006), characterized by the more abundant fluoranthene together with high-molecular weight PAHs such as benzo[a]pyrene, benzo[ghi]perylene, and chrysene in the moss samples. Though, it is important to keep in mind biological processes which promote degradation of PAHs, hence diagnostic ratios or other source indicators may be ambiguous.

In the following chapters the concentration of PAHs found at the industrial sites for both moss and air samples, will be presented individually. The results for the moss samples will be presented with respect to 16 PAHs, while results for the air sample focuses on 8 PAHs. More information regarding the selected PAHs is available in Table A 2 in Appendix B.

4.3.1 Eramet Porsgrunn

Only moss was collected at the industrial site in Porsgrunn. The moss sample collected close to the industrial site covered an area approximately 50x50 m² (see Figure 7). The most abundant compound within Σ₁₆PAHs (216 ng/g dw) was chrysene with 41 ng/g dw followed by benzo[b]fluorantene with 35 ng/g dw. They contributed with 19 and 16%, to the sum of 16 PAHs respectively (see Table A 2). The least abundant PAHs detected in the moss sample from the Porsgrunn location were the more volatile/lighter ones *i.e.* acenaphthene, acenaphthylene, fluorene and anthracene with 0.2, 0.5, 1 and 1.4 ng/g dw, correspondingly. Additionally, they

all contributed with < 1% to the Σ_{16} PAHs (see Table A 2). Results from the moss samples at the Porsgrunn locations are somewhat above the background levels (Table A 3).

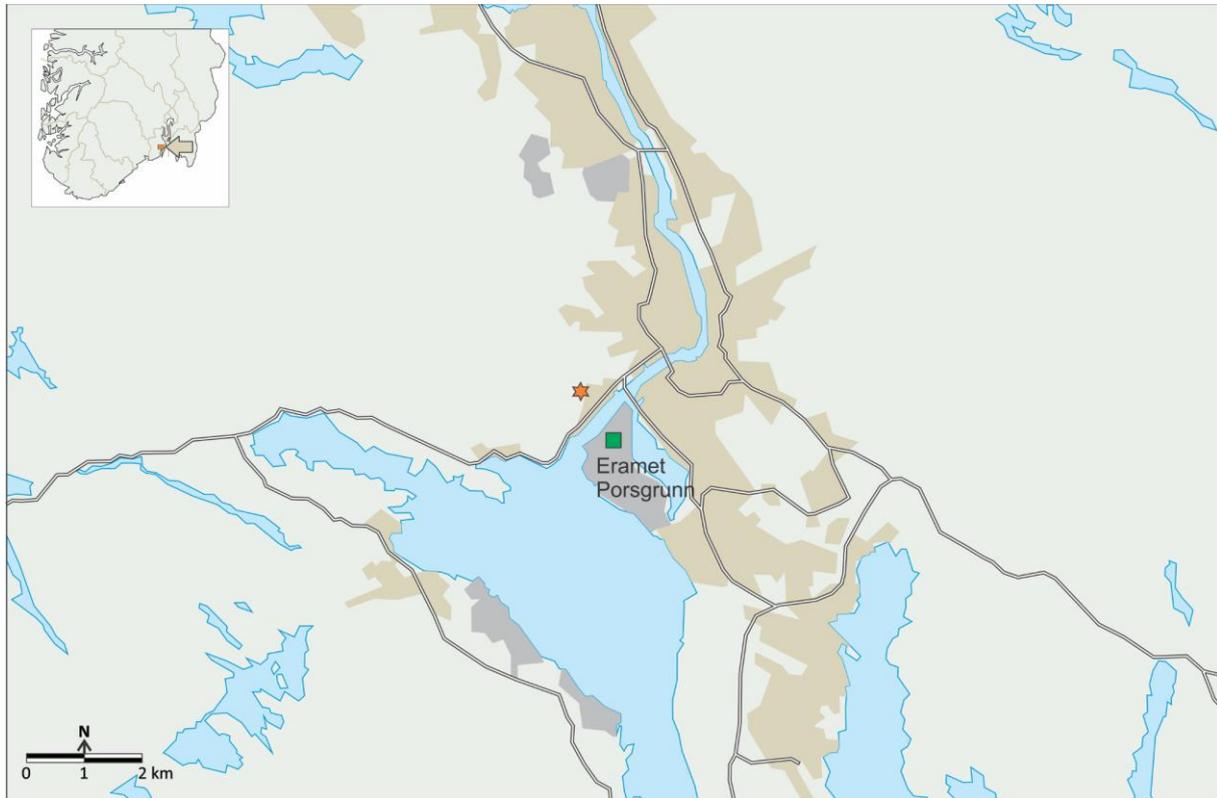


Figure 7: Location of moss sampling close to the industrial facility in Porsgrunn

4.3.2 Elkem Carbon Kristiansand

Regarding the industrial location in Kristiansand, only air samples was deployed (see Figure 9). Figure 8 shows the distribution of PAHs collected at selected sites surrounding the industrial site, Elkem Carbon in Kristiansand. Highest amounts of PAHs was found at Auglandstjønn with 1315 ng/sample of Σ_8 PAHs followed by Odderøya (1058 ng/sample), which is approximately ten to thirteen times the PAH level at the closest background site, Birkenes with ~ 100 ng/sample Σ_8 PAHs. All locations close to the industrial sites were recognized with amounts of PAHs far above the background levels, *i.e.* site with the lowest amount of PAHs was recognized with 493 ng/sample (Roligheten) for Σ_8 PAHs. For more information regarding Σ_{16} PAHs (see Table A 4). Phenanthrene, fluorene and fluoranthene was the most dominating components within the Σ_8 PAHs with 52 %, 25 % and 13 % to the average Σ_8 PAHs, respectively. Further in contrast to the other industrial sites, with exception from three sites close to Alcoa Mosjøen, naphthalene, was also a dominant component within PAHs. Acenaphthene and naphthalene contributed with 13 and 23 % to the Σ_{16} PAHs, correspondingly. Heavier PAHs contributes to a lesser extent (see Figure 8).

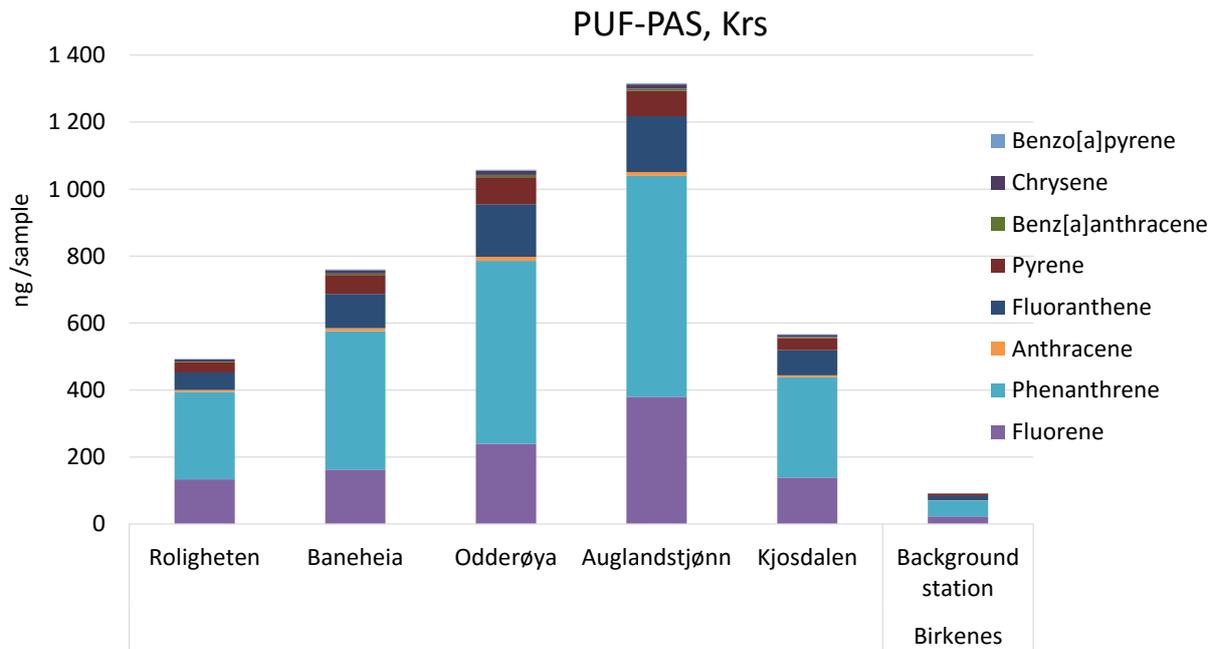


Figure 8: Distribution of selected PAHs in PUF-PAS deployed in vicinity to an industrial site in Kristiansand

Elkem Carbon is producing electrodes after the Sjøderberg technology and emission of PAHs from industrial processes at this site is highly probable (Sanderson et al., 2005). Nevertheless, the plant is located fairly close to the city Kristiansand and the levels of PAHs found in the samplers may as well be supported by other combustion sources, such as car traffic and domestic heating (see section 2.4). Figure 9 illustrates the distribution of PAS with respect to the industrial site. Higher amount of PAHs was found in the PAS closest to the industrial site (Auglandstjønn) also located in the main wind direction, indicating the industrial site to be the source. Nevertheless, it should be kept in mind that other combustions sources may also contribute to the levels of PAHs.

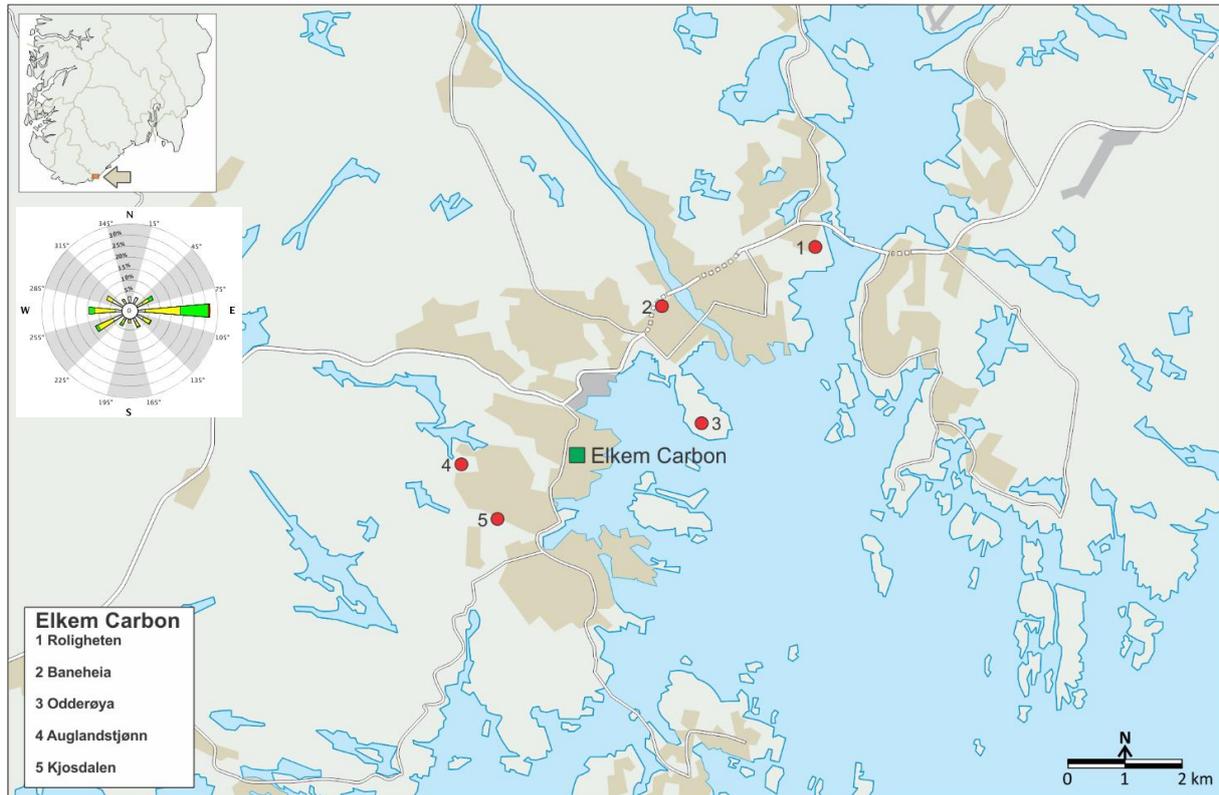


Figure 9: Distribution of passive air samplers around Elkem Carbon Kristiansand

4.3.3 Eramet Kvinesdal

According to the method described in section 2.1, also here the moss samples was collected in order to cover an area of 50x50 m² close to the industrial site in Kvinesdal (see Figure 10). The most frequently detected compound within 16 PAHs was fluoranthene, pyrene, phenanthrene and benzo[b]fluoranthene with 33 ng/g dw, 21 ng/g dw, 17 ng/g dw and 16 ng/g dw, respectively (see Table A 2). Each contributed with 22, 14, and 11% to sum of 16 PAHs (151 ng/g dw). The least abundant PAHs detected in the moss samples from this location was acenaphthylene, anthracene and acenaphthene with 0.8 ng/g dw, 1.2 ng/g dw and 1.3 ng/g dw which contributed with 0.5, 0.8, 0.9 %, respectively, to the Σ_{16} PAHs (see Table A 2). Comparing the results found in the moss samples with the closest background, the levels were far above, specifically the more heavier PAHs such as fluoranthene, pyrene and chrysene (see Table A 3).

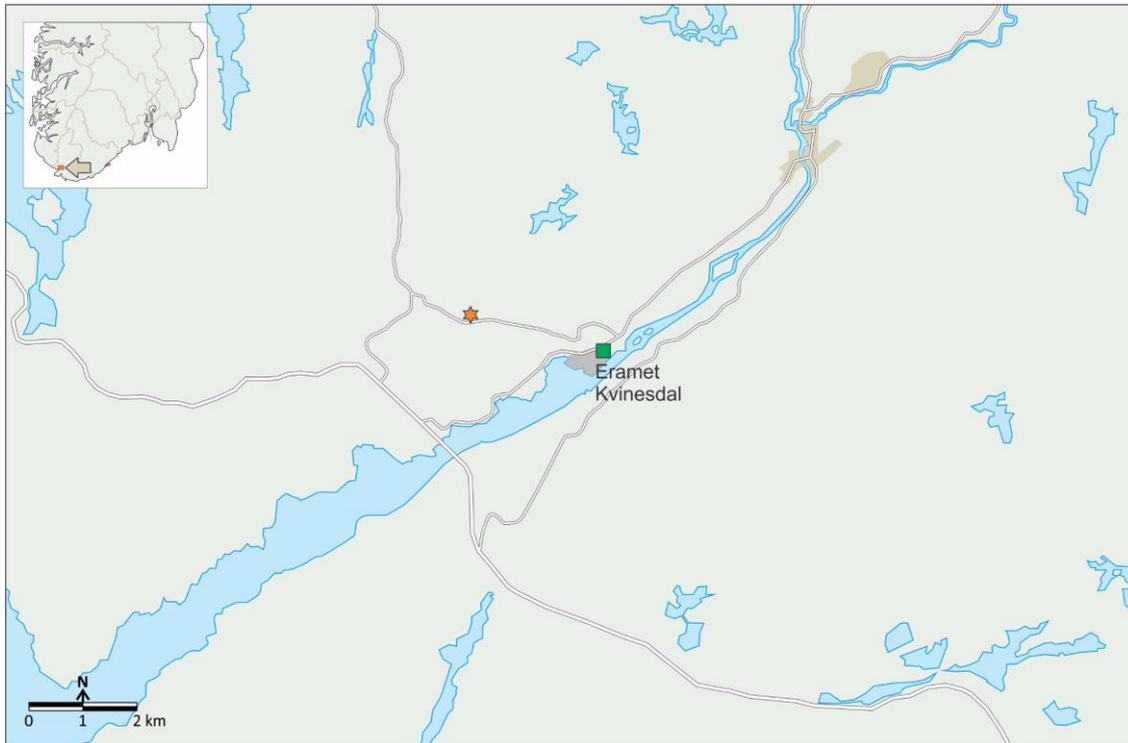


Figure 10: Moss sampling close to the industrial facility in Kvinesdal

4.3.4 Eramet Sauda

The most abundant PAHs within the moss samples collected covering an area 50x50 m² close to the industrial site in Sauda (see Figure 11) was fluoranthene, chrysene and pyrene with 35 ng/g dw, 25 ng/g dw and 21 ng/g dw, respectively. Each of these compounds contributed with 20, 14 and 12 % to the Σ_{16} PAHs (175 ng/g dw), correspondingly. PAHs detected with the lowest concentration in the moss samples were to a large extent the more volatile/lighter PAHs included, such as acenaphtylene and anthracene with 0.6 and 1 ng/g dw, correspondingly which again contributed with 0.4 % and 0.6 % to the Σ_{16} PAHs. Comparing the findings in the moss samples with the background levels, clearly revealed that the levels were remarkably higher close to the industrial site (see Table A 3). This is specifically evident for fluoranthene, pyrene, chrysene and benzo[b]fluoranthene.

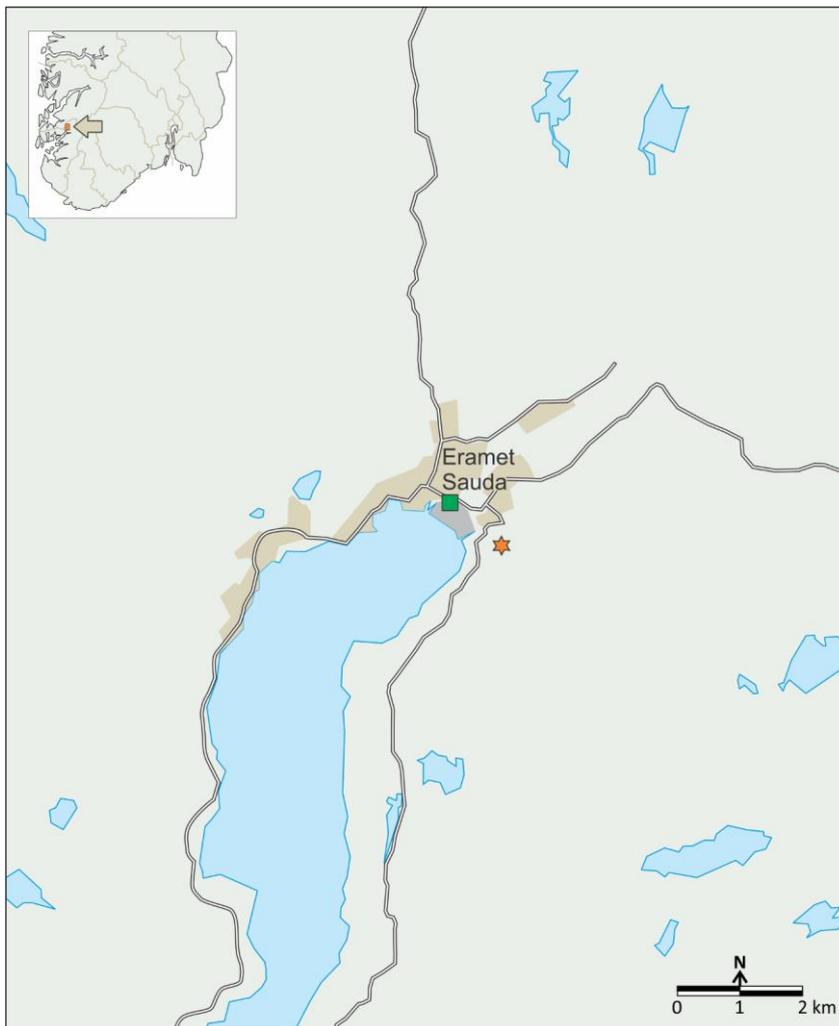


Figure 11: Moss sampling close to the industrial facility in Sauda

4.3.5 Elkem Bjølvefossen, Ålvik

At the Ålvik location both air and moss samples were collected. Figure 12 represents the location of the passive air samplers together with the moss sampling site around the industrial site.

4.3.5.1 Moss

Regarding the moss samples, the levels of PAHs was generally low at this location. The most abundant PAHs within 16 PAHs was fluoranthene (26 ng/g dw) followed by pyrene and benzo[b]fluoranthene (16 ng/g dw) together with phenanthrene (15 ng/g dw). Fluoranthene contributed with 19 % to the Σ_{16} PAHs, while both pyrene and benzo[b]fluoranthene contributed with 12 % and phenanthrene contributed with 11 % to the Σ_{16} PAHs (135 ng/g dw). Lowest levels was found for the lighter PAHs together with benzo[ah]anthracene (1.5 ng/g dw). Acenaphtylene was recognized with 0.8 ng/g dw, which contributed with 0.6 % to the Σ_{16} PAHs. Furthermore, also acenaphthene was detected at low concentrations, i.e. 1.2 ng/g dw and contributed with 0.9 to the Σ_{16} PAHs (see Table A 2). Comparing the moss results with the closest background (Stord), revealed that the moss results were to some extent higher for fluoranthene, chrysene and benzo[b]fluoranthene (see Table A 3).

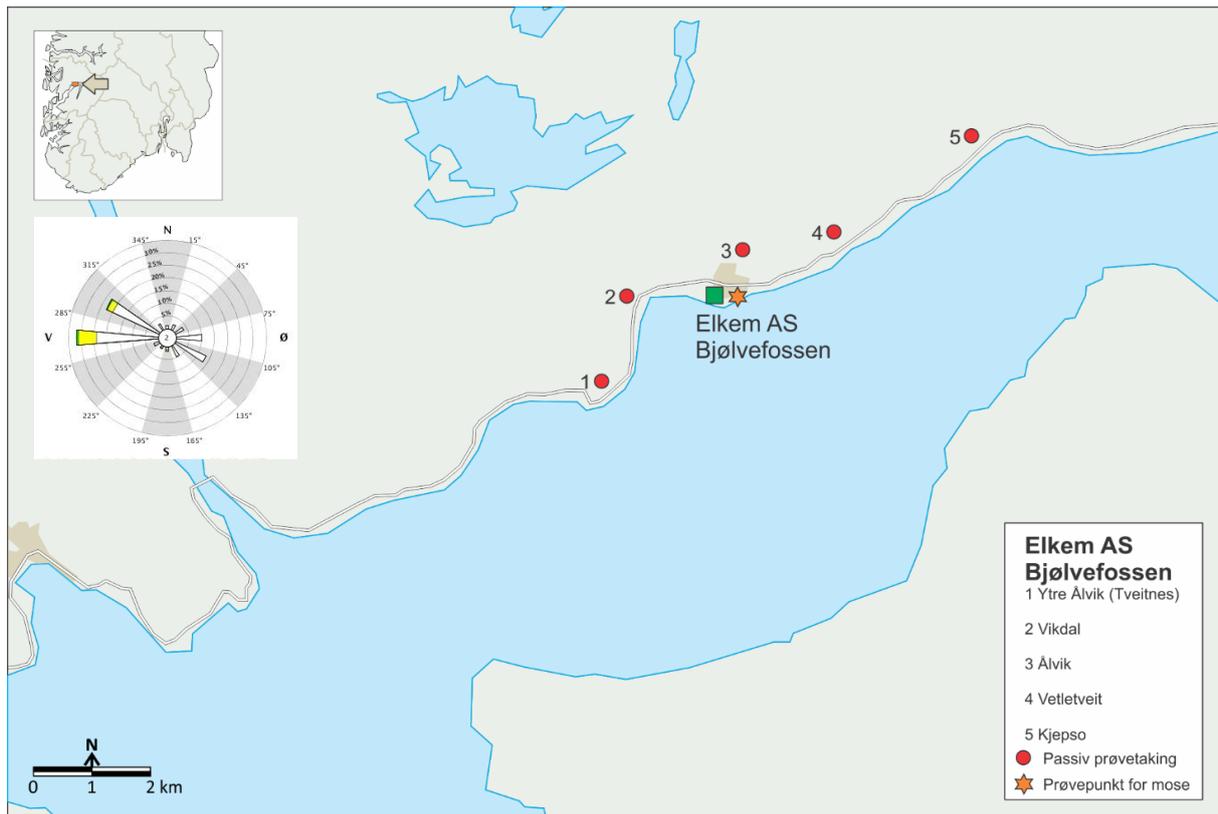


Figure 12: Distribution of passive air samplers (●) around Elkem Bjølvfossen together with the moss sampling location (★).

4.3.5.2 Air

The distribution of eight PAHs from the passive air samplers deployed close to the industrial location in Bjølvfossen are shown in Figure 13. The figure also includes levels of the same PAHs at the closest background station located at Birkenes, however Birkenes may not be representative for Bjølvfossen. Highest amounts of Σ_8 PAHs were found at Vikedal with 1082 ng/sample. PAHs was detected at a far lower levels for the other PAS locations. Here the amount per sample is more or less at the same level and ranges between 130 ng/sample (Vetletveit) to 271 ng/sample (Ytre Vålvik) (see Table A2). The most abundant PAH within Σ_8 PAHs for Vikedal was phenanthrene 635 ng/sample which contributed with 56 % to the total of the average Σ_8 PAHs, and 40 % when considering all 16 PAHs. The second most abundant PAHs was fluorene followed by acenaphtene with 231 and 171 ng/sample, correspondingly.

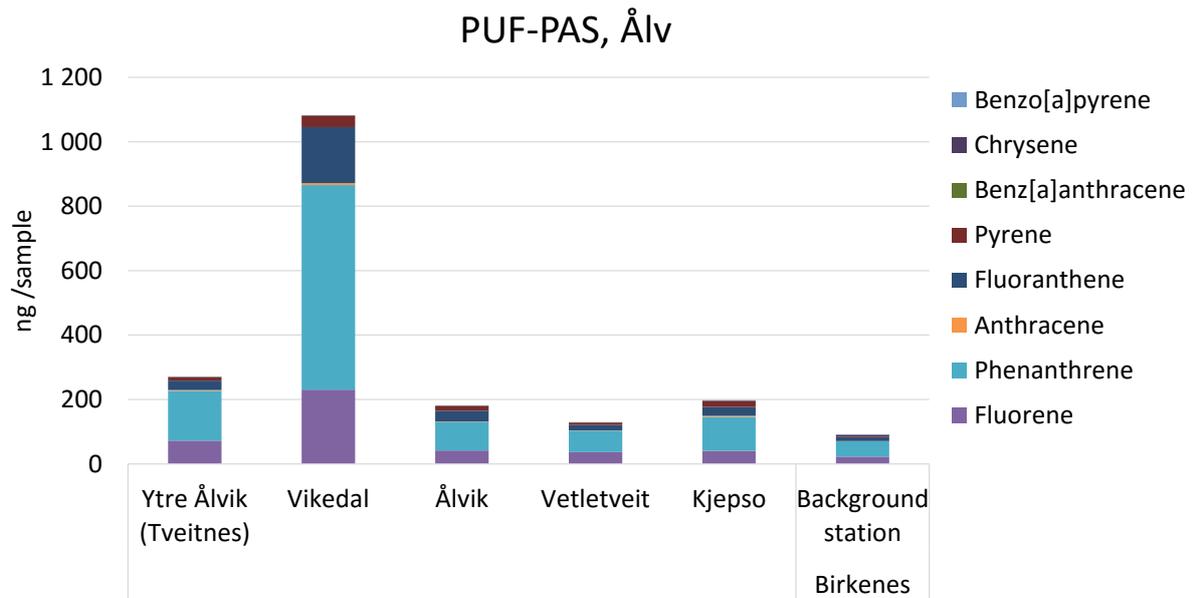


Figure 13: Distribution of selected PAHs in PUF-PAS deployed close to an industrial site in Ålvik

Elkem Bjølvefossen is a metallurgical industry which is known to emit PAHs during combustion processes. Nonetheless, that may not explain the elevated levels of PAHs at the location Vikedal. The topography around the industry is challenging as it is a mountain rich terrain and the wind follows the topography. Hence, it was difficult to deploy the samplers in the dominating wind direction. Figure 12 illustrates the location of PAS around the industrial site Elkem Bjølvefossen and Vikedal is located close to the site, and within the prevailing wind direction (see wind rose Figure 12). However, as already pointed out due to the steep terrain it was difficult to deploy the samplers, and whether they were located directly in the wind direction from the industry is unclear. Yet, the elevated levels found in the sampler in Vikedal should be considered more in details.

4.3.6 Hydro Aluminium Sunndal

Also for the Sunndal location, both air and moss samples were collected. Figure 14 represents the location of the passive air samplers together with the moss sampling site around the industrial site.

4.3.6.1 Moss

The pooled sample of moss from 50x50 m² collected close to the industrial site in Sunndal, was detected with the second highest PAH levels when compared to the other industrial sites included in this study, only the sample from Orkanger showed higher levels (4.2.7). Sum of all 16 PAHs was 1825 ng/g dw, with benzo[b]fluoranthene, fluoranthene, benzo[a]pyrene and chrysene as the most contributing PAH components. The concentration of benzo[b]fluoranthene was 244 ng/g dw, contributing with 13 % to the sum of 16 PAHs, where the levels of fluoranthene and benzo[a]pyrene was 218 and 217 ng/g dw, respectively and contributed with 12 % to Σ_{16} PAHs. Chrysene was detected at somewhat lower levels, i.e. 203 ng/g dw and contributed with 11 % to the Σ_{16} PAHs. Also for the Sunndal site, the lighter PAHs was detected at the lowest levels, with acenaphthylene (1 ng/g dw), naphthalene (7.6 ng/g dw) and acenaphthene (8.5 ng/g dw) all contributing to < 1% to the Σ_{16} PAHs (see Table A 2). A

comparison of the results from Sunndal with the findings for moss samples collected at closest background site (Godøy) clearly shows elevated levels in the moss sample collected in Sunndal. The levels were considerably higher for several PAHs, such as phenanthrene, fluoranthene, pyrene, benz[a]anthracene, chrysene, benzo[b]fluoranthene and also benza[a]pyrene to mention a few. Please find more information regarding these levels in Table A 3.



Figure 14: Distribution of passive air samplers (●) around Hydro Aluminium Sunndal, together with the moss sampling location (★).

4.3.6.2 Air

Figure 15 displays the distribution of Σ_8 PAHs in the air samples located around Hydro Aluminium Sunndal, together with the nearest background station (Kårvatn). Here, Σ_8 PAHs was detected with higher amounts for all sites contrasted to the background station at Kårvatn. Aluminium industry is known to emit amounts of PAHs due to Söderberg technology (Sanderson et al., 2005), but nowadays this technology has been phased out to a large extent. Evaluating the levels found at the locations around this industrial facility demonstrates that the levels of PAHs are high. Highest amount of PAHs was found at Oppdøl with 1687 ng/sample, secondly is the Nylykkjebekken with 1216 ng/sample, and thirdly at the Blakåsbukta with 1040 ng/sample (see Table A 4). As for the other industrial sites discussed earlier, the most abundant PAHs was the lighter PAH with 2-4-rings, e.g. phenanthrene, fluorene, fluoranthene and acenaphthene. Phenanthrene contributed with 57 % on the average loading of Σ_8 PAHs, while fluorene and fluoranthene contributed with 23 % and 13 %, correspondingly. Acenaphthene contributed with 8 % to the loading of Σ_{16} PAHs. Comparing the findings in the air samples with the background reveals that phenanthrene and fluorene was the most abundant components, but at a lower level. Heavier PAHs such as 5 to 7 ring PAH are to a lesser extent detected in the sampler, since they are often associated to particle phase which are not effectively sampled by the PAS.

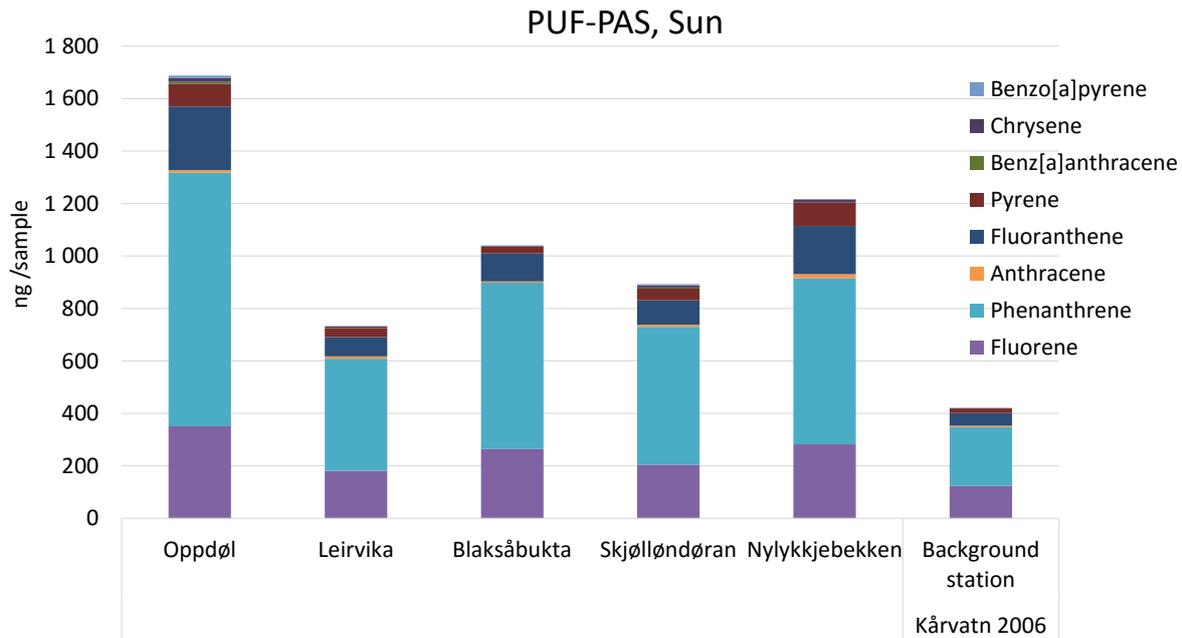


Figure 15: Distribution of selected PAHs in PUF-PAS deployed in vicinity to an industrial site in Sunndal

Figure 14 illustrates the distribution of PAS close the industrial site in Sunndal. Oppdøl and Nylykkjebekken is located upwind and downwind the industrial site, respectively, which may help to explain the elevated levels found at these sites. Even so, other sources than the industrial site may contribute to levels of PAHs collected by the air samplers.

4.3.7 Whacker Chemicals, Hemne

Also for the industrial location at Hemne, both air and moss samples were collected. Figure 16 represents the location of the passive air samplers together with the moss sampling site around the industrial site.

4.3.7.1 Moss

The moss sample collected at Hemne is pooled from four different locations (see 2.1.1 and Figure 16). Generally, the concentrations of PAHs found in the moss sample at the industrial site, were at a lower level for all 16 components. Fluoranthene, phenanthrene and pyrene were the most dominating compounds within Σ_{16} PAHs (290 ng/g dw), with 49 ng/g dw, 37 ng/g dw and 34 ng/g dw, respectively (see Table A 2). Individually they contributed with 17, 13 and 12 % to the sum of 16 PAHs, correspondingly. Concomitantly, chrysene, benzo[b]fluoranthene, benzo[a]anthracene and benzo[a]pyrene was also frequently detected in the sample. The least abundant PAHs in the moss sample was acenaphthylene with 0.6 ng/g dw and contributed to a small extent to the Σ_{16} PAHs, i.e. 0.2 %. Comparing these results with the results from the closest background (Mosvik) shows that the industrial moss samples were recognized with higher concentration for several PAHs, i.e. fluoranthene, pyrene, chrysene, benzo[b]fluoranthene and benzo[a]pyrene (Table A 3).

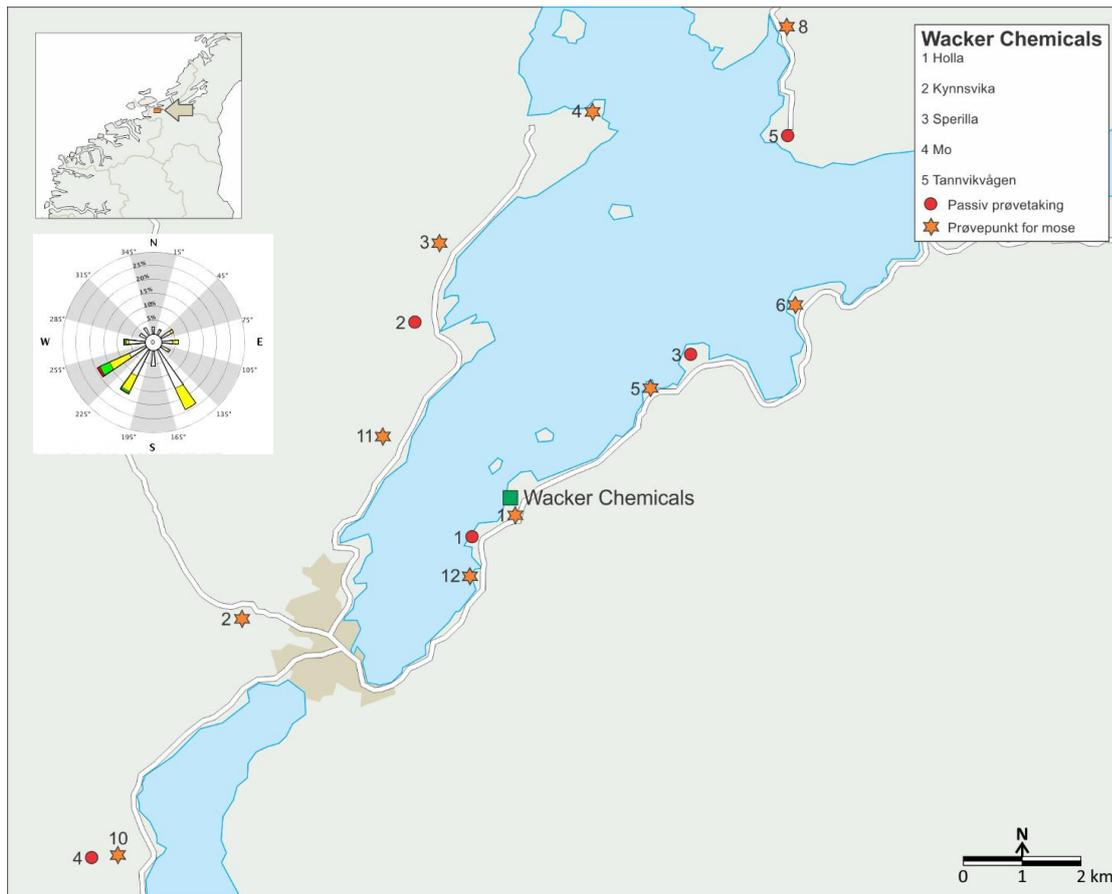


Figure 16: Distribution of passive air samplers (●) around Wacker Chemical Hemne, together with the moss sampling location (★)

4.3.7.2 Air

Figure 17 displays the levels of PAHs from the deployed passive air samples at selected sites close to the industrial site, Wacker Chemicals. The levels of PAH found in the samples is to a large extent lower contrasted to the nearest background site, Kårvatn, but also contrasted to the other industrial sites (see Figure 4). Highest amounts of PAHs was detected at Holla with 824 ng/sample Σ_8 PAHs. The most abundant PAHs was phenanthrene, fluorene and fluoranthene within the Σ_8 PAHs, which contributed with 44 %, 34 % and 10 % to the average Σ_8 PAHs, respectively. Acenaphtene was only detected at two out of five sites (Holla and Sperilla) where highest amounts was detected at the Holla site with 362 ng/sample which contributed with nearly 40 % to the average Σ_{16} PAHs. Regarding the other selected location around the industrial site, the amounts of PAHs were lower and often detected below LOD (see Table A 4 in Appendix B).

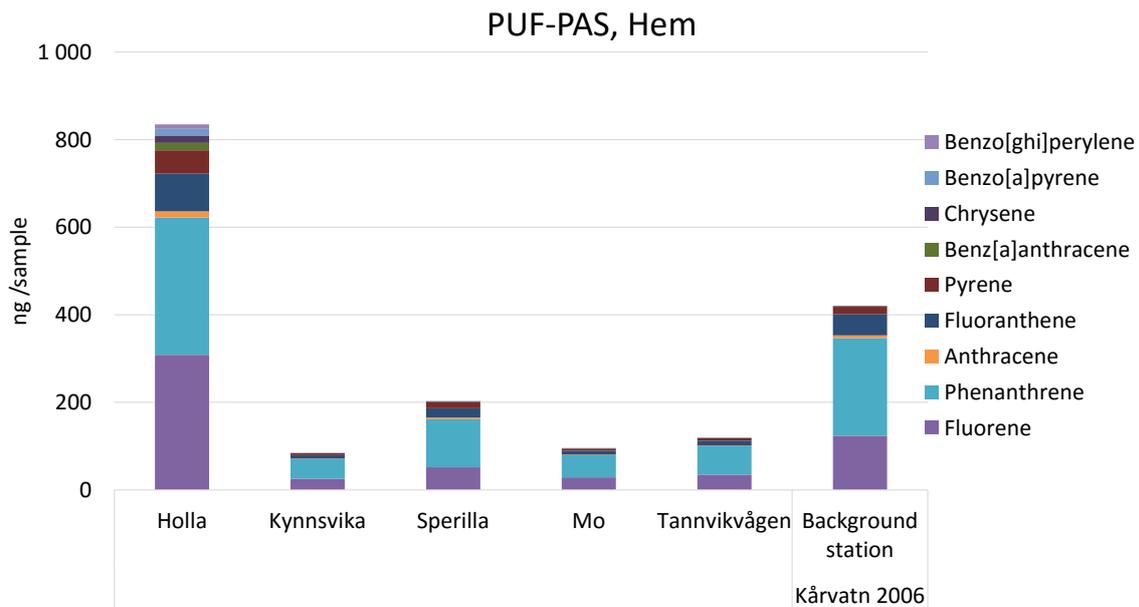


Figure 17: Distribution of selected PAHs in PUF-PAS deployed in vicinity to an industrial site in Hemne

The Holla site is located closest to the factory which produces silica and microsilica, but also closest to the industrial site in question (see Figure 16). In 2014, a study was conducted including several ferrosilium industrial sites in Norway where silica/microsilica is produced. At one of the sites, Finnfjord AS, PAS was included in addition to dust samples (Hak, Halse, & Halvorsen, 2016). Also here the most dominating component within PAHs in the air samples was phenanthrene, fluorene and fluoranthene, but the levels was not highest close to the industrial site. Hence, other sources contributing to the levels of PAHs, other than industrial processes are suspected (Hak et al., 2016).

4.3.8 Elkem Thamshavn, Orkanger

Both air and moss samples were collected close to the industrial site in Orkanger. Figure 18 represents the location of the passive air samplers together with the moss sampling site around the industrial site.

4.3.8.1 Moss

The highest levels of 16 PAH for all industrial sites included in the study was found in the moss sample collected close to the Orkanger industrial site(see Figure 18), as the Σ_{16} PAHs was 2334 ng/g dw. The following PAHs was all detected > 200 ng/g dw, i.e. fluoranthene, pyrene, benzo[b]fluoranthene, benzo[a]pyrene, chrysene and benzo[a]anthracene. Fluoranthene contributed with 16 % (372 ng/g dw), while pyrene contributed with 12% (290 ng/g dw), and benzo[b]fluoranthene with 11 % (259 ng/g dw) to the Σ_{16} PAHs. Furthermore, benzo[a]pyrene contributed with 11% (247 ng/g dw), chrysene 10 % (226 ng/g dw) and benzo[a]anthracene with 9 % (202 ng/g dw) to the Σ_{16} PAHs, respectively (see Table A 2). Acenaphthylene together with naphthalene was recognized with the lowest concentration of PAHs, with 0.5 and 5 ng/g dw, correspondingly. Moreover, they contributed only with 0.03 and 0.2 % to the Σ_{16} PAHs. Comparing the results found in the industrial site with the closest background (Mosvik) revealed that the levels found in the industrial moss samples where higher for a number of

PAHs. The levels were highest for fluoranthene, pyrene, chrysene, benz[b]fluoranthene and benz[a]pyrene (see Table A 3)

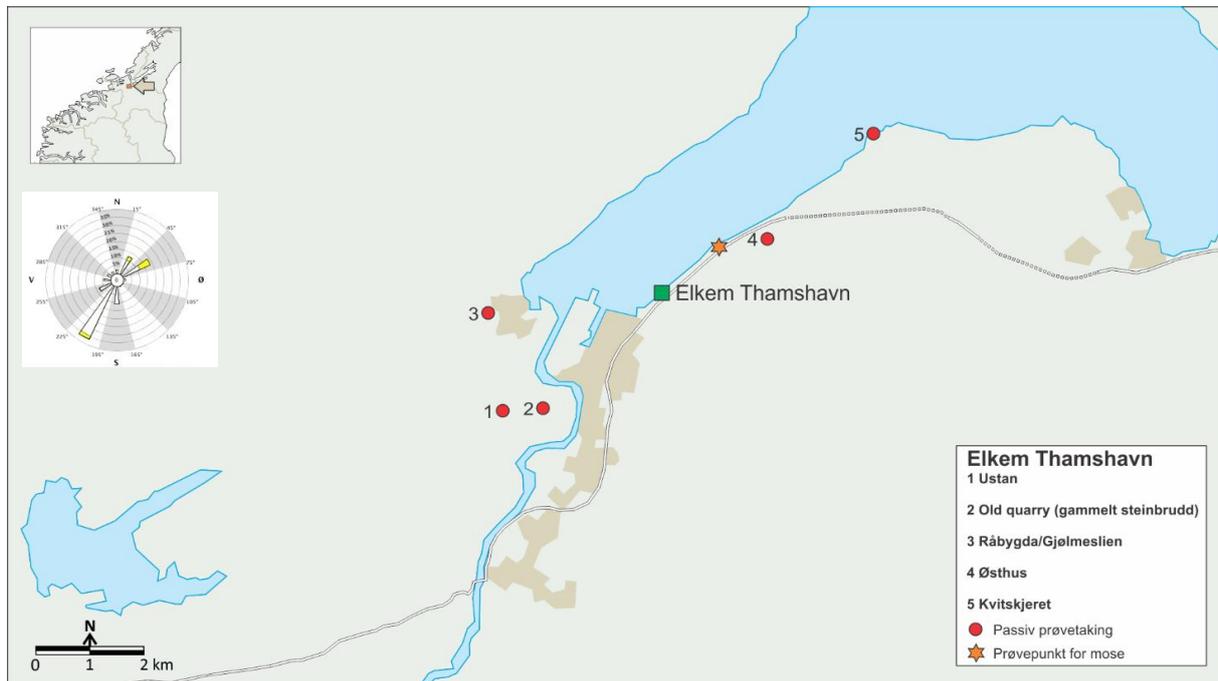


Figure 18: Distribution of passive air samplers around Elkem Thamshavn Orkanger (●), together with the moss sampling location (★).

4.3.8.2 Air

Figure 19 shows the levels of PAHs in passive air samples from five locations close to industrial site in Orkanger, and the nearest background station, Kårvatn. Highest amount of Σ_8 PAHs was found for Ustan and Kvitskjeret with 794 ng/sample, and 394 ng/sample, respectively (see Table A2 Appendix A). The lowest amount of Σ_8 PAHs was found at Råbygda with 158 ng/sample. The most abundant PAH within the Σ_8 PAHs for four out of five sites (Ustan, Kvitskjeret, Old quarry and Råbygda) was phenanthrene and fluorene. Estimating the individual contribution from these selected PAHs shows that phenanthrene contributes with 56 % to the average of Σ_8 PAHs, while fluorene contributed with 30 % (see Table A2). Another dominating PAHs detected in the air samples (not included within the Σ_8 PAHs) was acenaphene, which contributed with 21 % to the average of Σ_{16} PAHs, here phenanthrene and fluorene contributed with 38 and 20 %, correspondingly. The elevated levels of the former mentioned PAHs may be from industrial activities and other combustion sources as they emits PAHs (Ravindra et al., 2008).

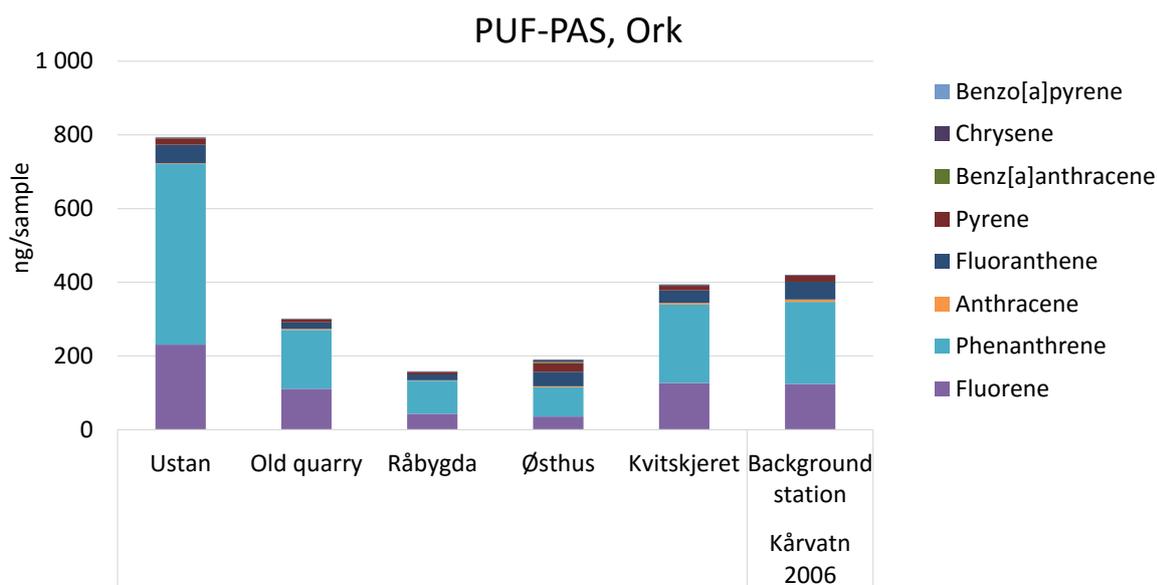


Figure 19: Distribution of selected PAHs in PUF-PAS close to a selected industrial site in Orkanger

Comparing the findings of PAHs at the industrial locations with the background stations reveals both higher and lower amounts of PAHs, *i.e.* the Σ_8 PAHs at Ustan was twice the level from the nearest background station Kårvatn (~400 ng/sample), while the Σ_8 PAHs at Kvitskjeret was at the same level. Thus, the detected amounts of PAHs around the industrial sites may also partly be long range transported. Figure 18 displays the location of the PAS with respect to the industrial site. PAS located close to the industrial site have lower concentration of PAHs, hence the industrial site may not be the cause of the elevated concentration found at Ustan. This is further supported by the prevailing wind direction during the sampling period which was mainly from south west. However, it should be kept in mind that in addition to wind direction, also location of the PAS is a central parameter in order to evaluate the potential emissions of PAHs from the industrial site.

4.3.9 Alcoa, Mosjøen

Both air and moss samples were collected close to the industrial site in Mosjøen. Figure 20 represents the location of the passive air samplers together with the moss sampling site around the industrial site.

4.3.9.1 Moss

The concentration for the individual PAHs found in the moss samples at this location was to a large extent evenly distributed, with exception of the lighter PAHs (see Table A 2). Benzo[b]fluoranthene, fluoranthene, benzo[a]pyrene and chrysene was the most dominating compounds followed by benzo[ghi]perylene, pyrene and benzo[1,2,3-cd]pyrene. Benzo[b]fluoranthene contributed with 12 % to the the Σ_{16} PAHs (497 ng/g dw), with 59 ng/g dw. Fluoranthene (55 ng/g dw) contributed with 11 %, and benzo[a]pyrene (51 ng/g dw) contributed with 10 %. Chrysene were recognized with 47 ng/g dw and contributed with 10 % to the Σ_{16} PAHs. The lighter PAHs was detected at a lower level, *i.e.* acenaphthylene and acenaphthene with 1.1 and 3.8 ng/g dw, correspondingly, and contributed to a minor extent to the Σ_{16} PAHs (Table A 2).

These results is also evident when comparing the results to the finding at the closest background site (Røysvik). The more heavier PAHs, i.e. fluoranthene, chrysene, benzo[b]fluroanthene to mention a few are detected well above background levels (Table A 3).

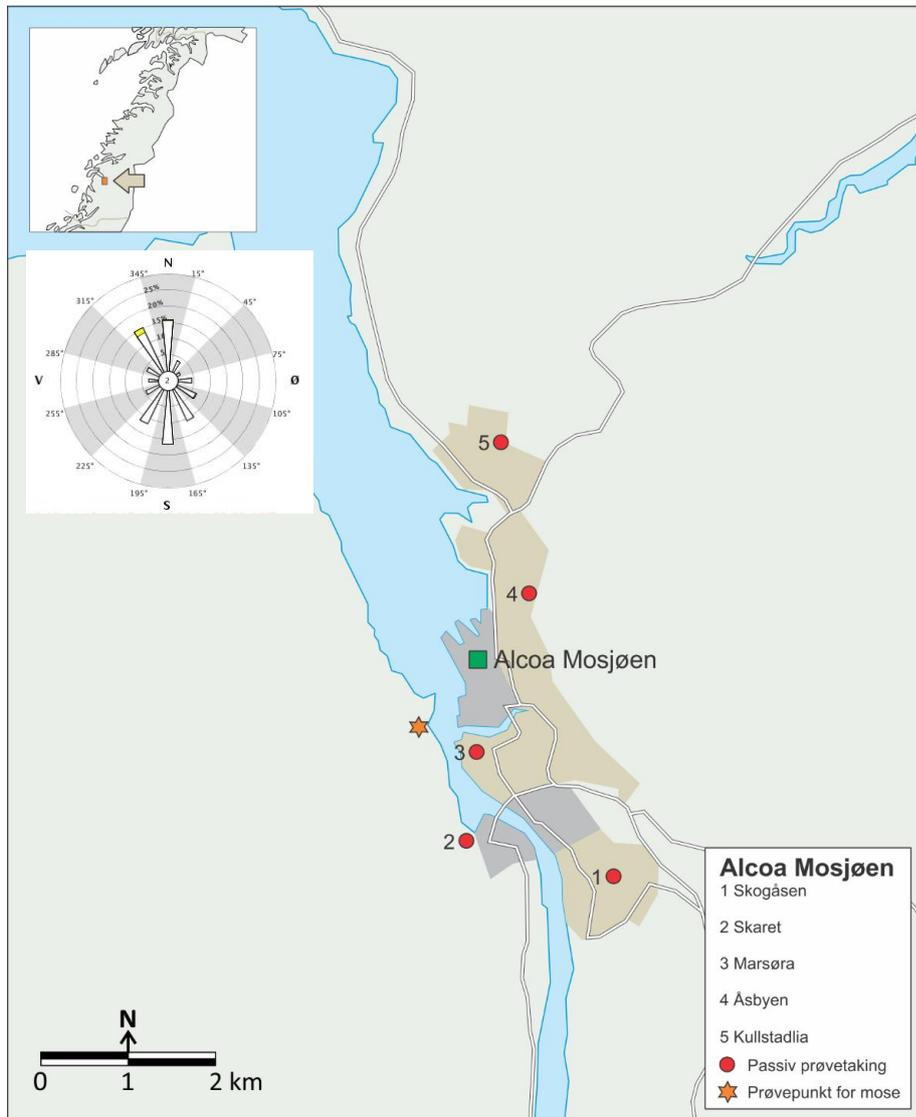


Figure 20: Distribution of passive air samplers around Alcoa Mosjøen(●), together with the moss sampling location(★).

4.3.9.2 Air

Figure 21 shows the levels of PAHs found in the passive air samplers from five locations close to the industrial site, Alcoa Mosjøen, and the closest background station Tustervatn which is located 30 km away from the industrial site. Highest amounts of Σ_8 PAHs were found at Åsbyen, Kullstadlia and Skogåsen, with 931, 680 and 631 ng/sample, respectively (see Table A 4). Lowest amounts was found at Marsøra with 300 ng/sample. Also for these industrial locations, the most abundant PAHs was phenanthrene, fluorene, acenaphthene and also to some extent fluoranthene. Phenanthrene, fluorene and fluoranthene contributed with 57 %, 24 % and 11% to the average Σ_8 PAHs, while acenaphthene contributed with 14 % to the

average of Σ_{16} PAHs. Figure 21 illustrates that the amount of the PAHs found in the PAS is at the same level as the background station, besides Åsbyen.

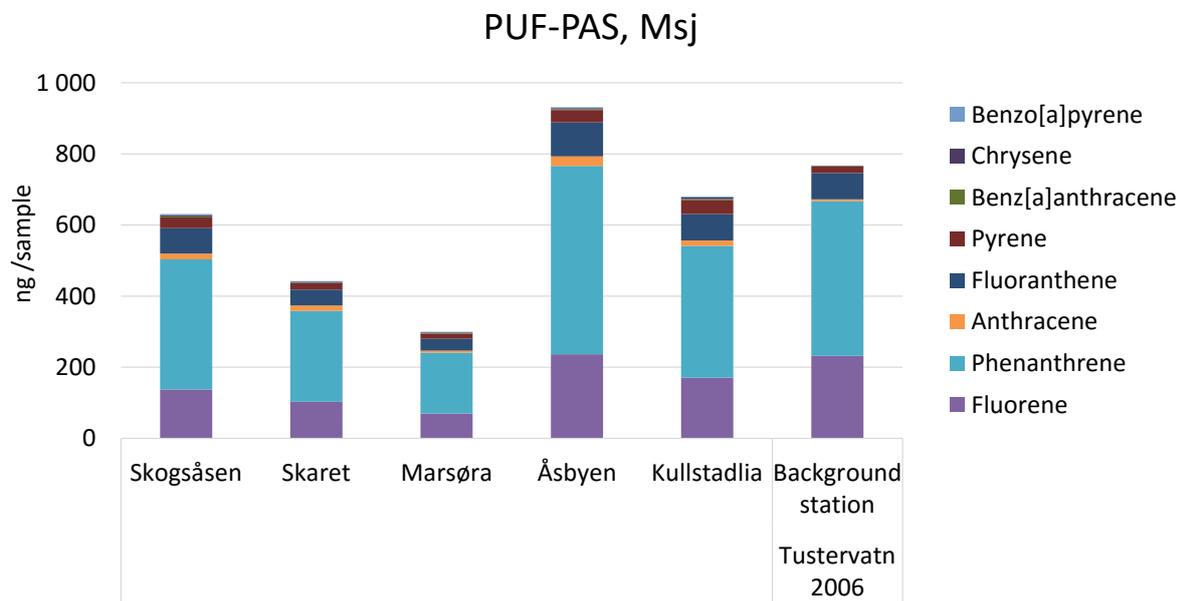


Figure 21: Distribution of selected PAHs in PUF-PAS deployed at a selected industrial site in Mosjøen

The Tustervatn background station is located to mainly monitor long range transported PAHs, and the levels of PAHs found at this background station are relatively high. Thus the PAHs levels found at the industrial site in Mosjøen may be from other sources than the industry since itself. However, the individual PAS might have been impacted by local conditions, such as wind speed and wind direction with respect to the industrial site. Figure 20: Distribution of passive air samplers around Alcoa Mosjøen(), together with the moss sampling location illustrates the location of the PAS with respect to the industrial site Alcoa Mosjøen. Highest levels were found at two sites located close to the industrial site (Åsbyen and Kullstadlia). Whether or not the levels of PAHs are due to emission from the industrial site is dependent on the wind direction and location of the sampler. Considering the wind rose in Figure 20 , these two sites are also located in the prevailing wind direction indicating that the industry may be the source to the levels of PAHs.

4.3.10 Glencore Manganese, Mo i Rana

Due to the more heavily industrialized loadings around Mo i Rana it was decided to collect three individual moss samples each covering an area approximately 50x50 m². The samples are identified as MiR-6, MiR-9 and MiR-11 (see Figure 22).

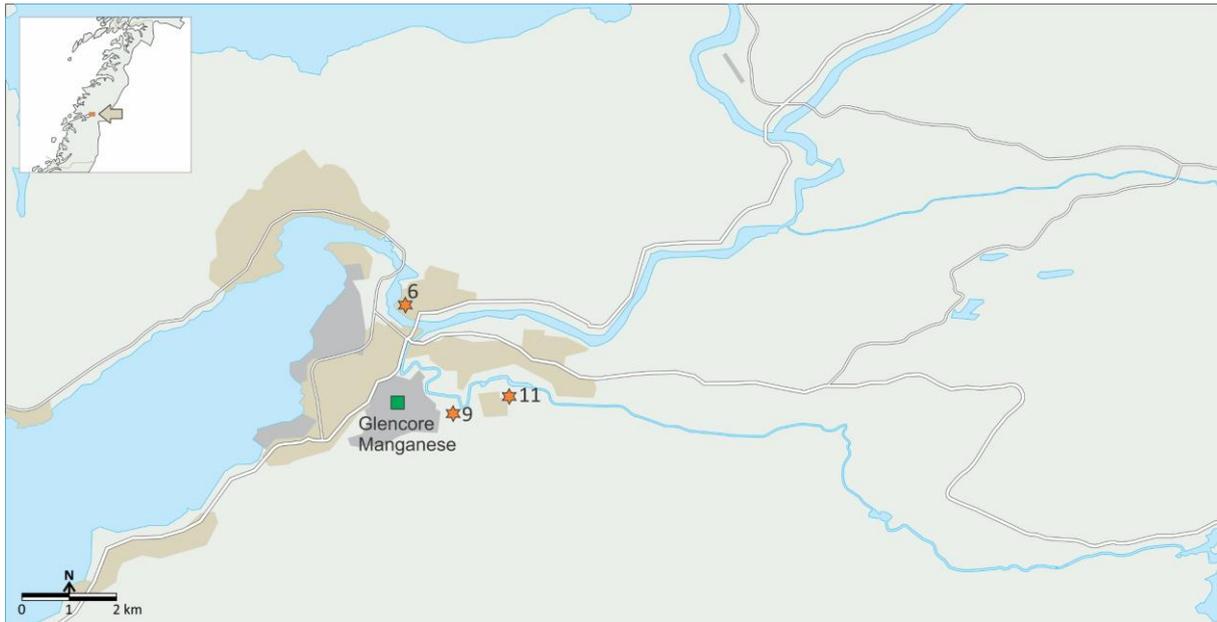


Figure 22: Location of three moss sampling sites around Glencore Manganese, Mo I Rana

4.3.10.1 MiR-6

The levels of PAHs detected in the moss samples at MiR-6 were to a large extent elevated and with several PAHs found with relatively high concentrations. Fluoranthene, chrysene, and benzo[b]fluoranthene were the most dominating compounds within 16 PAHs. Fluoranthene (58 ng/g dw) contributed with 15 % to Σ_{16} PAHs (238 ng/g dw) and both chrysene (53 ng/g dw) together with benzo[b]fluoranthene (52 ng/g dw) contributed with 13 % to Σ_{16} PAHs. Also here, the concentration of the lighter PAHs was detected with the lowest concentrations, i.e. acenaphtylene, acenaphtene and fluorene with 0.4, 2.3 and 2.8 ng/g dw, respectively. These compounds also contributed to a minor extent to the Σ_{16} PAHs with < than 1 % (see Table A 2). The moss sampling site is located north from the industrial site and when comparing the results with the closest background (Bodø) revealed to some extent higher levels in the moss samples collected close to the industrial site. Elevated levels was found for fluoranthene, chrysene, pyrene together with benzo[b]fluoranthene (Table A 3).

4.3.10.2 MiR-9

Similarly to MiR-6, the levels of PAHs were at higher levels contrasted to the former discussed sites. The most dominating compound within the 16 PAHs was fluoranthene, phenanthrene and pyrene with 115 ng/g dw, 97 ng/g dw and 67 ng/g dw, respectively. Fluoranthene contributed with 22 % to the Σ_{16} PAHs (533 ng/g dw), and phenanthrene with 18 %, while pyrene contributed with 12 % to the Σ_{16} PAHs (see Table A 2). The least abundant PAHs within the 16 PAHs detected at MiR-9 was acenaphtylene and dibenzo[ah]anthracene with 3.1 ng/g dw and 5.3 ng/g dw, correspondingly. Both compounds contributed with \leq 1% to the Σ_{16} PAHs (see Table A 2). Also for this site, the levels found in the moss samples collected close to the industrial site was higher contrasted to the background moss samples, and specifically for phenanthrene and fluoranthene (see Table A 3).

4.3.10.3 MiR-11

Analogous to MiR-6 and MiR-9, the levels found at MiR-11 were also relatively elevated. Similar to MiR-9, the most dominating compounds within the 16 PAHs detected in the moss samples were fluoranthene, phenanthrene and pyrene. Fluoranthene contributed with 21 % to the Σ_{16} PAHs (790 ng/g dw) with 162 ng/g dw, while phenanthrene contributed with 19 % with 153 ng/g dw. Pyrene was detected with somewhat lower concentrations, i.e. 93 ng/g dw and 12 % to the Σ_{16} PAHs (see Table A 2). Further, the lighter PAHs was also for this site detected at lower concentrations, such as acenaphtylene (6 ng/g dw) and anthracene (11 ng/g dw). Nonetheless, benzo[ah]anthracene which is recognized to be of the more heavier PAHs was detected with lower concentrations (8.2 ng/g dw) (Table A 2). The moss samples collected at this site (MiR 11) show the same tendency as for Mir 9, with highest levels for phenanthrene, fluoranthene and to some extent pyrene when contrasting the results with the moss results from the closest background.

4.3.11 Combined air and moss results

In order to evaluate whether combined moss and air sampling can be utilized as a complementary method to active air sampling for monitoring PAHs, moss and air was co-sampled at 6 industrial sites, as shown in Figure 23. All 16 PAHs have been included in the data set, but it should be kept in mind that naphthalene, acenaphtylene, benzo[k]fluoranthene, benzo[a]pyrene, indeno[1,2,3-cd]pyrene and benzo[ghi]perylene often were detected below LOD in the air samples, and consequently excluded from the dataset. Concerning the industrial site in Kristiansand, moss samples was not collected which is illustrated in Figure 23 as N.A. (not available). Keep also in mind that the results for the air samples is presented as ng/sample, while the moss results is presented as ng/g dw. However, the trends in the finding is believed to be comparable.

When comparing the individual PAHs for moss and air samples at the individual sites, it is apparent that lighter PAH, *i.e.* phenanthrene, fluorene together with acenaphthene are the dominating components in the air samples. On the contrary, when evaluating the results for the moss samples, the same tendency is not apparent. Here the heavier PAHs were more frequently detected, specifically in moss collected close to Elkem Thamshavn in Orkanger and Hydro Aluminium in Sunndal (see Figure 23). For these two locations, 4-7 ring PAHs, such as fluoranthene, chrysene, benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[a]pyrene, indeno[1,2,3-cd]pyrene and benzo[ghi]perylene are more dominating, see Table A2 in Appendix A for more information. The latter mentioned PAHs are to a large extent detected below LOD in the passive air samples. Hence, the results shown in Figure 23 illustrates that moss and air samples together provide a more complete information regarding the spatial distribution of PAH around the industrial sites.

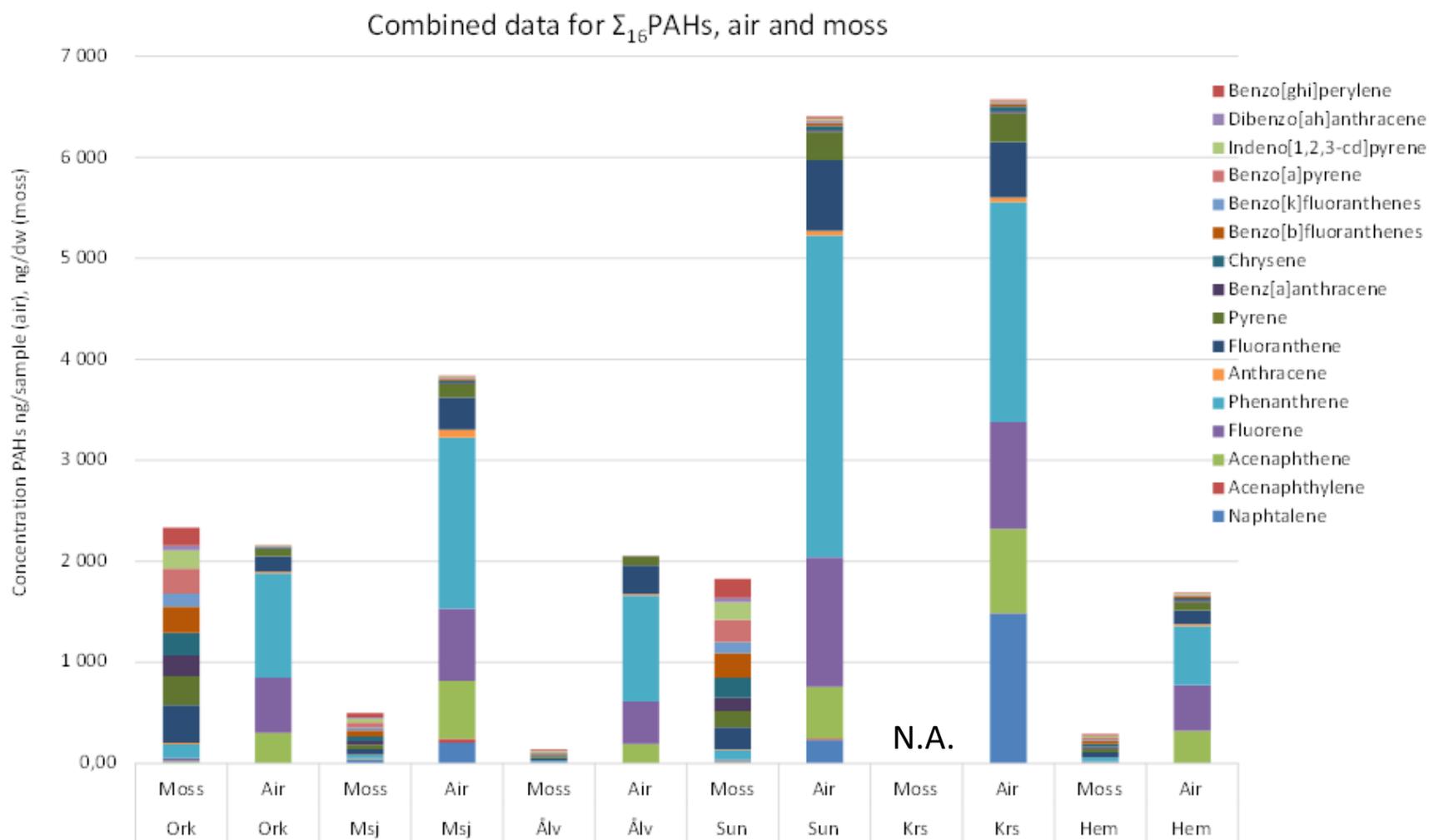


Figure 23: Distribution of Σ_{16} PAHs in moss and air samples at selected industrial sites; Porsgrunn = Por, Kristiansand = Krs, Kvinesdal = Kvi, Sauda = Sau, Ålvik = Ålv, Sunndal = Sun, Hemne = Hem, Orkanger = Ork, Mosjøen = Msj, Mo i Rana = Mir

5 Concluding remarks

Generally, the PAH level determined in moss collected around industrial sites were considerably higher for the more heavier PAHs than the PAH level found in moss collected at background sites. This applies in particular to the mosses collected in Sunndal, Orkanger and Mo i Rana and especially for the heavier PAHs such as phenanthrene, fluoranthene pyrene, chrysene benzo[b]fluoranthene and benzo[a]pyrene]. Compared to available emission data from 2014, it is likely that the elevated levels determined in moss is related to emissions from the industries. However, the ratio of selected congeners indicate that combustion of organic material other than fossil fuel may contribute to the PAH level at several locations.

The levels of PAHs found in the air samples were low and often at the same levels as found at the closest background site, for all out of two sites, i.e. Sunndal and Kristiansand. However, the highest levels within the individual locations were found in PAS deployed closest to the industrial site in the prevailing wind direction. Still there is no clear indication that the industry is the only source to the levels of PAHs.

The most dominating PAHs within all the PAS was the lighter PAHs such as 2-4 ring PAHs, whereas 4-7 ring PAHs were dominating in the moss samples.

Hence, results from this pilot study, illustrates that moss and air samples together provide more comprehensive information regarding the spatial distribution of PAH around the industrial sites. That said, information regarding local parameters such as wind direction and topography is important to consider in order to perform an adequate sampling campaign.

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Appendix A

Description and details regarding samples, location and deployment

Table A 1: Site description and details regarding moss and air samples included in the study.

Location	ID	Matrix	Latitude	Longitude	Start ¹⁾	End
Mo i Rana	MiR-6	Moss	66.33	14.17	27.06.15 ¹⁾	-
	MiR-9	Moss	66.31	14.19	27.06.15 ¹⁾	-
	MiR-11	Moss	66.31	14.21	27.06.15 ¹⁾	-
Mosjøen	Msj-5	Moss	65.84	13.18	28.06.15 ¹⁾	-
	Msj-1 Skogsåsen	Air, PUF-PAS	65.83	13.22	22.07.15	21.08.15
	Msj-2 Skaret	Air, PUF-PAS	65.83	13.19	22.07.15	21.08.15
	Msj-3 Marsøra	Air, PUF-PAS	65.84	13.19	22.07.15	21.08.15
	Msj-4 Åsbyen	Air, PUF-PAS	65.85	13.20	22.07.15	21.08.15
	Msj-5 Kullstadlia	Air, PUF-PAS	65.87	13.20	22.07.15	21.08.15
Sauda	SAU-5	Moss	59.64	06.37	05.07.15 ¹⁾	-
Sunndal	SUN-4	Moss	62.69	8.56	12.07.15 ¹⁾	-
	Sun-1 Oppdøl	Air, PUF-PAS	62.74	8.52	28.07.15	28.08.15
	Sun-2 Leirvika	Air, PUF-PAS	62.69	8.56	28.07.15	28.08.15
	Sun-3 Blaksåbukta	Air, PUF-PAS	62.68	8.52	28.07.15	28.08.15
	Sun-4 Skjølløndøran	Air, PUF-PAS	62.67	8.57	28.07.15	28.08.15
	Sun-5 Nylykkjebekken	Air, PUF-PAS	62.65	8.64	28.07.15	28.08.15

Orkanger	Ork	Moss	63.33	9.9	13.07.15 ¹⁾	
	Ork-1 Ustan	Air, PUF-PAS	63.30	9.79	09.07.15	11.08.15
	Ork-2 Old quarry	Air, PUF-PAS	63.30	9.82	09.07.15	11.08.15
	Ork-3 Råbygda	Air, PUF-PAS	63.32	9.79	09.07.15	11.08.15
	Ork-4 Østhus	Air, PUF-PAS	63.32	9.92	09.07.15	11.08.15
	Ork-5 Kvitskjeret	Air, PUF-PAS	63.35	9.96	09.07.15	11.08.15
Porsgrunn	Por	Moss	59.13	9.61	15.07.15 ¹⁾	-
Kvinesdal	Kvi	Moss	58.28	6.85	17.07.15 ¹⁾	-
Ålvik	Ålv	Moss	60.43	6.43	25.07.15 ¹⁾	-
	Ålv-1 Ytre Ålvik (Tveitnes	Air, PUF-PAS	60.40	6.38	15.07.15	21.08.15
	Ålv-2 Vikedal	Air, PUF-PAS	60.42	6.40	15.07.15	21.08.15
	Ålv-3 Ålvik	Air, PUF-PAS	60.43	6.43	15.07.15	21.08.15
	Ålv-4 Vetletveit	Air, PUF-PAS	60.42	6.45	15.07.15	21.08.15
	Ålv-5 Kjepso	Air, PUF-PAS	60.43	6.48	15.07.15	21.08.15
Hemne	Hem	Moss	63.26-63.39 ²⁾	09.00 - 09.24 ²⁾	08.10.15 ¹⁾	-
	Hem-1 Holla	Air, PUF-PAS	63.32	9.14	21.09.15	23.10.15
	Hem-2 Kynnsvika	Air, PUF-PAS	63.35	9.11	18.09.15	23.10.15
	Hem-3 Sperilla	Air, PUF-PAS	63.34	9.21	17.09.15	23.10.15
	Hem-4 Mo	Air, PUF-PAS	63.26	8.99	17.09.15	23.10.15
	Hem-5 Tannvikvågen	Air, PUF-PAS	63.38	9.24	17.09.15	23.10.15
Kristiansand	Krs-1 Roligheten	Air, PUF-PAS	58.15	8.04	06.08.15	11.09.15
	Krs-2 Baneheia	Air, PUF-PAS	58.15	7.99	06.08.15	11.09.15
	Krs-3 Odderøya	Air, PUF-PAS	58.13	8.00	06.08.15	11.09.15
	Krs-4 Auglandstjønn	Air, PUF-PAS	58.13	7.93	06.08.15	11.09.15
	Krs-5 Kjosdalen	Air, PUF-PAS	58.12	7.95	06.08.15	11.09.15

¹⁾ For moss samples, start is the day sampled

²⁾ Pooled sample. The coordinates are not accurate and presented as a range.

Appendix B

Concentration of individual PAHs in moss at selected industrial sites in Norway

Table A 2: Individual concentrations (ng/g dw) of PAHs in moss samples

Sites	Naphthalene	Acenaphthylene	Acenaphthene	Fluorene	Phenanthrene	Anthracene	Fluoranthene	Pyrene	Benz[a]anthracene	Chrysene	Benz[b]fluoranthene	Benz[k]fluoranthene	Benz[a]pyrene	Indeno[1,2,3-cd]pyrene	Dibenzo[a,h]anthracene	Benz[ghi]perylene	Σ_{16} PAHs	Σ_8 PAHs
Porsgrunn, Por	3.1	0.5	0.2	1	21.4	1.4	18	13	16	41	35	13	15	16	3.4	17	216	127
% contribution Σ_{16} PAHs	1	0.2	0.1	0.4	10	0.7	8	6	7	19	16	6	7	7	2	8	-	-
% contribution Σ_8 PAHs	2	0.4	0.2	0.8	17	1	14	10	12	32	28	10	12	12	3	14	-	-
Kvinesdal, Kvi	2.1	0.8	1.3	2.7	17	1.2	33	21	5.4	13	16	5.7	8.2	9.9	1.8	12	151	101
% contribution Σ_{16} PAHs	1	0.5	0.9	2	11	0.8	22	14	4	8	11	4	5	7	1	8	-	-
% contribution Σ_8 PAHs	2	0.8	1	3	17	1	33	21	5	13	16	6	8	10	2	12	-	-
Sauda, Sau	2.8	0.6	1.1	2.6	19	1	35	21	7.2	25	19	7.5	8	10	2.1	13	175	119
% contribution Σ_{16} PAHs	2	0.4	0.7	1.5	11	0.6	20	12	4	14	11	4	5	6	1	7	-	-
% contribution Σ_8 PAHs	2	0.5	1	2	16	1	29	18	6	21	16	6	7	9	2	11	-	-
Ålvik, Ålv	4.1	0.8	1.2	3.2	15	0.9	26	16	5.7	13	16	5.6	7.2	8.6	1.5	11	135	87
% contribution Σ_{16} PAHs	3	0.6	0.9	2	11	0.7	19	12	4	10	12	4	5	6	1	8	-	-
% contribution Σ_8 PAHs	5	0.9	1	4	18	1	29	18	7	15	18	6	8	10	2	12	-	-
Sunndal, Sun	7.6	1	13	13	94	8.5	218	164	127	203	244	110	217	176	41	189	1825	1044
% contribution Σ_{16} PAHs	0.4	0.1	0.7	0.7	5	0.5	12	9	7	11	13	6	12	10	2	10	-	-
% contribution Σ_8 PAHs	0.7	0.1	1	1	9	0.8	21	16	12	19	23	11	21	17	4	18	-	-
Hemne, Hem	5.1	0.6	4.9	7.6	37	4.4	49	34	22	28	26	12	22	17	4.1	18	290	203
% contribution Σ_{16} PAHs	2	0.2	2	3	13	1	17	12	7	10	9	4	8	6	1	6	-	-
% contribution Σ_8 PAHs	2	0.3	2	4	18	2	24	17	11	14	13	6	11	8	2	9	-	-
Orkanger, Ork	5	0.7	18	25	137	18	372	290	202	226	259	129	247	183	45	179	2334	1516
% contribution Σ_{16} PAHs	0.2	0.03	0.8	1	6	0.8	16	12	9	10	11	6	11	8	2	8	-	-
% contribution Σ_8 PAHs	0.3	0.05	1	2	9	1	25	19	13	15	17	9	16	12	3	12	-	-
Mosjøen, Msj	39	1.1	3.8	5.3	31	6.5	55	41	35	47	59	27	51	41	9.5	44	497	272
% contribution Σ_{16} PAHs	8	0.2	1	1	6	1	11	8	7	10	12	5	10	8	2	9	-	-

Sites	Naphthalene	Acenaphthylene	Acenaphthene	Fluorene	Phenanthrene	Anthracene	Fluoranthene	Pyrene	Benz[a]anthracene	Chrysene	Benzo[b]fluoranthene	Benzo[k]fluoranthene	Benzo[a]pyrene	Indeno[1,2,3-cd]pyrene	Dibenz[a,h]anthracene	Benzo[ghi]perylene	Σ_{16} PAHs	Σ_8 PAHs
% contribution Σ_8 PAHs	14	0.4	1	2	11	2	20	15	13	17	22	10	19	15	4	16	-	-
Mo i Rana, MiR-6	3	0.4	2.3	2.8	22	1.9	58	39	24	53	52	21	38	33	7.4	38	395	238
% contribution Σ_{16} PAHs	0.8	0.1	0.6	0.7	6	0.5	15	10	6	13	13	5	10	8	2	10	-	-
% contribution Σ_8 PAHs	1	0.2	1	1	9	0.8	24	16	10	22	22	9	16	14	3	16	-	-
Mo i Rana, MiR-9	7.9	3.1	8.9	18	97	7	115	67	23	44	47	15	22	24	5.3	30	533	393
% contribution Σ_{16} PAHs	1.5	0.6	2	3	18	1	22	12	4	8	9	3	4	4	1	6	-	-
% contribution Σ_8 PAHs	2	1	2	5	25	2	29	17	6	11	12	4	6	6	1	8	-	-
Mo i Rana, MiR-11	15	6	14	26	153	11	162	93	35	67	68	23	33	35	8.2	42	790	580
% contribution Σ_{16} PAHs	2	1	2	3	19	1	21	12	4	9	9	3	4	4	1	5	-	-
% contribution Σ_8 PAHs	3	1	2	4	26	2	28	16	6	12	12	4	6	6	1	7	-	-

<: the concentrations were below the estimated LOD

Table A 3: Concentration of moss at industrial and closest background sites (ng/g)

Location	Location type	Naphthalene	Acenaphthylene	Acenaphthene	Fluorene	Phenanthrene	Anthracene	Fluoranthene	Pyrene	Benz[a]anthracene	Chrysene	Benzo[b]fluoranthenes	Benzo[k]fluoranthenes	Benzo[a]pyrene	Indeno[1,2,3-cd]pyrene	Dibenzo[a,h]anthracene	Benzo[ghi]perylene	Σ ₁₆ EPA PAH	Σ possibly carcinogenic
Mo i Rana (Mir-6)	Industry	3	0.4	3	3	22	2	58	39	24	53	53	21	38	33	7	38	396	175
Mo i Rana (MiR-9)		8	3	9	18	97	7	115	67	24	44	47	15	23	24	5	30	534	137
Mo i Rana (MiR-11)		15	6	14	26	153	11	162	93	35	67	68	23	33	35	8	42	790	202
Bodø	Background	<3	<0.1	<0.3	<1	<21	<0.2	2	1	0.4	1	1	0.6	0.7	1	0.1	1	<26	4
Mosjøen (Msj-5)	Industry	39	1	4	5	31	7	55	41	35	47	59	27	51	41	10	44	497	222
Røysvik	Background	<3	<0.1	<0.3	<1	<21	<0.2	<2	<0.9	0.2	0.5	0.9	0.3	0.5	0.6	0.1	0.6	<26	3
Sauda (Sau-5)	Industry	3	0.6	1	3	19	1	35	21	7	25	19	8	8	11	2	13	175	54
Ålvik (Ålv-3)		4	0.8	1	3	15	0.9	26	16	6	13	16	6	7	7	2	11	135	45
Stord	Background	<3	1	<0.3	<1	<21	<0.2	7	5	2	4	5	2	3	3	0.6	4	36	15
Sunndal (Sun-4)	Industry	8	1	13	13	94	9	218	164	127	203	244	110	217	176	41	189	1825	915
Godøy	Background	<3	0.2	<0.3	<1	<21	<0.2	11	9	3	8	13	5	6	10	2	10	78	39
Orkanger (Ork-4)	Industry	5	0.7	18	25	137	18	372	290	202	226	259	129	247	183	45	179	2335	1065
Hemne (Kyrk 10.8.3.4)		5	0.6	5	8	37	4	49	34	22	28	26	12	22	17	4	18	291	102
Mosvik	Background	<3	<0.1	<0.3	<1	<21	<0.2	2	1	0.3	1	1	0.5	0.7	0.9	0.1	1	<26	4
Kvinesdal (Kvi-3)	Industry	2	0.8	1	3	17	1	33	21	5	13	17	6	8	10	2	12	151	48
Birkenes	Background	<3	<0.1	<0.3	<1	<21	<0.2	2	1	0.4	1	2	0.5	0.7	0.8	0.1	1	<26	4
Porsgrunn (Por-16)	Industry	3	0.5	0.2	1	<21	1	18	13	16	41	35	13	16	16	3	17	201	98
Risør	Background	<3	1	<0.3	<1	<21	1	20	16	7	14	24	10	11	20	3	19	151	74

<: the concentrations were below the estimated LOD

Concentration of individual PAHs in air samples deployed close to selected industrial sites in Norway

Table A 4: Individual concentration (ng/sample) of PAHs in the air samples, including also the % contribution to the average of sum 16 and 8 PAHs for each site.

Sites	Naphthalene	Acenaphthylene	Acenaphthene	Fluorene	Phenanthrene	Anthracene	Fluoranthene	Pyrene	Benz[a]anthracene	Chrysene	Benz[b]fluoranthenes	Benz[k]fluoranthenes	Benz[a]pyrene	Indeno[1,2,3-cd]pyrene	Dibenz[ah]anthracene	Benz[ghi]perylene	Σ_{16} PAHs	Σ_8 PAHs
Ustan (Ork-1)	< 95	< 1.8	133	231	490	2.2	50	18	1.1	1.6	1.2	0.5	0.9	0.8	< 0.3	0.9	1027	794
Old quarry (Ork-2)	< 95	2.4	118	111	160	2.6	18	8	0.8	1.1	0.8	0.3	0.6	0.4	< 0.3	0.8	519	302
Råbygda (Ork-3)	< 95	< 1.8	< 22	43	90	1	16	6	0.7	1.3	0.9	0.4	0.6	0.6	< 0.3	0.7	279	158
Østhus (Ork-4)	< 95	< 1.8	< 22	35	80	2.5	39	23	3.6	5.8	2.2	0.9	1.0	0.9	< 0.3	1.1	314	191
Kvitskjeret (Ork-5)	< 95	< 1.8	95	127	213	4.1	34	13	1.1	1.9	1.2	0.5	0.8	0.6	< 0.3	0.9	590	394
% contribution to average Σ_{16} PAHs	-	-	21	20	38	0.5	6	3	0.3	0.4	0.2	0.1	0.1	0.1	-	0.2	-	-
% contribution to the average Σ_8 PAHs	-	-	31	30	56	1	9	4	0.4	0.6	0.3	0.1	0.2	0.2	-	0.2	-	-
Skogsåsen (Msj-1)	129	6.5	129	138	366	16	71	30	2.7	3.8	3.4	1.5	2.6	2.5	0.4	2.5	905	631
Skaret (Msj-2)	< 95	3.0	89	103	256	15	45	18	1.7	2.9	2.8	1.2	1.6	1.8	0.3	1.8	637	443
Marsøra (Msj-3)	< 95	4.3	72	70	171	5.8	34	15	1.4	2.1	1.7	0.8	1.2	1.1	< 0.3	1.1	475	300
Åsbyen (Msj-4)	133	15	170	237	530	27	95	35	2.4	3.5	2.7	1.2	2.0	1.7	0.3	1.9	1257	931
Kullstadlia (Msj-5)	132	8.6	113	171	371	15	74	39	3.4	5.1	3.5	1.6	2.3	2.2	0.4	2.6	944	680
% contribution to average Σ_{16} PAHs	16	1	14	18	42	2	8	3	0.3	0.4	0.3	0.2	0.2	0.2	0.04	0.2	-	-
% contribution to the average Σ_8 PAHs	22	1	19	24	57	3	11	5	0.4	0.6	0.5	0.2	0.3	0.3	0.1	0.3	-	-
Ytre Ålvik (Tveitnes-Ålv-1))	< 95	< 1.8	40	72	155	2.4	29	10	0.5	1.1	0.4	< 0.1	< 0.2	< 0.2	< 0.3	0.2	408	271
Vikedal (Ålv-2)	< 95	< 1.8	171	231	635	5.9	174	35	0.3	0.9	0.3	< 0.1	< 0.2	< 0.2	< 0.3	0.2	1350	1082

Sites	Naphthalene	Acenaphthylene	Acenaphthene	Fluorene	Phenanthrene	Anthracene	Fluoranthene	Pyrene	Benz[a]anthracene	Chrysene	Benzo[b]fluoranthenes	Benzo[k]fluoranthenes	Benzo[a]pyrene	Indeno[1,2,3-cd]pyrene	Dibenz[ah]anthracene	Benzo[ghi]perylene	Σ_{16} PAHs	Σ_8 PAHs
Ålvik (Ålv-3)	< 95	< 1.8	23	42	88	1.5	34	14	0.6	1.3	0.3	< 0.1	< 0.2	< 0.2	< 0.3	< 0.2	302	182
Vetletveit (Ålv-4)	< 95	< 1.8	< 22	37	67	0.8	17	7	0.2	0.6	0.2	< 0.1	< 0.2	< 0.2	< 0.3	< 0.2	248	130
Kjepso (Ålv-5)	< 95	< 1.8	< 22	40	106	3.3	28	18	0.9	1.7	0.5	0.2	< 0.2	0.1	< 0.3	0.3	317	198
% contribution to average Σ_{16} PAHs	-	-	15	16	40	0.5	11	3	0.1	0.2	0.1	-	-	-	-	-	-	-
% contribution to the average Σ_8 PAHs	-	-	21	23	56	1	15	5	0.1	0.3	0.1	-	-	-	-	-	-	-
Oppdøl, 2 (Sun-1)	72	3.1	117	351	967	9.8	243	86	8.6	15	12.6	5.7	8.1	6.6	1.1	7.7	1913	1687
Leirvika, 4 (Sun-2)	83	4.4	68	181	428	8.7	74	34	1.9	4.3	1.9	0.7	0.7	0.8	< 0.3	1.2	892	732
Blaksåbukta, 5 (Sun-3)	< 95	< 1.8	152	264	635	4.6	107	26	1.1	2.4	2.0	0.9	1.4	1.2	< 0.3	1.6	1295	1040
Skjølløndøran, 7 (Sun-4)	92	2.4	60	205	525	8.6	93	44	4.5	8.3	6.4	2.9	4.6	3.9	0.4	5.0	1065	893
Nylykkjebekken, 8 (Sun-5)	79	6.4	114	282	634	15.2	184	89	< 0.3	12	7.3	3.1	< 0.2	3.6	0.5	4.4	1434	1216
% contribution to average Σ_{16} PAHs	6	0.3	8	19	48	1	11	4	0.3	0.6	0.5	0.2	0.3	0.2	0.1	0.3	-	-
% contribution to the average Σ_8 PAHs	8	0.4	9	23	57	1	13	5	0.4	0.8	0.5	0.2	0.3	0.3	0.1	0.4	-	-
Roligheten (Krs-1)	384	2.3	136	134	261	5.9	52	30	2.1	6.4	3.2	1.1	1.3	1.3	< 0.3	1.9	1022	493
Baneheia (Krs-2)	304	2.1	118	163	413	9.4	102	57	3.8	10	5.0	1.9	2.1	2.2	0.3	3.7	1197	760
Odderøya (Krs-3)	310	1.4	193	240	546	12	157	81	6.8	12	6.5	2.5	3.0	2.6	0.2	3.5	1577	1058
Auglandstjønn (Krs-4)	223	1.5	275	380	660	11	167	76	6.3	12	6.8	2.5	2.8	2.7	< 0.3	3.7	1830	1315
Kjosdalen (Krs-5)	264	< 1.8	111	139	300	5.7	75	37	3.0	6.6	3.6	1.4	1.5	1.5	< 0.3	2.3	952	566
% contribution to average Σ_{16} PAHs	23	0.1	13	16	33	1	8	4	0.3	0.7	0.4	0.1	0.2	0.2	-	0.2		

Sites	Naphthalene	Acenaphthylene	Acenaphthene	Fluorene	Phenanthrene	Anthracene	Fluoranthene	Pyrene	Benz[a]anthracene	Chrysene	Benzo[b]fluoranthene	Benzo[k]fluoranthene	Benzo[a]pyrene	Indeno[1,2,3-cd]pyrene	Dibenz[ah]anthracene	Benzo[ghi]perylene	Σ_{16} PAHs	Σ_8 PAHs
% contribution to the average Σ_8 PAHs	35	0.2	20	25	52	1	13	7	0.5	1	0.6	0.2	0.3	0.2	-	0.4		
Holla (Hem-1)	< 95	3.5	362	309	314	14	87	53	17	17	14	8.1	14.9	9.4	2.4	10.4	1329	824
Kynnsvika (Hem-2)	< 95	< 1.8	< 22	26	45	0.7	8	4	< 0.3	0.5	0.1	< 0.1	< 0.2	< 0.2	< 0.3	< 0.2	203	85
Sperilla (Hem-3)	< 95	< 1.8	26	52	110	3.7	21	14	0.8	1.6	0.4	< 0.1	< 0.2	< 0.2	< 0.3	< 0.2	326	203
Mo (Hem-4)	< 95	< 1.8	< 22	29	51	1.1	9	5	0.3	0.7	0.2	< 0.1	< 0.2	< 0.2	< 0.3	< 0.2	214	95
Tannvikvågen (Hem-5)	< 95	< 1.8	< 22	35	65	0.7	12	6	0.2	0.8	0.2	< 0.1	< 0.2	< 0.2	< 0.3	0.1	238	119
% contribution to average Σ_{16} PAHs	-	-	42	19	25	1	6	3	1	1	1	-	-	-	-	-	-	-
% contribution to the average Σ_8 PAHs	-	-	73	34	44	2	10	6	2	2	1	-	-	-	-	-		-

<: the concentrations were below the estimated LOD

Appendix C

Concentration of individual PAHs in moss (ng/g dw) and air (ng/sample).

Table A 5: Concentration of individual PAHs, together with $\Sigma 16$ PAHs and $\Sigma 8$ PAHs in moss and air, and the blank values

Compounds	Air ng/sample				Blank values, air ng/sample		Moss ng/g dw				Blank values, moss ?	
	Median	Average \pm SD	Range (min-max)	LOD/MDL	Average \pm SD	Range (min-max)	Median	Average \pm S.D	Range (min-max)	LOD/MDL	Average \pm SD	Range (min-max)
Naphtalene	95	130 \pm 80	72 ¹⁾ -384	95	27 \pm 22	4-71	5	9 \pm 11	2 ¹⁾ -39	2.6	1.4 \pm 0.4	1-2
Acenaphthylene	2	3 \pm 3	1 ¹⁾ -15	2	0.4 \pm 0.5	0.1 ²⁾ -2	1	1 \pm 2	0.4-6	0.1	0.05 \pm 0.02	0.03 ²⁾ -0.1
Acenaphthene	103	101 \pm 80	22-362	22	3 \pm 6	0.2 ²⁾ -19	4	6 \pm 6	0.2 ¹⁾ -18	0.4	0.2 \pm 0.07	0.1 ²⁾ -0.2
Fluorene	136	149 \pm 104	26-380	4	1 \pm 0.9	0.3-3	5	10 \pm 9	1-26	1	0.7 \pm 0.3	0.4-1
Phenanthrene	280	324 \pm 238	45-967	7	3 \pm 1	1.4-5	31	58 \pm 52	15 ¹⁾ -153	21	6 \pm 5	2-15
Anthracene	6	7 \pm 6	0.7-27	0,3	0.09 \pm 0.06	0.03 ²⁾ -0.2	4	6 \pm 5	0.9-18	0.2	0.07 \pm 0.06	0.01 ²⁾ -0.2
Fluoranthene	51	72 \pm 60	8-243	3	1 \pm 0.5	0.4-2	55	104 \pm 109	18-372	2.3	0.8 \pm 0.5	0.3-2
Pyrene	24	31 \pm 25	4-89	2	0.7 \pm 0.4	0.3-1	39	73 \pm 85	13-290	0.7	0.4 \pm 0.1	0.3-0.5
Benzo[a]anthracene	1	2.6 \pm 3.5	0.2-17	0.2	0.06 \pm 0.06	0.01 ²⁾ -0.2	23	45 \pm 62	5-202	0.1	0.04 \pm 0.03	0.01-0.07
Chrysene	3	5 \pm 5	0.5-17	0.3	0.1 \pm 0.07	0.1-0.3	44	69 \pm 74	13-226	0.1	0.06 \pm 0.03	0.03-0.09
Benzo[b]fluoranthenes	2	3 \pm 4	0.1 ¹⁾ -14	0.2	0.07 \pm 0.04	0.01 ²⁾ -0.2	47	76 \pm 88	16-259	0.1	0.04 \pm 0.03	0.01 ²⁾ -0.08
Benzo[k]fluoranthenes	0,8	1 \pm 2	0.1-8	0.1	0.04 \pm 0.03	0.02 ²⁾ -0.1	15	34 \pm 43	6-129	0.04	0.01 \pm 0.01	0.005 ²⁾ -0.03
Benzo[a]pyrene	1	2 \pm 3	0.2-15	0.2	0.06 \pm 0.06	0.02 ²⁾ -0.2	22	61 \pm 86	7-247	0.04	0.01 \pm 0.01	0.005 ²⁾ -0.03
Indeno[1,2,3-cd]pyrene	1	1.6 \pm 2.1	0.1 ¹⁾ -9	0.2	0.06 \pm 0.04	0.03 ²⁾ -0.1	24	50 \pm 65	9-183	0.06	0.02 \pm 0.01	0.01 ²⁾ -0.04
Dibenzo[ah]anthracene	0,3	0.4 \pm 0.4	0.2 ¹⁾ -2	0.3	0.09 \pm 0.06	0.03 ²⁾ -0.2	5	12 \pm 16	2-45	0.03	0.02 \pm 0.01	0.01 ²⁾ -0.02
Benzo[ghi]perylene	1	2 \pm 2.4	0.1 ¹⁾ -10	0.2	0.06 \pm 0.04	0.03 ²⁾ -0.2	30	54 \pm 65	11-189	0.07	0.02 \pm 0.02	0.01 ²⁾ -0.05
$\Sigma 16$ PAHs	898	835 \pm 513	203-1913	136	38 \pm 33	7-81	395	668 \pm 734	135-2334	30	10 \pm 7	4-20
$\Sigma 8$ PAHs	530	592 \pm 425	85-1687	17	7 \pm 3	3-11	238	426 \pm 459	87-1516	26	8 \pm 6	3-18

1) Below MDL

2) One or more samples was below LOD (from the instrument)

NILU – Norwegian Institute for Air Research

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