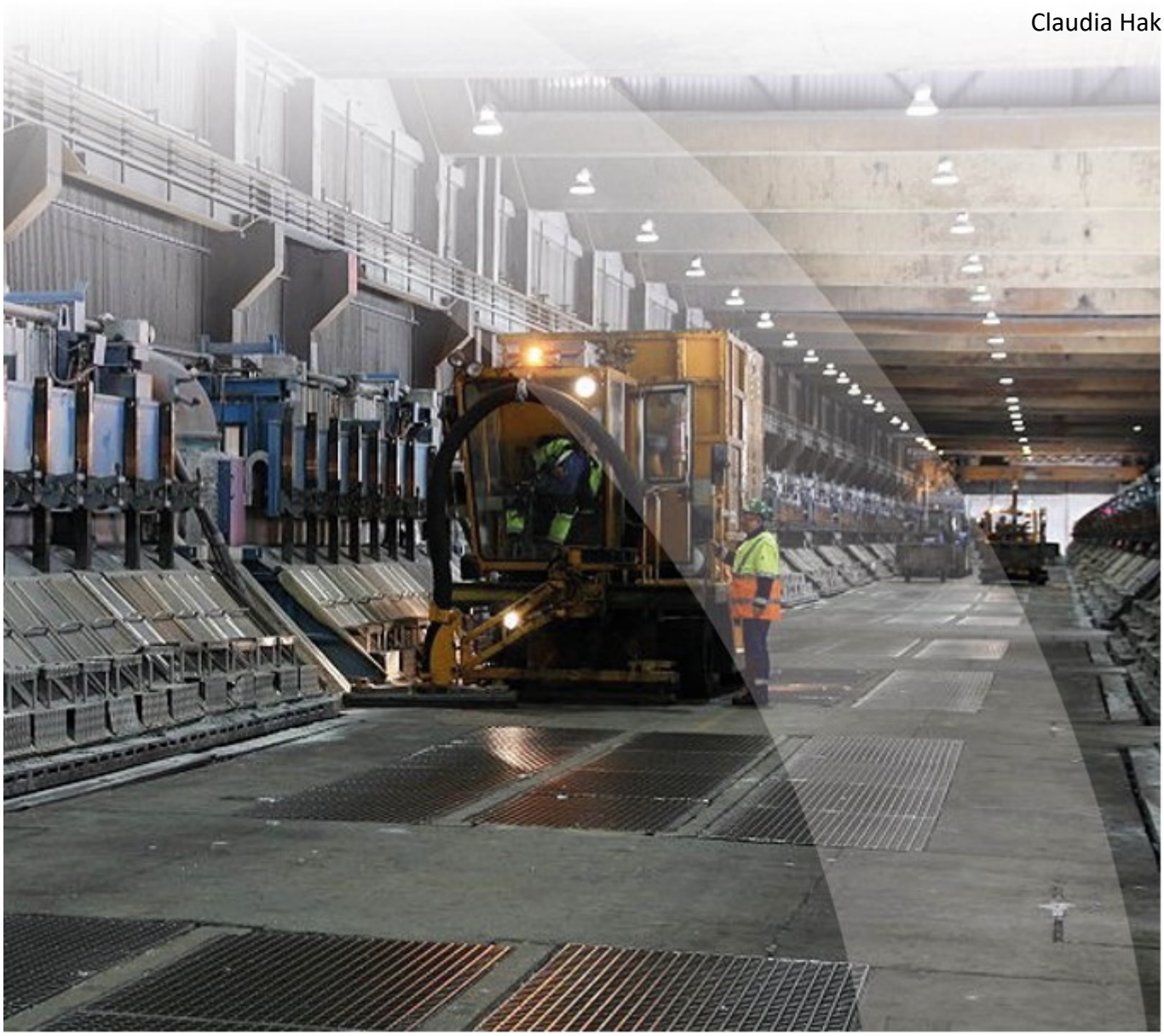
Norsk institutt for luftforskning
Norwegian Institute for Air Research

Air quality assessment in the surroundings of aluminium smelters

Effect of emissions on air quality in the past (1992 – now)

Claudia Hak



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ABSTRACT

On behalf of Aluminiumindustriens Miljøsekretariat (AMS), NILU – Norwegian Institute for Air Research reviewed existing data on ambient air quality around aluminium smelters from the period 1992 – 2020. Changes in production technologies and treatment technologies have been implemented in this time period.
Emissions to air and ambient concentrations of most compounds typically measured (PAHs, fluorides, sulphur dioxide, particulate matter, heavy metals) have decreased since the beginning of the 1990s as a result of improvement of the production technology.

NORWEGIAN TITLE

Vurdering av luftkvalitet i omgivelsene av aluminiumssmelteverk. Effekt av utslipp på luftkvalitet i perioden 1992 – nå.

KEYWORDS

Air quality | Industrial pollution | Aluminium industry

ABSTRACT (in Norwegian)

På oppdrag fra Aluminiumindustriens Miljøsekretariat (AMS) har NILU – Norsk institutt for luftforskning gjennomgått eksisterende data om luftkvalitet rundt aluminiumssmelteverk fra perioden 1992 – 2020. Endringer i produksjons-teknologier og renseteknologier har blitt implementert i denne tidsperioden. Utslipp til luft og omgivelseskonsentrasjoner av de fleste forbindelser som typisk måles (PAH, fluorider, svoveldioksid, partikler, tungmetaller) har gått ned siden begynnelsen av 1990-tallet som følge av forbedring av produksjonsteknologien.

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Preface

This project has been carried out by NILU – Norwegian institute for air research on behalf of Aluminiumindustriens Miljøsekretariat (AMS). The background for the project is to assess the effect of aluminium production on the environment surrounding aluminium smelters. Changes in production technology and treatment technology over the past three decades (1992 – 2020) led to decreased emissions to air and lower ambient concentrations of several air pollutants.

The work was carried out by Claudia Hak, collecting data and compiling the information in the report.

Data sources for this report were:

- NILU reports
- Data available at NILU
- Other open reports available
- Information/data provided by the industries

Some smelters are covered very well with studies over time. For some smelters, hardly any information/studies is available. This does not necessarily mean that no measurements have been carried out. Possible additional data was not made available for the study.

Contents

Summary

The effect of aluminium production on the environment surrounding aluminium smelters has been studied over several decades. NILU has studied their effects on air quality, both in measurements and modelling studies, since the early 1970s. The "Effect Study" in the beginning of the 1990s gave an overview over the effects of aluminium production on vegetation, water, farm and game animals and human health.

ESPIAL (Ensuring the Environmental Sustainability of production of PrImary Aluminium) is a multidisciplinary study initiated and sponsored by "Aluminiumindustriens Miljøsekretariat" (AMS) to update and supplement the Effect Study. The present report is a contribution to this update, focusing on ambient concentrations of polycyclic aromatic hydrocarbons (PAHs), fluorides, sulphur dioxide (SO_2), particulate matter (PM) and heavy metals around aluminium smelters over the past 30 years.

The historical emissions from aluminium smelters have been assessed in a literature and data review focusing on reports, data and other publications available on smelters participating in the ESPIAL project. Technical data, like production method and production volume, and their historical development were provided by the industries.

An evaluation of the effect of historical emissions of polycyclic aromatic hydrocarbons (PAHs), sulphur dioxide (SO_2), fluorides, particulate matter (PM) and heavy metals (HM) on ambient air quality over the time period 1992 – 2020 was carried out, assessing the evolution and the effects associated with the development that the aluminium industry has gone through. Note that most studies were carried out before the conversion from Söderberg to prebaked anodes, which took place in the period 2000 – 2010 for most aluminium smelters. A few studies carried out after the conversion were available, show significant decrease in ambient concentrations of air pollutants in the surroundings of the smelters.

The most recent measurement study of several compounds in ambient air was carried out in summer 2019 around Hydro Sunndal, which is the largest smelter and located in a topographically difficult area. Although there are differences in the production technologies of the aluminium smelters, levels measured at Sunndal may serve as upper limits of the concentration ranges probable to be observed around aluminium smelters today.

The data evaluation in the present report focused on the historical time variation of emissions, assessing the effectiveness of the technical developments of the aluminium industry (e.g., effectiveness of cleaning devices, introduction of new technologies, etc.), and establish which issues still may be of concern.

As a consequence of technical conversions, PAH-emissions have decreased significantly since the 1990s at all aluminium smelters included in the study. The target value of benzo(a)pyrene (BaP, 1.0 ng/m^3, annual average) is not assumed to be exceeded based on today's emissions and considering the most recent measurement results.

For fluorides, emissions have decreased slightly since the 1990s at most aluminium smelters included in the study. From the few recent measurements carried out, no clear tendency can be inferred. However, levels are clearly below the former WHO-limit for total fluoride at 1 µg/m^3 (annual average). There are currently no limit values, recommendations or air quality criteria for fluorides in ambient air.

SO_2-emissions have decreased significantly at most smelters since the 1990s. However, not at the Icelandic smelters, which do not have wet scrubbers due to the natural abundance of SO_2. Based on the few measurement studies carried out, a decrease of ambient levels of SO_2 is observed. Also, background concentrations of SO_2 in Norway have decreased (75 – 91% since 1990). The annual limit

value of SO_2 is not assumed to be exceeded in the vicinity of aluminium smelters based on today's emissions and the most recent measurement results.

Particle emissions have decreased at most smelters since the 1990s as a consequence of technical conversions. Based on the few measurement studies carried out recently, a decrease of ambient levels of PM in the vicinity of aluminium smelters over the past decades is observed. Also, background concentrations of PM in Norway have decreased (> 35% since 2000).

Heavy metal emissions have decreased at many smelters since 2000. The emissions of heavy metals to air have not been reported before 2000. Based on the few measurement studies available, a possible decrease of ambient levels of some metals is observed.

Air quality assessment in the surroundings of aluminium smelters

Effect of emissions on air quality in the past (1992 – now)

1 Introduction

Background and scope

The effect of aluminium production on the environment surrounding aluminium smelters has been studied over several decades. NILU has studied their effects on air quality both in measurement and modelling studies since the early 1970s. In the beginning of the 1990s, the "Effect Study" was commissioned by the Norwegian aluminium industry, focusing mainly on effects on vegetation, water, farm animals, game animals and human health. An update of the Effect Study, including effects on air quality, is being carried out now.

In order to establish up-to-date knowledge on the ambient air quality status in the surroundings of aluminium plants today, field campaigns were carried out at selected smelters. The 10 smelters participating in the ESPIAL[1] project are placed at locations largely differing regarding dispersion conditions, population exposure, topography etc. This makes it difficult to conclude on the situation around other smelters based on measurements at only one distinct location. Two separate campaigns were carried out. Lista and Sunndal were indicated as suitable sites, one located in a flat area at the coast, the other in a topographically complex terrain. The results of these measurement studies are described in separate reports and summarised here. The present report covers a literature and data study for all 10 smelters, back to the early 1990s.

The main aim of this project is to advance the knowledge regarding the environmental consequences associated with emissions to air from the production of primary aluminium from the production technologies available today. The aim is achieved through the assessment of the effect of historical emissions on air quality in the past (this report) and measurement of the most relevant air pollutants emitted during aluminium production (in surroundings of selected smelters: Hydro Sunndal, Hak, 2021a; Alcoa Lista, Hak, 2021b). The outcome from these activities will contribute to knowledge creation at the Al-industries and to secure sustainability of the aluminium industry in Norway/Northern Europe.

Primary aluminium is produced by means of electrolytic reduction of alumina. The most important pollutants emitted from the primary aluminium electrolysis process are sulphur dioxide (SO_2), carbon monoxide (CO), polycyclic aromatic hydrocarbons (PAHs) and the greenhouse gas carbon dioxide (CO_2). Polyfluorinated hydrocarbons and fluorides are also produced during the electrolysis process. Dust is emitted mainly during the electrolysis stage in the primary production of aluminium.

1.1 Compounds emitted in primary aluminium production

The production of primary aluminium is a highly energy-demanding/intensive process and connected with the emission of a number of pollutants to air. Especially the electrolysis stage has a high energy use. An important source of air emissions from primary aluminium production occurs during the reduction of aluminium oxide to aluminium metal in the pot room. The main compounds of local air quality concern are fluorides (in gaseous and particulate form), sulphur dioxide (SO_2), particulate matter (PM) and polycyclic aromatic hydrocarbons (PAH). Furthermore, some heavy metals may be associated with the PM.

[1] ESPIAL – Ensuring the Environmental Sustainability of production of PrImary ALuminium.

Measurements in ambient air are the sum of a background concentration and contributions from local sources. For some compounds, e.g. fluorides, the aluminium smelters are the only local sources. For PAHs, SO_2 and heavy metals, the aluminium smelters are the main local sources.

Fluoride

Fluorine is an element that forms a wide range of compounds with other substances. Fluorides are acid and salt compounds of fluorine. In ambient air, fluoride is present both on particles and in gaseous form. Fluorides that are in the gas phase or bound to particles are almost completely absorbed into the respiratory tract. Fluoride in gaseous form is strongly bound by absorption on surfaces and can lead to acute and chronic damage to vegetation, even in low concentrations.

The most important source of fluorides emissions into the air in Norway is the aluminium industry (electrolysis halls). Previously, emissions of total fluoride from this industry were so high that the concentration in ambient air caused extensive environmental damage in the surrounding areas. The introduction of new technology led to a significant decrease of emissions from the mid-1980s to 1990. At a measuring station in Øvre Årdal, 1.5 µg/m^3 was measured in winter 1989/1990 against 7.4 µg/m^3 in 1986/87. Since then, it seems that emissions from the aluminium industry have stabilised. Fluoride emissions, in the form of gaseous hydrogen fluoride and sodium and aluminium fluorides and unused cryolite as particulates, are the major undesirable fume component produced in the aluminium smelting process. Such emissions can be reduced through the use of fume control systems, operational good practice and improved technology. Fluorine compounds can cause damage to humans, animals and vegetation. The most important transport from the source to the environment takes place by air, and the meteorological and topographical conditions are of great importance for the ambient levels of the fluorine compounds.

Sulphur dioxide

Sulphur dioxide (SO_2) is formed by the combustion of substances containing sulphur, mainly heavy oil and coal, as well as by a number of industrial processes. The largest sources of sulphur dioxide emissions in Norway are industry and mining. These sources accounted for 70% of emissions in 2020[2]. The metal industry is by far the most important source of emissions[3] in the process industry. In aluminium production, sulphur dioxide comes from the consumption of anodes in the electrochemical process. Anodes contain sulphur-containing petroleum coke (reducing agent in aluminium production), which in turn forms SO_2 when the anode is consumed. To reduce SO_2 emissions, aluminium plants have installed flue gas treatment, such as seawater scrubbers.

Sulphur dioxide is easily soluble in water and contributes to acidification of water and soil and damages materials. Sulphur dioxide pollution has been a significant environmental and health problem. However, as a result of strict guidelines and extensive treatment, SO_2 emissions have decreased strongly in Norway and elsewhere in Europe over the past 30 years.

When exposed to sulphur dioxide, different people respond with very different sensitivities. Healthy individuals first respond at an exposure of several thousand µg/m^3, while asthmatics are more susceptible; in some subjects, a response effect on lung function was registered at exposure to about 1000 µg/m^3 over 15 minutes (Norwegian Institute of Public Health).

Polycyclic aromatic hydrocarbons (PAHs)

Polycyclic aromatic hydrocarbons (PAH) constitute a group of compounds that are formed mainly by incomplete combustion of organic material, both through anthropogenic (i.e. industrial and domestic

[2] https://www.ssb.no/natur-og-miljo/forurensning-og-klima/statistikk/utslipp-til-luft
[3] www.norskeutslipp.no

use) and natural processes. The most important sources of emissions are vehicle traffic, residential heating (e.g., wood combustion) and various types of industry. An important source of PAH emissions to air was electrolysis with Söderberg anodes in aluminium production. PAH evaporate from the electrode mass when the temperature becomes high. This source has been strongly reduced over the past decades, due to technical modernisation in the aluminium industry. PAHs are also emitted during the production of anode paste and prebaked anodes. Vehicle traffic and residential heating with oil products and wood also emit PAHs. Some of the PAH compounds are carcinogenic and may therefore pose a health risk.

Benzo(a)pyrene (BaP) is the most studied PAH. BaP exists in polluted air and is used as a marker for carcinogenic PAH. PAHs are regulated in the Aarhus protocol on POPs (UN/ECE, 1998) and the EU air quality directive (EU, 2004). Several industrial sites and cities are imposed to monitor PAH in air since 2008.

PAHs consist of hydrogen and carbon arranged in the form of two or more fused benzene rings. PAH compounds differ in the number and position of aromatic rings and in the position of substituents on the basic ring system. PAH covers several hundred compounds with different properties. They are metabolised in living beings and thus hardly accumulate in food chains. Many different PAH-compounds have been studied thoroughly, while the effect of others is less known. PAHs appear in polluted air in the gas phase and bound to particles (PM). Samples from Øvre Årdal, Årdalstangen as well as Oslo collected in winter 1991 (January – March, see Hagen, 1991) were analysed separately for gaseous PAHs (polyurethane foam) and particle-bound PAHs (filters). Figure 1 shows how PAHs split between gaseous and particle-bound state. 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 long range transport. Heavier PAHs (> 5 benzene rings) are more attached to particles, and thereby less mobile and prone to be deposited close to source regions. Consequently, it appears likely that heavier PAHs are found in moss, while the lighter ones are collected by the air sampler (Halse et al., 2017). 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.

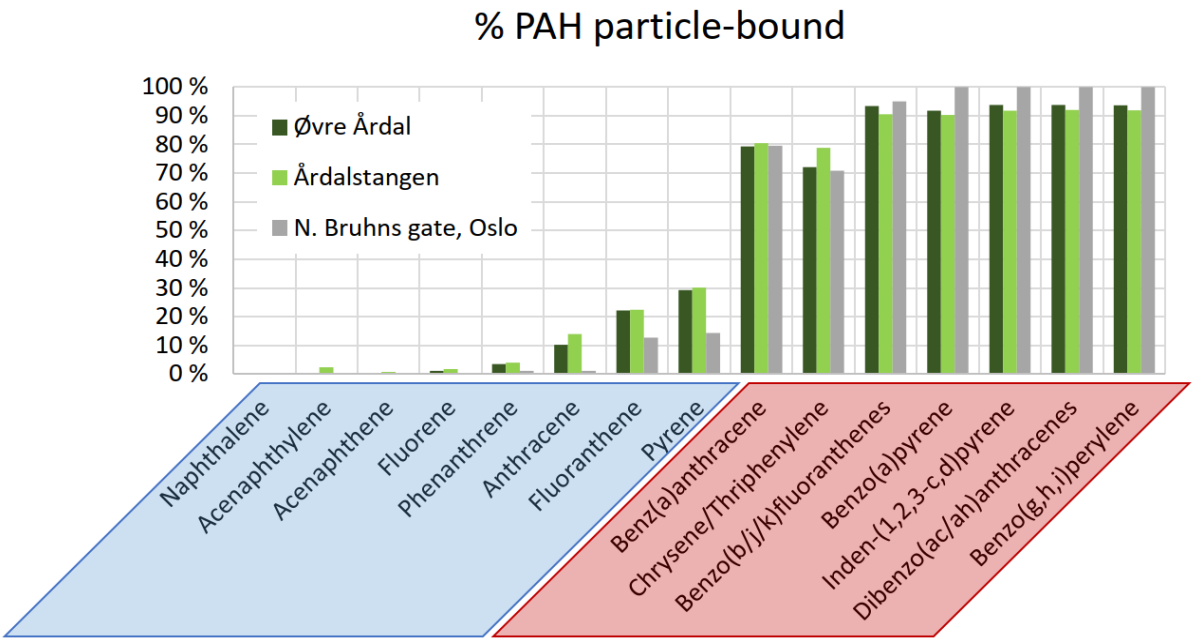


Figure 1: Split of 16 priority PAHs into mainly gaseous compounds (blue background) and mainly particle-bound compounds (red background). The height of the bars corresponds to the percentage of the compound concentration occurring in particle form. Data from measurement in Årdal and Oslo in winter 1991 (Hagen, 1991).

Environmental concern has focused on two-ring (naphthalene) to seven-ring (coronene) structures. Unsubstituted two- or three-ring PAHs are not carcinogenic but are the PAHs most commonly associated with acute toxicity. Four- to seven-ring unsubstituted PAHs are significantly less toxic than two- or three-ring PAHs, but some are carcinogenic, mutagenic or teratogenic to a variety of organisms, including fish and birds[4].

Particulate matter (PM)

Particulate matter (PM) is a complex mixture of microscopic particles in the air that can originate from a variety of natural and man-made sources. They can be formed by combustion reactions and mechanical wear, industry, resuspension by wind or formed directly in the atmosphere by condensation of gases.

Process emissions from metal production are the second most important source of airborne dust in Norway after wood burning[5]. In the aluminium industry, the production of anodes also leads to particulate emissions.

Particulate matter is divided into different classes according to particle size. The most common categories are PM_{10} – particles smaller than 10 µm and $PM_{2.5}$ – particles smaller than 2.5 µm (fine fraction). Particle size is considered to be a decisive factor for the health effects of particulate matter. Apart from the concentration and size of the dust particles, shape, surface properties and chemical composition are also important for health effects. Particulate matter has a very complex composition that varies greatly depending on which sources give rise to the particles. Combustion particles consist of soot or carbon cores. Particles can bind a number of different compounds to the surface, such as

[4] Ecological risk assessment for use of wet scrubbers at Alcoa Fjarðaál aluminium plant in Reyðarfjörður, Fjarðabyggð, Iceland, September 2005

[5] https://www.ssb.no/statbank/table/08942

metals, sulphur and nitrogen oxides, various gases, PAHs, endotoxin (bacterial component), mould fragments and allergens, which are probably of great importance for how harmful the dust is.

Exposure to airborne dust can contribute to aggravation of a number of respiratory diseases by activating inflammatory reactions in the lungs. Exposure to airborne dust also appears to cause acute effects on the cardiovascular system. The current limit values for air pollution are based on the weight concentration of PM_{10} and $PM_{2.5}$, and thus do not take into account the composition of the dust, with the exception of heavy metals.

Heavy metals

Heavy metals in ambient air are found as metallic elements or metal oxides that occur bound to particulate matter. There are many different sources that contribute to metal emissions, e.g. traffic, industry and other combustion processes. In primary aluminium production, heavy metals may originate both from contaminants in the alumina and from the anodes. Emissions of heavy metals from industry depend on both the amount produced and the content of heavy metals in the raw materials. The concentrations of heavy metals in the emissions to air are very low and therefore difficult to measure. Emissions from aluminium production are therefore calculated individually for each plant, based on emission volume.

High concentrations of metals in the air have been shown to cause undesirable health effects when inhaled (Norwegian Institute of Public Health). Metals in air can also be deposited in soil and taken up in plants. Intake through food will thus also lead to increased uptake in humans. Combustion particles often contain water-soluble metals (zinc Zn, arsenic As, vanadium V, nickel Ni). These have been linked to inflammatory reactions. For lead (Pb), arsenic (As), cadmium (Cd) and nickel (Ni), limit or target values have been set to protect human health. The concentrations of arsenic, cadmium and nickel are assessed on the basis of the total content in the PM_{10} fraction, as an average over a calendar year ("forurensningsforskriften"[6]; WHO, 2000). For manganese (Mn) and vanadium (V), air quality criteria[7] are set to prevent harm to human health.

Lead (Pb): Vehicle traffic used to be the dominant source of lead in urban areas, as it was used as an additive to petrol. In recent years, the use of lead in petrol has been phased out, and this is no longer an important source. Industrial sources of lead (Pb) include battery production and secondary metal smelting. Lead is a serious environmental toxin. Exposure to lead can affect the heart, nervous system and immune system. It is not assumed that there are health effects with current concentrations in air in Norway, but because the substance accumulates in organisms and food chains, previously high emissions of the substance represent a health hazard.

Arsenic (As): Sources of arsenic in air are volcanic eruptions, bacterial degradation of arsenic compounds, impregnation of wood, tobacco, fossil fuels and industry. The most serious health consequence is the development of lung cancer and the air quality criterion (see Table 1) is determined on the basis of this.

Emission sources for arsenic are metal smelters and power plants that burn arsenic-rich coal. Arsenic is a carcinogen for humans, which after inhalation in particular can affect the lungs. There are organic and inorganic arsenic compounds in the environment. Inorganic arsenic compounds (arsenate) are highly acute and chronically toxic to most organisms, where even small concentrations can cause cancer. Organic arsenic compounds, on the other hand, are far less toxic. The National Institute of Public Health and the Norwegian Environment Agency has set an air quality criterion for arsenic of 2 ng/m^3 as an annual average value. The WHO cannot recommend a safe level of exposure to arsenic by inhalation, if a linear dose-effect ratio is assumed (WHO, 2000).

[6] https://lovdata.no/dokument/SF/forskrift/2004-06-01-931/kap7#kap7 (in Norwegian)
[7] https://www.fhi.no/nettpub/luftkvalitet/ (in Norwegian)

Cadmium (Cd): Cadmium has mainly industrial sources, especially metal industry. Total emissions in Norway correspond approximately the amount that comes via long-distance transport pollution. Exposure to cadmium in ambient air is through particulate matter and tobacco smoke (Norwegian Institute of Public Health). The largest intake, however, is via water and food. Cadmium may have effects on the respiratory system and long-term exposure may cause lung cancer. Direct inhalation of cadmium in ambient air is generally not considered a health problem, but precipitation can cause accumulation in soil and increased intake through food which in turn can cause kidney and skeletal damage. On this background an air quality criterion of 2.5 ng/m^3 is set, which is stricter than the target value in the Directive. The air quality criteria are not legally binding.

It is classified as a carcinogen for humans (group I), i.e. that there is sufficient evidence of carcinogenicity in humans. 50% of the inhaled cadmium is taken up and concentrated. Cadmium is excreted very slowly and there is a build-up of cadmium levels in the body throughout a lifetime. Exposure to cadmium in the working environment, as well as experimental studies, have shown an increased risk of developing lung cancer. In addition, high intake of cadmium can lead to impaired kidney function.

Nickel (Ni): Industry and the combustion of oil and coal are the main sources of nickel. Nickel is a harmful substance typical of heavily industrialised areas and larger cities. Exposure may pose a risk of developing cancer of the lungs, nose and throat and an air quality criterion of 10 ng/m^3 has been set based on this. In practice, the greatest health significance is through air intake in the work environment and through cigarette smoke. Nickel compounds are carcinogenic to humans by inhalation. They affect the airways.

Mercury (Hg): Mercury occurs in various chemical forms, such as inorganic mercury and methylmercury. Depending on the chemical form, the ability of mercury to trigger damage in different organs also varies. Important sources of mercury emissions to air are crematoria, waste incineration, metal industry and other combustion processes. Since mercury accumulates in food chains, the WHO considers it important to keep the air pollution of mercury as low as possible to prevent possible health effects in the near future. Mercury causes kidney damage and is harmful to the nervous system and can cause cell changes.

Chromium (Cr): Chromium occurs naturally in the earth's crust in large quantities. Most common is 3-valent chromium (Cr III). A certain intake of chromium through food is necessary and contributes to the energy metabolism in the body, but too large quantities can be harmful. 6-valent chromium (Cr VI) will be converted to Cr III chromium in the body, but this transformation is harmful and can cause damage to the kidneys, liver, skin, respiratory tract and can lead to cancer. Therefore, an air quality criterion for Cr VI of 0.1 ng/m^3 has been set. The share of Cr VI is usually not analysed.

1.2 Air quality guidelines and limit values

Humans can be adversely affected by exposure to air pollutants in ambient air. National and international limit and guideline values and air quality objectives have therefore been established for a number of pollutants present in the air. The limit, threshold and guideline values for compounds relevant for aluminium production are summarised in Table 1. They apply over differing periods of time because the observed health impacts associated with the various pollutants occur over different exposure times. Norwegian limit and target[8] values are equal to EU limit and target values (except for PM where Norway has stricter limit values). Limit values (as defined in Forurensningsforskriften and EU air quality directives) are legally binding. In case of exceedances, authorities must develop and

[8] Target values are set out in the same way as limit values. They are to be attained where possible by taking all necessary measures not entailing disproportionate costs.

implement air quality management plans which should aim to bring concentrations of air pollutants to levels below the limit and target values.

The World Health Organisation's (WHO) guideline values are set for the protection of health, and are generally stricter than the comparable politically agreed EU standards. Air quality criteria[9] are adopted by the Norwegian Environment Agency and the Institute of Public Health. They are stricter than the limit and target values. The air quality criteria are based on existing knowledge about the potential effects of exposure to air pollution. The criteria are set at a level that most people can be exposed to without experiencing harmful health effects. Guideline values and air quality criteria are recommendations.

Table 1: National limit/target values and air quality guidelines for compounds related to aluminium production. Note that Norwegian national limit values for particulate matter (defined in forurensningsforskriften FF) are stricter than EU limit values defined in the Air Quality Directive (AQD).

Compound	Averaging period	Limit value (FF[10])	WHO Air Quality Guidelines	Air quality criterion (LKK[11])
Particulate matter (PM)				
PM_{10}	Day (24 hours)	50 µg/m^3 (max. 25 exceedances) (AQD: max. 35 exceedances)	50 µg/m^3	30 µg/m^3
	Calendar year	20 µg/m^3 (AQD: 40 µg/m^3)	20 µg/m^3	20 µg/m^3
$PM_{2.5}$	Day (24 hours)	-	25 µg/m^3 (99th percentile)	15 µg/m^3
	Calendar year	10 µg/m^3 (AQD: 25 µg/m^3)	10 µg/m^3	8 µg/m^3
Sulphur dioxide (SO_2)				
SO_2	10 min		500 µg/m^3	
	15 min			300 µg/m^3
	1 hour	350 µg/m^3 (not to be exceeded more than 24 times per calendar year)		
	Day (24 hours)	125 µg/m^3 (not to be exceeded more than 3 times per calendar year)	40 µg/m^3	20 µg/m^3

[9] Luftkvalitetskriterier. https://www.fhi.no/nettpub/luftkvalitet/

[10] FF: Forurensningsforskriften (Norwegian air quality regulation, embedding European air quality limit values). URL: https://lovdata.no/dokument/SF/forskrift/2004-06-01-931/KAPITTEL_3-1#KAPITTEL_3-1

[11] LKK: Luftkvalitetskriterier (Air quality criteria, set by Norwegian institute of public health and Norwegian environment agency). URL: https://www.fhi.no/globalassets/dokumenterfiler/rapporter/2013/luftkvalitetskriterier---virkninger-av-luftforurensning-pa-helse-pdf.pdf

Compound	Averaging period	Limit value (FF[10])	WHO Air Quality Guidelines	Air quality criterion (LKK[11])
	Winter period 1.Oct – 31.March (ecosystem)	20 µg/m^3		
	Calendar year	20 µg/m^3		
Metals				
Arsenic (As) in PM_{10}	Calendar year	Target value 6 ng/m^3		2 ng/m^3
Lead (Pb) in PM_{10}	Calendar year	Limit value 0.5 µg/m^3		0.1 µg/m^3
Cadmium (Cd) in PM_{10}	Calendar year	Target value 5 ng/m^3		2.5 ng/m^3
Chromium (Cr) Cr VI	Calendar year			0.1 ng/m^3
Manganese (Mn)	Calendar year			0.15 µg/m^3
Nickel (Ni) in PM_{10}	Calendar year	Target value 20 ng/m^3		10 ng/m^3
Vanadium (V)	Day, 24 hours		1 µg/m^3	0.2 µg/m^3
Polycyclic aromatic hydrocarbons (PAHs)				
BaP in PM_{10}	Calendar year	Target value 1 ng/m^3		0.1 ng/m^3

The limit values for particulate matter in Norway (FF) have been revised twice (2016 and 2022) and are stricter than limit values defined in the EU air quality directive.

There are no EU limit values, recommendations or air quality criteria for fluorides today. In previous recommendations for fluoride levels in ambient air, a limit was set at 1 µg/m^3 (total fluoride) as annual average, to protect plants and crops (WHO, 2000). This concentration was also considered more than adequate to protect human health. WHO currently has no recommendations for air quality guidelines for fluorides based on available information from exposure studies. In the 1980s, two limit values for total fluoride (gaseous and particulate), taking into account human health, were in force in Norway: 25 µg/m^3 for daily averages and 10 µg/m^3 for six month averages (SFT, 1982). SFT's recommended air quality criteria for gaseous fluoride earlier were set for protection of animals and vegetation (SFT, 1992), 1.0 µg/m^3 as average over 24 hours, 0.4 µg/m^3 as average over 30 days and 0.3 µg/m^3 as average over 6 months. The criterion for animals was at 0.15 µg/m^3 averaged over 30 days.

The Norwegian Institute of Public Health (FHI) has set an air quality criterion for 24 hour averages of SO_2 (20 µg/m^3) which is based on studies of health effects of low concentrations in larger population groups, and a 15-min criterion (300 µg/m^3) based on clinical studies of asthmatics. WHO (WHO, 2021) has recently revised its recommendations and increased the recommendation for SO_2 from 20 µg/m^3 to 40 µg/m^3 based on the latest research.

Although there are some hints for toxic effects of aluminium, especially in the respiratory tract and nervous system, the knowledge of exposure condition is so incomplete that FHI has chosen not to set air quality criteria for aluminium. Most studies, however, suggest that high concentrations of aluminium are needed before triggering health effects. This may indicate that the air quality criteria

for particulate matter also will protect against health effects of aluminium. It is in accordance with international assessments not to set an air quality criterion for aluminium (FHI, 2013).

For PAH, there is no limit value. The EU has set a target value for benzo(a)pyrene, which is one of the compounds of PAH (see Table 1). There is an air quality criterion for benzo(a)pyrene (BaP) as an indicator for carcinogenic effects of PAHs. The Norwegian air quality criterion is 0.1 ng/m^3 as annual average concentration. PAHs are regulated in the Aarhus protocol on POPs (UN/ECE, 1998) and the EU air quality directive (EU, 2004).

Within the premises of industries, the Limit values[12] for pollutants in the work atmosphere (former "Administrative norm") given by the Norwegian Labour Inspection Authority (Arbeidstilsynet) apply. The limit value for particulate PAHs collected on filters, based on the sum of 21 given[13] particulate PAH-compounds is 0.04 mg/m^3 (equal to 40 µg/m^3).

1.3 Challenges

There are several challenges connected to assessing the air quality from measurement and modelling studies and comparing the results of individual studies. A main challenge is that not many studies are available. Most measurement studies are older than 10 years and many of the studies have been carried out before the most recent technological conversions.

If several measurement studies of the same compound exist, it is desired to compare their results. However, several parameters need to be considered:

- It needs to be considered where the measurements were carried out in relation to the plant, in which season measurements were carried out and which wind directions are most common in the course of a calendar year. Comparisons to previous studies have added uncertainty when the measurement site has been moved.
- It also needs to be considered in which season measurements were carried out. Many measurement studies only cover a few months and are not representative for an entire calendar year. Meteorological conditions in the season measurements were carried out, may be more or less typical for the average season, which also influences the representativeness of the measurement results. The meteorological conditions/prevailing wind direction change in the course of a year.
- It needs to be considered which measurement or sampling method was used. Comparisons to previous studies have added uncertainty when the measurement or sampling method was changed. For several compounds/compound groups relevant in connection with emissions from aluminium industries, the composition of the reported parameter may vary. While fluorides are separated into gaseous and particulate fluorides in some studies, other studies report total fluorides. For PAHs, it is often uncertain which compounds are included in "sum PAH". Since analysis capabilities have been improved over the years, "sum PAH" included 33 compounds in the 1990s, while it includes over 45 compounds today. In modelling studies, it is often not specified which compounds are included in the term "PAHs".
- It needs to be considered which sampling frequency and sampling duration (for each individual sample) was used. Comparisons to previous studies have added uncertainty when there are differences in the sampling frequency. As the concentrations of air pollutants can vary greatly from day to day both due to variations in the emissions and in the meteorological conditions (wind direction, wind speed, stability), the average values become

[12] https://lovdata.no/dokument/SF/forskrift/2011-12-06-1358

[13] Limit values for pollutants in the work atmosphere:
https://www.arbeidstilsynet.no/regelverk/forskrifter/forskrift-om-tiltaks--og-grenseverdier/

somewhat uncertain, and it can be difficult to give a correct assessment of the change in the ambient concentrations from one period to another.

The results of measurement and modelling studies may not always be relevant to compare. Measurements are carried out at a defined site. Modelling results are often reported as worst case scenarios and may indicate a maximum concentration somewhere in the modelling domain. To find out whether the comparison of measurement results with modelling results is feasible, the assumptions the model calculations are based on need to be considered carefully.

Differences between smelters with regard to production technologies and capacities, as well as location/topography, must be considered, such that results observed at one smelter location may not be directly applicable to other smelter locations.

1.4 Aluminium smelters

This report focuses on concentrations of pollutants in ambient air around 10 aluminium smelters located in Norway, Iceland and Sweden. The plants are described in the following subsections.

1.4.1 Alcoa Fjarðaál

Location and physical geography

The aluminium plant lies in the Hraun industrial area at the north shore of Reyðarfjörður at the East coast of Iceland. The area is fairly open, but the fjord is surrounded by up to 1000 m high mountains. The land surface is mainly an old lava field with sparse vegetation. Hraun was chosen mainly with regard to air dispersion, as meteorological readings had shown that air dispersion conditions there were better than at Leirur at the end of the fjord.

Figure 2: Alcoa Fjarðaál at Reyðarfjörður. (Left): View towards west. (Right): Map over Reyðarfjörður.

The climate is windy, humid and cool, with monthly averages of around 10°C in the summer and 1-2°C in winter. The mountains around the fjord channel the wind in easterly and westerly directions, and in summer it can fluctuate in direction due to land-sea-breeze effect[14].

[14] Sea breeze effect: The solar heating causes the air in the valley to heat up and rise. Cooler air is drawn in from the fjord. This sets up an air flow up the valley, which is most developed in the middle of the day and in the afternoon. On clear nights, strong cooling of the air near the ground can set up a light wind out of the valley.

Habitation, occupation and business

The smelter lies in the Fjarðabyggð municipality, where the largest communities are Neskaupstaður, Reyðarfjörður and Eskifjörður, each with 1000 – 1400 inhabitants. The total population is 5100. The smelter is the dominating industry and employer in the area, some of which are also commuting from the county capital Egilstadir and other locations. Fishing and small scale farming, mainly sheep, are other occupations.

Production and emissions

The development of the Fjarðaál smelter came in parallel with the Kárahnjúkar hydroelectric power plant, and the first pots were started in April 2007. The production from the two potrooms quickly rose to the present level of about 350 000 tonnes per year. Production and emissions are illustrated and discussed in Section 2.

Náttúrustofa Austurlands has been monitoring the impact of the smelter on the environment[15] since 2006, covering the pollutants associated with aluminium production. Baseline measurements were carried out in the area in the years 2004 – 2006, before the operation of the smelter began and monitoring has continued every year since then. Measurements of air quality parameters are carried out at four permanent monitoring stations around the smelter and cover pollutants associated with the smelter: particulate matter (PM_{10}), fluoride (gaseous and particulate), and sulphur dioxide and particle-bound PAHs. Fluorine and sulphur dioxide measurements are automated and averages are recorded every ten minutes. Fluorine is also collected on filters, 1 and 5 days at a time, to measure particle-bound and gaseous fluorine. Particulate matter is collected every 6 days on filters, 24 hours a day to analyse fluoride in dust and PAH compounds (48 samples per year). The stations are distributed as shown in Figure 3. Station 1 is at Hjallaleira at the western end of the fjord Reyðarfjörður, station 2 is at the old landfill at Ljósá between the town Reyðarfjörður and the smelter, station 3 is in Hólmar east of the smelter and station 4 is at the opposite side of the fjord south of the smelter.

[15] The environmental monitoring covers air quality and meteorological measurements, chemical measurements of vegetation, chemical measurements of surface water, visual assessment of plant health, measurement of pine tree growth, visual inspection of livestock and chemical analysis and visual assessment of sheeps' jaws, and pollutants in the sea/ at the shore.

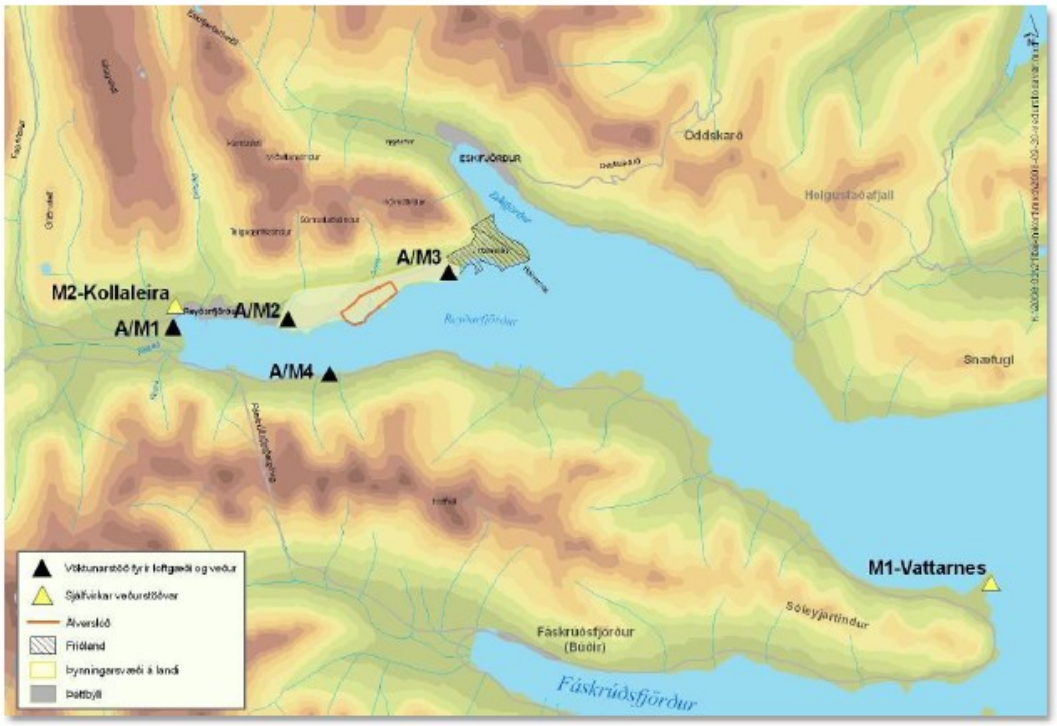


Figure 3: Location of the four permanent air quality monitoring stations around Alcoa Fjarðaál and Reyðarfjörður. Source: Alcoa (2011)

1.4.2 Alcoa Lista

Location and physical geography

Alcoa Lista is located in the Farsund municipality in the Agder County in the very south of Norway. The surrounding area is characterised by flat terrain with a generally high wind exposure and good dispersion conditions so that emissions can be dispersed over larger areas. The prevailing wind direction is from north-west during much of the year. This will generally carry airborne pollutants seawards.

Figure 4: Alcoa Lista at Farsund. (Left): View towards southwest and the North Sea. (Right): Map over Farsund.

The climate is mild and humid, with a mean annual temperature of +7.6°C and annual precipitation of approximately 1050 mm.

The areas towards east are barren, low hills with sparse vegetation. Towards south-east, there is a small forest between the plant and the Lomsesanden Beach. The aluminium plant is close to the Husebysanden beach towards south-west. Towards west and north-west, there is mixed agricultural land with patches of forest and some built-up areas. A school and a pre-school are located in this area. To the north, there is a harbour area in Lundevågen.

Habitation, occupation and business

The municipality has a population of nearly 9 800, whereof one-third are living in the town Farsund. The aluminium plant employs about 265 in addition to some regular maintenance contractors. It is the largest industrial workplace in the municipality. It delivers raw materials to Aludyne, an aluminium casting plant and previously an integrated part of Alcoa. About one-third of the workforce in the municipality work in industry sector.

Production and emissions

The aluminium plant was established in 1971 and was the last in Norway to be built with Söderberg technology. Specific to Söderberg is that the anode is baked in operation and PAHs evaporate from the anode top. The plant has three pot rooms with a total production capacity of about 94 000 tonnes p.a. This is an increase of about 17% since 1992. In addition, scrap aluminium and purchased metal are remelted and upgraded.

Alcoa has upgraded the Söderberg technology to reduce environmental emissions while production results are comparable to what is achieved with prebake-technology. At traditional Söderberg, the anode top is open. New Söderberg technology involves closing the anode tops to reduce emission of process gases, point feeders for oxide and fluoride, modified paste recipe, etc. With regard to furnace operation, the addition of oxide was changed from large additions a few times a day, when the oven was opened, implicating emissions of process gases and dust, to a closed system with small frequent additions via point feeders. The potline has three separate gas treatment systems: One for the pot off-gas (dry scrubber + seawater scrubber), one for anode off-gas (dry scrubber) and one for potroom ventilation (seawater scrubbers). All cells have been upgraded with a closed point feeding system (alumina is fed continuously in closed systems), which has increased the capacity and reduced greenhouse gas emissions. An improved pot gas collection system collects gases such as PAHs and fluorine and dust from aluminium production with closed ovens/furnaces, so that they do not escape into the oven hall or into the atmosphere. Anode gases are collected and sent via treatment plants. Point feeding and improvements at the gas treatment plants have resulted in a large reduction in emissions of PAHs, fluorides and dust. The technological improvements provide a better working environment, reduced emissions and keeps high productivity. The development of New Söderberg was done in the 1990s. A large part of the transition was completed in 2000. Closing of anode tops and treatment plants were completed in 2006 – 2007.

Upgrade to New Söderberg:

- March 1995: Anode top covers with associated treatment plant in entire hall 3 (closing upper part of the ovens)
- December 1996: Point feeders in entire hall 3 (closing lower part of the ovens)
- 1999: Point feeders in hall 2
- 2000: Point feeders in hall 1

- 2006: Anode top covers in hall 2
- 2007: Anode top covers in hall 1

The development in production and emissions from 1992 to 2020 is discussed and illustrated in Section 2.

Measurements have been carried out at Huseby (1 km northwest of the smelter) in all measurement studies (Hagen, 1991; Hagen, 2002; Hak, 2021b). In 2020, Hanangermona was selected as additional site located 4 km west of the smelter towards Vanse (Hak, 2021b).

1.4.3 Alcoa Mosjøen

Location and physical geography

The aluminium plant lies directly north of Mosjøen centre (in the south of Nordland, Norway), at the mouth of the Vefsna and Skjerva rivers into Vefsnfjord. Vefsndalen valley is a long, relatively open valley flanked on both sides by mountains about 800-1000 meters high. Further down the Vefsnfjord, there are mountains 600-800 meters high in the west and north, while the hills to the east, facing Fustvatnet, are lower. There are conifer forests along the Vefsndalen valley, while vegetation is sparse further down the fjord and on the steepest mountain sides.

Figure 5: Alcoa Mosjøen. (Left): View towards south, with the city south of the smelter. (Right): Map over Mosjøen.

The prevailing wind is up the valley in the summer and during the day, while there is often a wind from the land in winter and at night. The wind distribution frequency shows that it blows much more often from the emission source towards built-up area in Mosjøen in the summer[16] season than in the winter season (Tønnesen, 2007).

[16] Meteorological measurements in Mosjøen were carried out in summer 1967 to assess stability conditions in the area (Sivertsen, 1967).

Habitation, occupation and business

Vefsn municipality has ca. 13 400 inhabitants, most of them living in Mosjøen itself. The aluminium plant is the major industry in the municipality since the sawmill and the weaving mill were closed down around 2008/09. In addition, there is some mechanical industry and some mining.

Forestry is also important, and there is some farming based on sheep, cattle and some poultry. There are a few fishermen living in the municipality, and the Vefsna is an important salmon river and tourist attraction.

Production and emissions

The aluminium plant started in 1958 with an annual production of 25 000 tonnes. “Mosal”, as the plant in Mosjøen was originally called, was based on Söderberg technology, but in 1987-89 half of the oven fleet (two lines) was converted to prebake technology. In 2001-02, the rest of the ovens were converted to prebake, and the number of pots was increased from 332 to a total of 404. Today, the plant consists of four potrooms, all prebake, with a total capacity of nearly 200 000 tonnes per year. A new, large anode plant was completed in 2008, with a capacity of 300 000 tonnes of baked anodes per year. The anode plant supplies anodes to Alcoa Mosjøen smelter and Alcoa Fjarðaál in Iceland.

The development in production and emissions from 1992 to 2020 is discussed and illustrated in Section 2.

Over the years, measurements were carried out at different sites. In the 1970s, SO_2 was measured at Mosjøen gymnas, Mosjøen kino and Olderskog skole (Hagen, 1978; Hagen, 1977). These measuring points were located further from the plant than the later measuring point in Finnskoggata (2004). Mosjøen gymnas was the nearest measuring station and also closest to Finnskoggata. Measurements (PM, F, PAH) in the beginning of the 1980s (Thrane, 1983b; Thrane, 1983a) and PAH measurements in the beginning of the 1990s were carried out in a residential area 500 m south of the aluminium smelter. The measurement station was located so that it is more exposed in summer than in winter, as wind is blowing down the valley in winter. Fluoride and SO_2 were measured at Finnskoggata in 2004 (Hagen, 2005), just south and in the main wind direction from the aluminium plant. The station is assumed to be little exposed to emissions from vehicle traffic and possible wood burning. The most recent measurements in 2009 (Haugsbakk, 2010) were carried out at Helgelandskraft, ca. 1 km south of Finnskoggata.

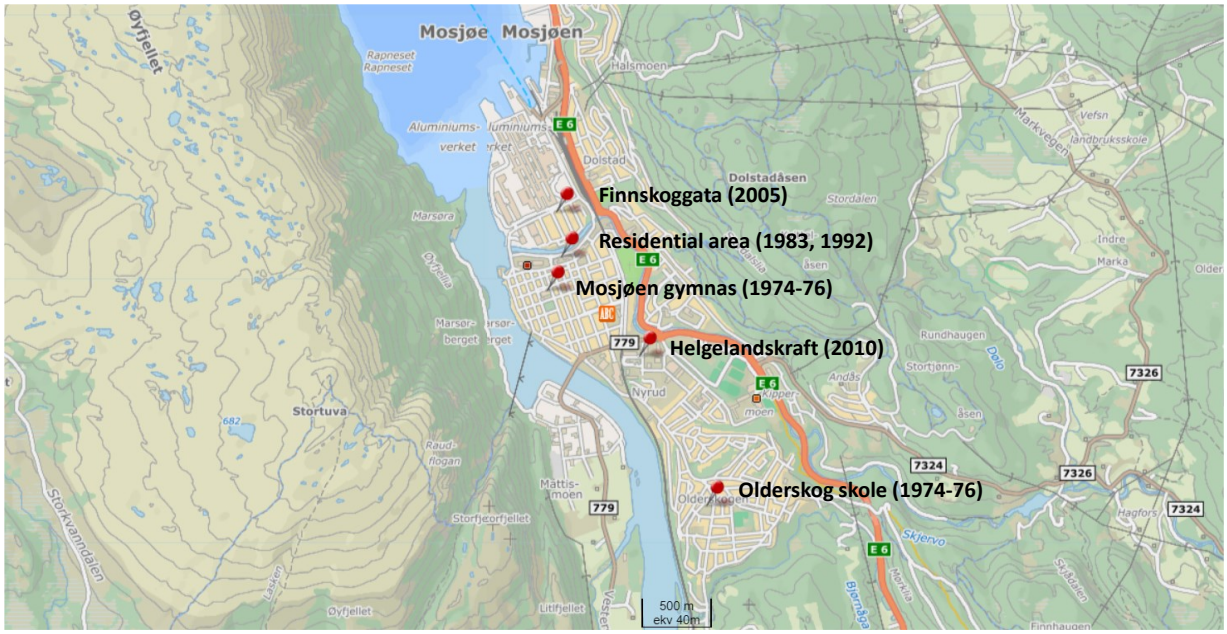


Figure 6: Overview map for sites in the surroundings of the aluminium plant used for sampling in different years.

1.4.4 Hydro Husnes

Location and physical geography

Hydro Husnes is located at an isthmus between the bay Husnesvågen and the lake Opsangervatnet, at the mouth of the Hardangerfjord in western Norway. The area is relatively open, but directly to the east of the aluminium plant lies a mountainous area with peaks up to 1000 m high. A golf course separates the plant from the nearest residential areas west of the plant. North and west of the plant is the Hardangerfjord. The mountains affect the wind directions, which are mainly north-south. A northerly wind prevails in spring, and a southerly wind the rest of the year as a rule. The area has a mild coastal climate, with relatively high precipitation.

Figure 7: Hydro Husnes at Hardangerfjord. (Left): View towards northwest and Hardangerfjord. (Right): Map over Husnes.

Habitation, occupation and business

Kvinnherad municipality has approximately 13 000 inhabitants, about 2 200 of whom live at Husnes. About 350 people are employed at the smelter; in addition there are a number of contractors working there. Other businesses are mechanical engineering, shipping, food processing, aquaculture and tourism. There is limited agriculture at Husnes.

Production and emissions

The plant started up in 1965 under the name Sør-Norge Aluminium (Søral) with Alusuisse as majority owner. Hydro Aluminium later came in as a part-owner, and since 2014 as sole owner. The plant originally had two potrooms, both prebake. Potroom B was temporarily shut down in 2009 as a result of the financial crisis, but a decision to reconstruct it was taken in 2018, restarting in 2020. Production capacity is 94 000 tonnes p.a., which will increase to 195 000 tonnes when potroom B is in full production. The plant does not have its own anode plant; anodes are purchased elsewhere.

The development in production and emissions from 1992 to 2020 is discussed and illustrated in Section 2.

1.4.5 Hydro Høyanger

Location and physical geography

The Hydro Høyanger plant is located in the little town of Høyanger in western Norway, at the head of the Høyangsfjord, which is a small branch of the Sognefjord. Høyanger is located in a narrow U-shaped valley which extends about 15 km north-eastwards from Høyanger. The surrounding mountains reach heights of 800-1 400 m

Figure 8: Hydro Høyanger. (Left): View towards northeast into Dalsdalen. (Right): Map over Høyangsfjorden.

For much of the year, the prevailing wind direction is up the valley, but in summer there is often an easterly morning breeze blowing down the fjord. In winter, wind usually blows down the valley. The prevailing wind directions in the Sognefjord are east-west, and this often leads to pollutants accumulating in the Høyangsfjord area, and being swept back up the valley in the evening.

Habitation, occupation and business

There are about 4 100 inhabitants in Høyanger municipality, 2 200 of them in Høyanger itself. The aluminium plant represents the main industry. The place was originally a small community with about 150 inhabitants whose chief livelihood was farming. Since the agricultural areas have largely been turned over to industrial uses and housing, there is limited farming in the area today.

Production and emissions

The Høyanger plant started up in 1916 with carbide production and in 1917 aluminium production commenced. The plant today has one prebake potline (built in 1981). The last Söderberg line was closed in 2006. Anodes are mainly imported from Årdal.

The development in production and emissions from 1992 to 2020 is discussed and illustrated in Section 2.

The location of the measurement station in Høyanger was unchanged for PAH measurements in the beginning of the 1980s, winter 1991 and winter 2002. Measurements were carried out in the town, ca. 500 m northeast of the smelter (see, e.g., Hagen, 2002). At Høyanger, the wind is usually down the valley in winter, i.e. the measuring station is little exposed to the emissions from the plant in winter.

1.4.6 Hydro Karmøy

Location and physical geography

Hydro Karmøy is located at Karmsundet, the sound at the east side of Karmøy island in the southwest of Norway. The surrounding area consists of a flat or slightly undulating coastal landscape dominated by farmland, low hills and heather-covered slopes.

Figure 9: Hydro Karmøy. (Left): View towards east and over Karmsundet. (Right): Map over the area.

The climate is mild, windy and humid. The prevailing wind is from the north-west in spring and summer. In autumn and winter, the wind direction is more variable, but it tends to be easterly or southerly. The flat terrain and wind cause emissions to disperse rapidly, so that the area affected is relatively small. Dispersion conditions are usually good at Karmøy.

Habitation, occupation and business

The population of Karmøy municipality is about 42 000. The population is distributed among a number of communities, the administrative centre of Kopervik, ca. 3 km south of the plant, being the largest. The town Haugesund, which is a separate municipality on the mainland, lies 8-9 km north of the plant.

The main occupations are industry, shipping, fishing and trading. The aluminium plant is the main industrial employer. There are also many small and medium sized farms in the municipality.

Production and emissions

Hydro Karmøy was started in 1967 as an integrated plant with reduction plant, cast house, rolling mill and extrusion plant. The reduction capacity was initially 80 000 tonnes p.a., based on Söderberg technology. This was expanded to 110 000 tonnes p.a. in 1972. Since then, a prebake line was built in three construction stages in 1982, 1987 and 1997. After the fourth expansion in 1987, the annual production at Hydro Karmøy reached 220 000 tonnes. The total capacity reached 290 000 tonnes per year in 2008, before the Söderberg lines were shut down in 2009. Therewith, the last electrolysis cells using Söderberg technology in Hydro was shut down.

In 2018, a new potline with a capacity of 75 000 tonnes per year came in production. This is a full-scale pilot stage applying the latest technologies, and is prepared for further expansion up to 330 000 tonnes per year, three times as much as the previous Söderberg lines on the same physical footprint. This could bring total production up to 530 000 tonnes per year, the largest smelter in Northern Europe.

Dry and wet scrubbers are used to treat the off-gases from the pots.

The development in production and emissions from 1992 to 2020 is discussed and illustrated in Section 2.

The measurement station for PAH sampling in 1991 and 2002 was located close to the southern end of the smelter, near Austevikvegen (see Hagen, 1991; Hagen, 2002).

1.4.7 Hydro Sunndal

Location and physical geography

The Sunndal plant lies at Sunndalsøra in the northern part of Southern Norway, at the mouth of the Driva river into the Sunndalsfjord. The Sunndal valley is a long, deep, U-shaped valley, flanked on both sides by 1500 – 1800 m high mountains as illustrated in Figure 10. The prevailing wind direction driven by the sea breeze is up the valley in summer and during daytime, and down the valley in winter and at night-time. The topographic conditions around Sunndalsøra provide somewhat complicated dispersion conditions. Wind direction and speed can vary from one location to another within a short distance. To the south, there is a narrow valley, Litledalen. Sunndalen and Litledalen open out into the Sunndalsfjord. Wind coming into the fjord from the north will transport emissions from Hydro Aluminium Sunndal into Sunndalen in a south-easterly direction, while drainage winds down Sunndalen will transport the emissions out into the fjord, where the dispersion conditions also are influenced by wind coming down Litledalen.

Figure 10: Hydro Sunndal at Sunndalsøra. (Left): View from Sunndalsfjord towards southeast into the valley. (Right): Map over Sunndalsøra.

Habitation, occupation and business

The municipality Sunndal has a population of about 7100, whereof nearly 60% are living at Sunndalsøra. The aluminium plant employs about 700 and is the largest industrial workplace in the municipality.

There is extensive agriculture in the flat valley between Sunndalsøra and Gjøra, some 30 km southeast of Sunndalsøra. Grain and potatoes are the main products, but a substantial amount of livestock is also kept, for both meat and milk production. Due to risk of fluorosis, milk production was earlier restricted in the lower parts of the valley, but these restrictions were lifted since 2000.

Production and emissions

The Sunndal plant started up in 1954 with one potline (SU1), and the next (SU2) commenced operations in 1958. Both these potlines were based on Söderberg technology. In 1968, SU3 was started, based on prebake technology. Another expansion came in 2002-04, when a new prebake line (SU4) gradually replaced SU1 and SU2. Following the financial crisis, SU3 was temporarily closed in 2009 and gradually restarted in 2011-15. Increased amperage over the years has also resulted in increased output, up to a total of 409 000 tonnes per year in 2020.

The Sunndal plant also has a production of about 80 000 tonnes of anodes per year, covering about 40% of the anode consumption in the potlines. The remaining amounts of anodes are imported.

- 1954 Sunndal plant started up with one potline (SU1)
- 1958 The next potline (SU2) commenced operations. Both SU1 and SU2 were based on Söderberg technology
- 1968 SU3 was started, based on prebake technology
- 1969 Production capacity was doubled to 120 000 tonnes when the modern prebake plant (SU3) with 168 cells became operational
- 2002 Söderberg plant with 300 electrolytic cells was operational until 2002. The last Söderberg oven was shut down in the end of 2002

- 2002-04 Another expansion in 2002-04, modernisation, when a new prebake line (SU4, 340 cells) gradually replaced SU1 and SU2[17]. In connection with the expansion, three treatment plants were built for the recovery of fluorine from the new electrolysis plant SU4. The old treatment plants for SU3 were replaced by a new facility.
- 2009 SU3 was temporarily closed following the financial crisis
- 2011-15 SU3 gradually restarted

The development in production and emissions from 1992 to 2020 is discussed and illustrated in Section 2.

Measurement stations in central Sunndalsøra were located at Pensjonistsenteret (Hagen, 2003; Hagen, 2006; Hak, 2021a). Measurements in the 1990s were carried out 50 m from the original measurement site from the 1980s, as the original measurement site (which is not named in detail in the reports) has been built up. The measurement site at Pensjonistsenteret (and the built-up area) is located so that it is less exposed to emissions in winter than in summer, because wind blows usually down the valley in winter. In the latest studies (Hagen, 2003; Hagen, 2006; Hak, 2021a), measurements were also carried out 6 km up the valley, at Vennevold.

1.4.8 Hydro Årdal

Location and physical geography

The Hydro Årdal facilities comprise a primary metal smelter at Øvre Årdal (left picture), at the inlet to the lake Årdalsvatnet, and anode production facilities at Årdalstangen at the head of the Årdalsfjord. The distance between the two plants is about 12 km.

[17] In connection with the modernisation and expansion of production at Hydro Aluminium Sunndal in the period 2001 – 2004, three treatment plants were built for the recovery of fluorine from the new electrolysis plant Su4. Furthermore, a new plant was built to replace the almost thirty-year-old treatment plants for the electrolysis plant Su3. Increased aluminium production also required expanded cleaning capacity. All four treatment plants have been expanded in 2008 to bring the emission of fluoride to air below the authorities' requirements of 12 kg/h on an annual basis and 14 kg/h on a monthly basis.

Figure 11: Hydro Årdal and Årdalstangen. (Left, upper): Hydro Årdal, towards east-southeast. (Left, lower): Årdalstangen, with Årdalsvatnet in the background. (Right): Map over area around Årdalsvatnet. The blue areas in Øvre Årdal and Årdalstangen show the locations of the plants.

The topographical conditions in Øvre Årdal are complicated. The plant lies in a narrow valley surrounded by high mountains. At Øvre Årdal, the valley branches into the Moadalen, Utladalen, Fardalen and Nundalen valleys. Wind blowing up and down the valley occur with roughly the same frequency. There is little difference between winter and summer in this respect. The climate is relatively dry, and similar to an inland climate, with warm summers and cold winters. In Årdal, the sea breeze effect is of great importance in summer, giving a high frequency of wind up the valley (and into Utladalen and Moadalen) during the day. Drainage wind down the valley at night transports the emissions over Årdalsvatnet and south towards Årdalstangen. During quiet and cold periods in winter, the dispersion conditions are very poor in Øvre Årdal. The concentrations around the plant largely depend on the meteorological conditions. The emissions vary relatively little over the year.

Habitation, occupation and business

The population of Årdal expanded rapidly after the establishment of the aluminium plant just after the war. After a peak of around 7500 in the 1970s, the population decreased to about 5300 in 2018. The population is concentrated around Øvre Årdal (~3000) and Årdalstangen (~1400). Both these locations are fairly urban. There are also some residential areas in Seimsdalen and in Utladalen valleys.

About 630 people are employed at the Hydro facilities, including the Technology Center. In addition, there are some service industries with Hydro as main customer. NorSun is another major industrial employer at Tangen, producing wafers for solar panels.

There is some agriculture in the municipality, mainly free grazing sheep, goats and some cattle, in addition to some hay harvesting. Some areas, which previously had too high fluoride content in the grass, are now again in use for these purposes.

Production and emissions

The Årdal plant started up in 1948 using Söderberg technology. The Å-III potroom (Söderberg) became operative in 1961 with 168 pots. In 2007, Å-III was closed. Today the plant consists of two regular reduction lines, both prebake, and a test centre where Hydro's technology department is testing improved reduction technology. The total production capacity is about 210 000 tonnes p.a.

Årdal Carbon at Årdalstangen manufactures anodes for prebake plants. A little more than half of the anode production of 190 000 tonnes per year goes to the metal plant in Øvre Årdal, the rest goes to Høyanger and to other Hydro plants.

The development in production and emissions from 1992 to 2020 is discussed and illustrated in Section 2.

The measurement station in Øvre Årdal in the 1990s was located close to Årdal videregående skole (Hagen, 1991; Hagen, 1992; Mikalsen et al., 1994; Hagen, 2002). Passive samplers in 2012 (Hak and Castell, 2012a) were located over all Øvre Årdal and towards Utladalen. The measurement station for PAHs at Årdalstangen (Hagen, 1991) was located at Hagavegen northeast of Årdal Carbon. Measurements of particulate matter around Årdalstangen in the period 2003 – 2009 were carried out at three sites, (Å1) main entrance Årdal Carbon, (Å2) Hagavegen 11, 200 m northeast of Årdal Carbon, (Å3) Langvollvegen 9, 300 m east of Årdal Carbon. These results are not documented in a report. Since there are emissions both from the metal plant in Øvre Årdal and from the anode plant at Årdalstangen, the sampling sites in Øvre Årdal that lie between the plants can be exposed both when it blows in and out of the valley. Depending on the wind direction, Øvre Årdal can be exposed to emissions from Årdalstangen and Årdalstangen to emissions from Hydro Årdal.

1.4.9 Kubikenborg Aluminium (KUBAL)

Location and physical geography

KUBAL is located in Sundsvall municipality in the Västernorrland County in Sweden. It is located quite close to the city of Sundsvall at the mouth of the fjord Sundsvallfjärden. The climate is tempered with distinct seasonal variations, averaging around 20°C in the summer and -10°C in the winter. The wind climate is quite gentle, with north-west as the dominant direction. The hills around the fjord tend to channel the wind along the fjord. In the summer, land-sea breeze may occur.

Figure 12: Kubikenborg Aluminium (KUBAL) at Sundsvall. (Left): View towards north-northwest. The city of Sundsvall is located west-northwest of the aluminium smelter. (Right): Map over Sundsvall.

There are built-up areas to the north, north-west and south of the plant, as well as across the fjord at Ankarsvik. The hill Stadsberget to the west and south-west is covered with mixed forest. The island Alnön to the east has patches of farmland in between forest areas.

Habitation, occupation and business

The municipality has a population of nearly 100 000, whereof nearly 60 000 are living in the city of Sundsvall. The municipality has varied industrial segments, with some heavy industries, such as wood industry, chemicals, the aluminium plant and graphical industries. KUBAL employs about 450 people.

Production and emissions

The aluminium plant was established in 1942 and is Sweden's only operating primary aluminium plant. The initial owner was SAKO, later Gränges, Glencore and since 2006 Rusal. The production was initially based on Söderberg technology. One potroom was converted from Söderberg to prebake in 1987, and the second larger one in 2007/08. The plant now has two potrooms with a total capacity of about 134 000 tonnes p.a.

During the Söderberg period, the plant had quite heavy emissions, and was regarded as one of Sweden's worst polluters. With prebake technology and good gas treatment facilities, the plant is now in line with other modern aluminium plants.

In November 2008, the last Söderberg furnace was closed down at the Kubal aluminium smelter and production of aluminium continued with the prebake production method.

In 2013, roof ventilators were installed in Plant 2, changing from stack-led emissions to roof ventilators.

Kubikenborg Aluminium AB has been measuring fluorides in Sundsvall since 1985. In the period 1985 – 2009, when the smelter was converted to prebake technology, also PAHs were measured. The locations of the three measurement stations are shown in Figure 13. (1) Villa Marieberg, Haga, station 5 (3.3 km northwest from smelter) (2) Björneborgsgatan, Brandstation, "station 2" (2 km west-northwest of smelter) (3) Kubikenborgsskolan, Kuben, "station 6" (right west of smelter). Campaigns for measuring HF and SO_2 were carried out in 2012, 2018, 2019 and 2021 at Kuben, Fläsian (1.3 km south of smelter) and Vindhem (3.3 km southwest of smelter).

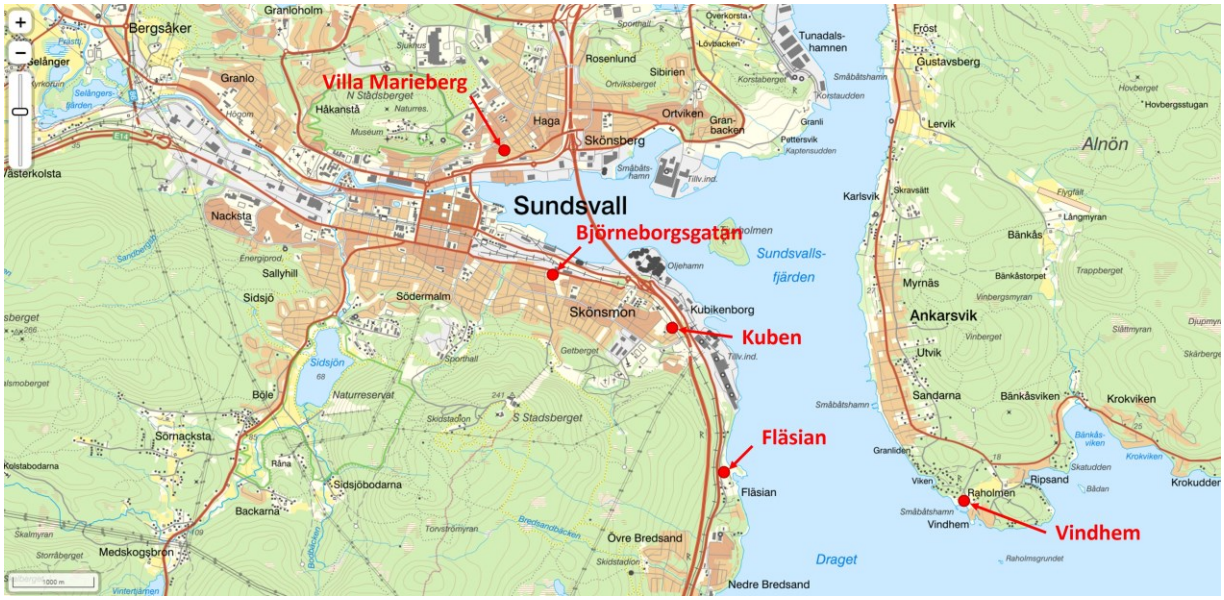


Figure 13: Overview map for Kubal's sampling sites in Sundsvall.

1.4.10 Rio Tinto Iceland (ISAL)

Location and physical geography

The aluminium plant lies at a small peninsula at Straumsvik near Hafnarfjörður, along the highway between Reykjavik and Keflavik in the west of Iceland. The area is quite flat and open to wind. The land surface is mainly a lava field with sparse vegetation.

Figure 14: Rio Tinto Iceland (ISAL) at Hafnarfjörður. (Left): View towards east. (Right): Map showing surroundings of the plant, west of Hafnarfjörður.

The climate is windy, humid and cool, with monthly averages of around 13°C in the summer and 1-2°C in winter.

The dominating wind direction is from west-northwest in the summer, and mainly from east and southeast the rest of the year.

Habitation, occupation and business

Hafnarfjörður municipality has a population of about 30 000, the third largest town in Iceland. The smelter is the main industry, in addition it has an important fishing and commercial harbour. Due to its proximity to the capital, many of the people living here commute to Reykjavik and Kópavogur.

Production and emissions

Contracts for the construction of an aluminium smelter in Iceland were signed by Alusuisse in 1966. In 1969, production began in the first potroom. The production capacity of the plant was initially about 33 000 tonnes per year in 120 pots. The first potroom was then lengthened and 40 additional pots were put into service in 1970. A second potroom was put into operation in 1972, and in 1980, this was extended, reaching an overall capacity of about 100 000 tonnes per year. The third potroom came into operation in 1997, raising production to 162 000 tonnes.

Extensive investments were made in 2011-2014. With these investments and an emphasis on continuous improvement, the production capacity has now reached over 211 000 tonnes per year.

Measurement data are collected from a station in Hvaleyrarholt, 2 km northeast of ISAL. Wind data are collected in Straumsvik (Þórðarson, 2011).

2 Emissions and concentrations in air

Concentrations of pollutants in air reported from measurement and modelling studies in the period 1992 – 2020 were collected. Variations of emissions, background concentrations and concentrations in ambient air close to the smelters over time are shown in this section. Concentrations are compared to today's limit values and air quality criteria.

The variations of concentrations of relevant compounds at Norwegian background stations in the same time period are discussed for comparison.

2.1 Polycyclic aromatic hydrocarbons (PAHs)

After the conversion of most aluminium smelters to prebake technology, the plants in Lista, Sunndal and Årdalstangen are the three remaining facilities with notable PAH-emission today. Alcoa Lista uses new Söderberg technology and at Sunndal and Årdalstangen, PAH-emissions are due to anode production. Alcoa Mosjøen also has anode production, but using more efficient production and emission controls, the PAH emissions to air are minor. The evolution of PAH-emissions (kg/year) for the individual plants in the period 1992 – 2020 are shown in Section 2.1.2, together with the yearly production (tonnes) and results from measurement and modelling studies.

2.1.1 Background concentrations

PAHs, especially benzo(a)pyrene (BaP, see Section 1.1), have been measured at the background stations Birkenes (since 2008), Zeppelin (since 2010) and Andøya[18] (2011 and 2012) in Norway. Figure 15 shows how BaP-concentrations at Norwegian background sites have developed over the last decade, showing a decreasing trend especially at Birkenes between 2009 and 2015. There is an annual variation of BaP-concentrations in the regional background, with highest levels in winter and lowest levels in summer. For BaP, no trend analysis exists yet (Bohlin Nizzetto et al., 2021).

[18] The background station at Andøya was shut down in the end of 2021.

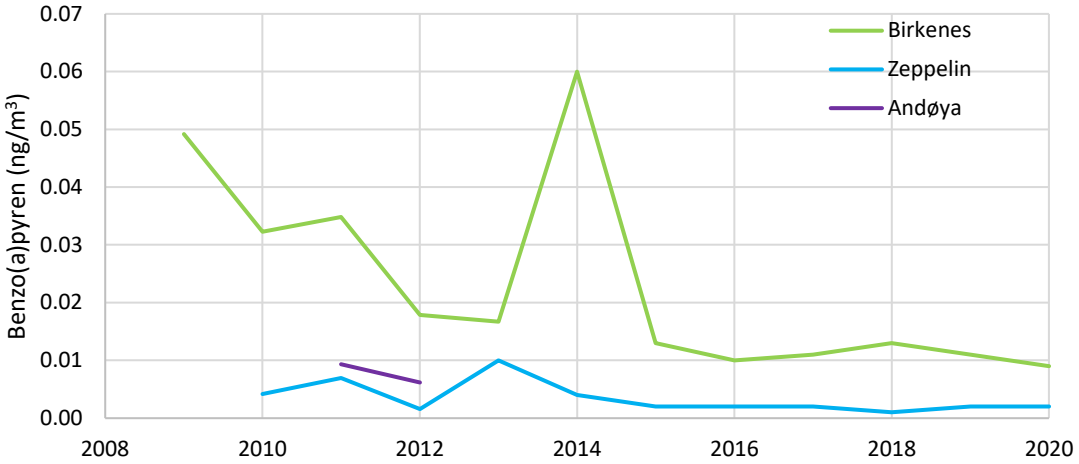


Figure 15: Variation of benzo(a)pyrene concentration (annual averages, ng/m^3) at Norwegian background sites in the period 2009 – 2020.

2.1.2 Emissions and ambient concentrations

Fjarðaál

PAH emission data from Fjarðaál were not available for the study. The plant has no anode production, and hence has practically no emissions of PAH.

The Alcoa Fjarðaál smelter was launched in April 2007. Continuous PAH-measurements have been carried out since 2006 at four stations around the smelter (see Section 1.4.1). Annual averages of PAH concentrations in the period 2006 – 2020 are shown in Figure 16 (Náttúrustofa Austurlands, 2014-2021). The ambient concentrations measured were highest in 2007 when the production started. There was another peak in concentrations in 2010 and a minor peak in 2019. Since 2012, annual average PAH concentrations have been below 100 ng/m^3 at all stations. It is not indicated which PAH compounds are covered by "PAH". Benzo(a)pyrene is not reported separately. Generally speaking, PAH concentrations vary similarly at the four measurement stations.

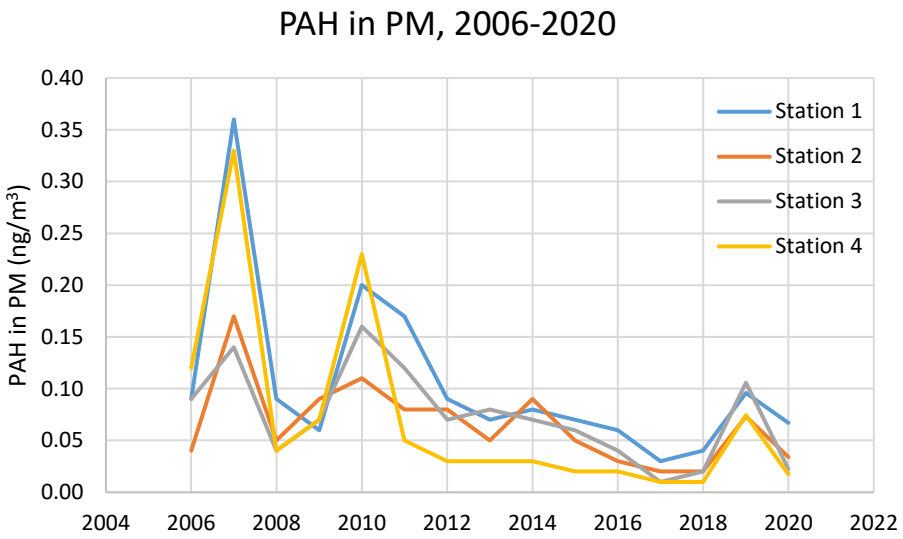


Figure 16: Average annual concentrations of particle-bound PAHs in the years 2006 – 2020 at the four monitoring stations around Alcoa Fjarðaál.

Lista

Figure 17 illustrates the development in production and PAH emissions from 1992 to 2020, as reported by Alcoa Lista (www.norskeutslipp.no). For PAH to air (kg per year), the NS-8515 standard was used until 2015, and this standard is used here in order to give a correct picture of the relative change. With some reservations regarding the accuracy of early measurements, the figure indicates a 75% reduction in this period.

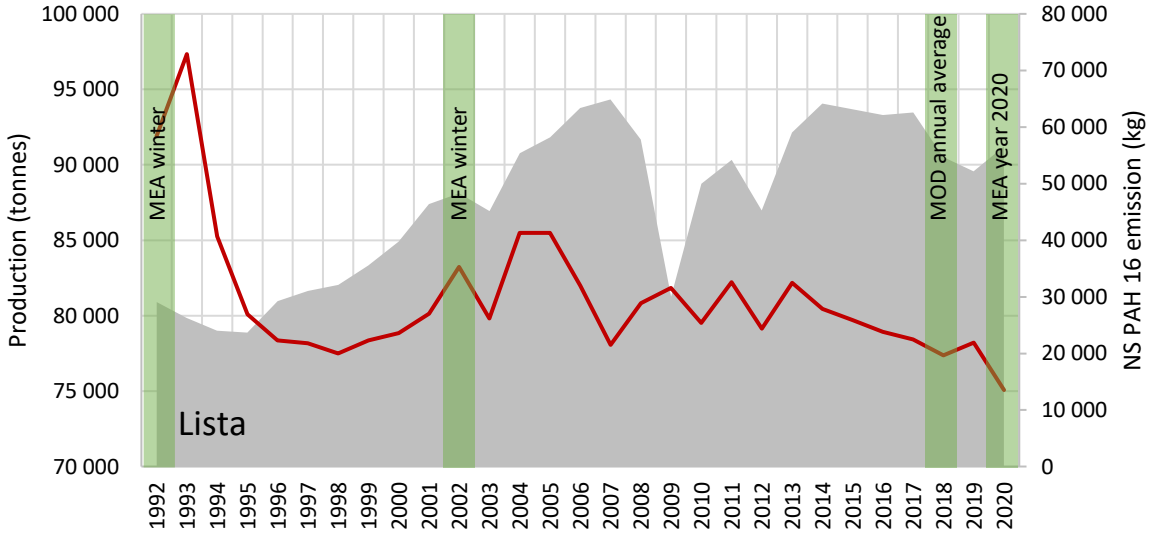


Figure 17: Emissions of PAHs (red line, unit: kg per year, right-hand y-axis) at Alcoa Lista from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). The years measurement (MEA) or modelling (MOD) studies were carried out, are highlighted.

The most recent measurements were carried out in the calendar year 2020 (Hak, 2021b) at two stations, Huseby and Hanangermona (see Section 1.4.2). For comparing the results from 2020 to

earlier measurements, carried out in 1991 and 2001, several differences in the measurements have to be noted:

- In 2020, weekly samples were merged to monthly samples. In 1991 and 2001, daily samples (24 hours) were analysed. This means that the air volume sampled was much lower than in the monthly samples, which has an effect on the method's detection limits[19], i.e. lower detection limits for weekly and monthly samples compared to daily samples. The daily samples for the earlier studies were collected once a week and thus did not continuously cover the measurement periods. In addition, daily results are more sensitive to time variations (regarding emissions and meteorological parameters like, e.g., wind direction) and are not directly comparable to long-term mean values over a month.
- In 2020, particle-bound PAHs were sampled and analysed, while in 1991 and 2001, the sum of particle-bound and gaseous PAHs were analysed. Some of the lighter PAHs are mainly gaseous (discussed in Section 1.1). The PAH-profiles from earlier studies will therefore differ from the PAH-profile from 2020.
- In 2020, PAH samples were analysed for 16 priority PAHs (EPA 16 PAHs). In 1991 and 2001, 33 PAHs were analysed. For comparison, the 16 priority PAHs were selected. Modelling results (Tønnesen, 2018) using emissions from 2017 show the sum of NS 16 PAHs[20].

In previous measurement campaigns, PAHs were only sampled at Huseby. Compared to previous campaigns at Lista, PAH-concentrations in 2020 were lower. Note, however, that only particle-bound PAHs were analysed in 2020. The average concentration for sum PAH_{16} from 24-hour samples in winter 2001 was 56 ng/m^3. Compared with similar measurements in winter 1991 (sum PAH_{16} 194 ng/m^3, see Hagen, 1991), the average concentration of both total PAH and BaP in winter 2001 was significantly reduced at Lista. PAH-emissions at Lista have been reduced by 50-70% between winter 1991 and winter 2001/02. In the period 2001 – 2020, emissions were reduced by further 50%.

A general observation from measurements in the surroundings of aluminium plants in 1991 and 2001/02 was that the concentration of BaP was reduced more than the concentration of sum PAH. Since BaP is also emitted by car traffic and is amongst the heavier PAHs (molar mass 253), this may indicate that PAH emissions from car traffic were even more reduced than those from aluminium plants in the period 1991 – 2001 (Hagen, 2002) or that reduction measures at the smelter have been more effective for the heavy PAHs than for the volatile compounds. Measurement results from Lista, especially PAH profiles, are discussed in more detail in Hak (2021b).

Benzo(a)pyrene, which almost exclusively occurs in the particle phase, has decreased strongly between 1991 and 2001. In winter 2001, the BaP-level at Lista was reported to be 83% lower than in winter 1991. The benzo(a)pyrene concentration at Huseby in the period 17. January – 22. March 1991 was 2.9 ng/m^3. In winter 2001 (1. November 2001 – 3. January 2002), a BaP-concentration of 0.5 ng/m^3 was measured at Huseby (Figure 18). In winter 2019/20 and winter 2020/21, average BaP concentrations of 0.1 ng/m^3 and 0.8 ng/m^3, respectively, were measured at the same site. The average over both winter seasons (0.46 ng/m^3) was comparable to the winter average in 2001, although PAH-emissions are reported to have decreased by 50% between 2001 and 2020. The annual BaP average for the year 2020 was 0.48 ng/m^3, i.e. slightly above the lower assessment threshold.

[19] The higher the air volume, the lower the detection limit.

[20] Norwegian standard NS-9815 covered 16 PAH compounds to be included in the calculation of the total amount of PAHs. In 2015, the Norwegian standard has been replaced by two new international ISO standards. In the new reporting format, the sum of the 16 PAH compounds included in the US EPA standard must be reported. The transition to the new standard entails an apparently higher PAH emission. This is because the US EPA standard included a number of volatile PAH compounds that were not included in the Norwegian standard.

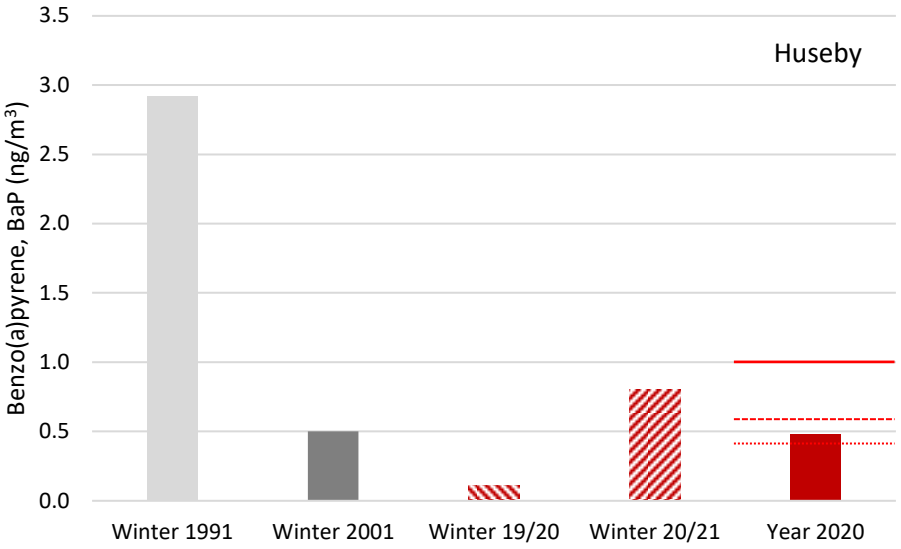


Figure 18: Average benzo(a)pyrene concentration (ng/m³) at Huseby in winter 1991 (10 weeks, January – March), winter 2001 (10 weeks, November – January), winter 2019/20 (January – March) and winter 2020/21 (November – December) and annual average for 2020. The annual target value (1.0 ng/m³), upper assessment threshold (0.6 ng/m³) and lower assessment threshold (0.4 ng/m³) are also shown.

It needs to be pointed out again that 24-hour samples were collected in the previous campaigns (1991 and 2001), once a week, and that the concentrations are reported to have varied a lot from day to day. There is an uncertainty in the representativeness of the seasonal averages from winter 1991 and winter 2001 compared to the current measurements which evenly cover every month.

Emissions of PAHs are reported to have decreased, especially in the beginning of the 1990s. The production, however, has increased by ca. 13% since 1992 (see Figure 17). The aluminium plant at Lista is using Söderberg technology which is strongly associated with PAH emission due to the construction of the anode that consists of coke and anthracite aggregates bound together with coal tar pitch. In the 1990s, an upgraded Söderberg technology was implemented at the plant (see Section 1.4.2). PAH-emissions decreased further from ca. 2005 and onwards. The decrease of emissions is reflected in Figure 17.

For comparison, in a recent modelling study (Tønnesen, 2018), dispersion calculations for PAHs in air were carried out using meteorological data from Lista fyr from the period 2012 – 2017 and PAH emission data from 2017. An annual BaP-average of 1.3 ng/m³ was calculated at Huseby. For PAHs, the calculated annual average at Huseby was 76 ng/m³. The model calculations from 2018 showed good agreement with previous measurements for PAHs, but gave a somewhat higher BaP concentration level at Huseby than the measurements in winter 2001/02, where 0.5 ng/m³ were measured (Hagen, 2002). Both operating and emission conditions have changed in the period 2001-2017. As shown in Figure 17, the emissions have decreased between 2001/02 and 2017. The calculated area with BaP concentrations exceeding the target value of 1.0 ng/m³ ranged 1 km north and south of the smelter and ca. 2 km west and southeast of the smelter. The highest concentrations of PAH and BaP occur inside the premises of the plant between the halls. Calculated maximum concentrations in this area were 32.5 ng/m³ BaP and 3.5 µg/m³ PAH. Note that within the industry premises, the limit values for pollutants in the work atmosphere apply (0.04 mg/m³, i.e. 40 µg/m³ for particulate PAHs, see also Section 1.2). The model results from 2017/2018 gave considerably higher BaP concentration at Huseby than measured in 2020. This may be explained by a combination of several factors. First of all, the model is conservative, i.e. it interprets uncertainties in a way that calculated concentrations may overestimate the experienced levels “to be on the safe side”.

Production in 2020 was reported to be 2% lower than in 2017. The emission of sum PAH_{16} reported for 2020 was 40% lower than in 2017, the emission of BaP was 20% lower in 2020 than in 2017. The named factors support higher concentrations to be estimated for 2017. Both years had a distribution of wind directions which corresponds to the long-term average at Lista.

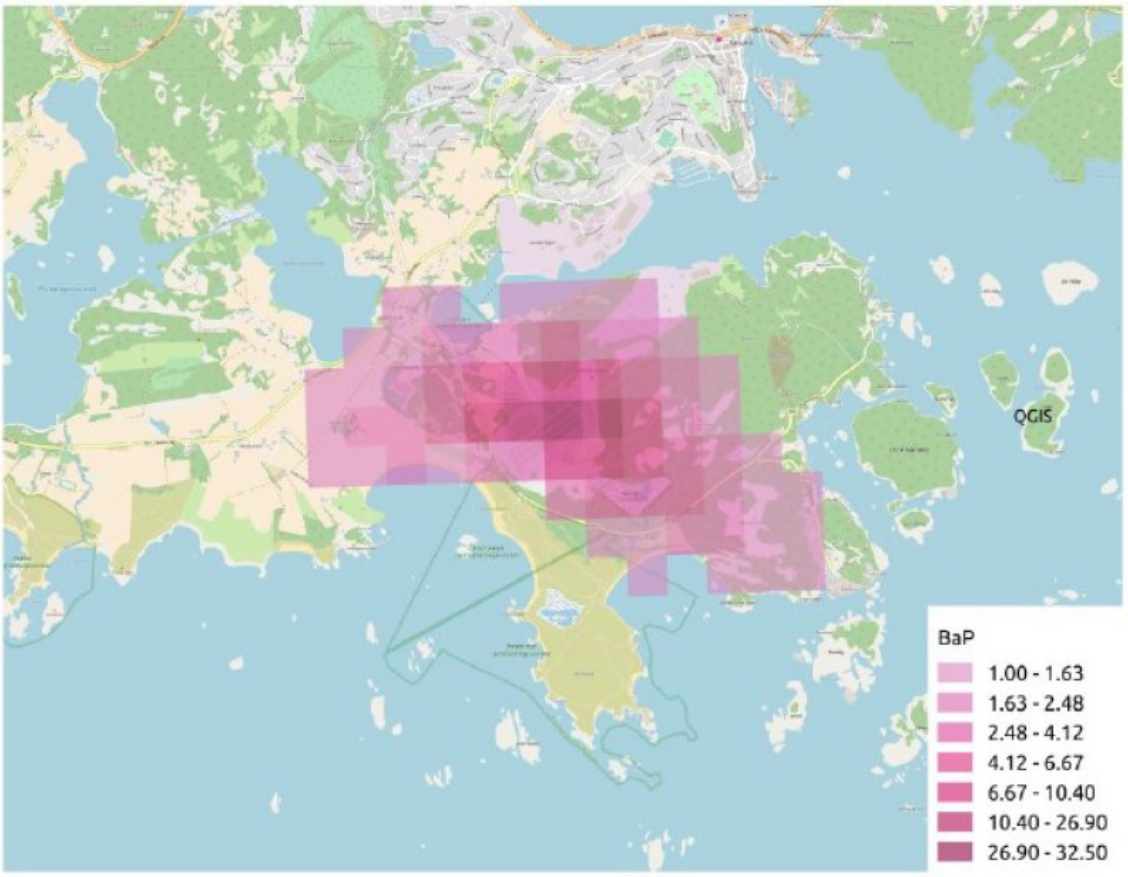


Figure 19: Calculated annual average concentration of BaP around Alcoa Lista. Unit ng/m^3. Values above 1.0 ng/m^3 (target value for BaP). Size of each square 250 m x 250 m.

More details, e.g., comparison of measured PAH-profile to emitted PAH-profile, can be found in Hak, 2021b.

Mosjøen

Figure 20 illustrates the development in production and PAH emissions at Alcoa Mosjøen from 1992 to 2020. For comparability, the emissions for PAH to air (kg per year) are based on the NS-16 standard, since all reports up to 2015 were based on this standard. The reductions compared to the early 1990s have been around 95% for emissions to air. Most of the reduction in PAH emissions came as a result of the closure of the Söderberg potlines in 2003. The remaining PAH-emissions after 2008 are coming from the anode production.

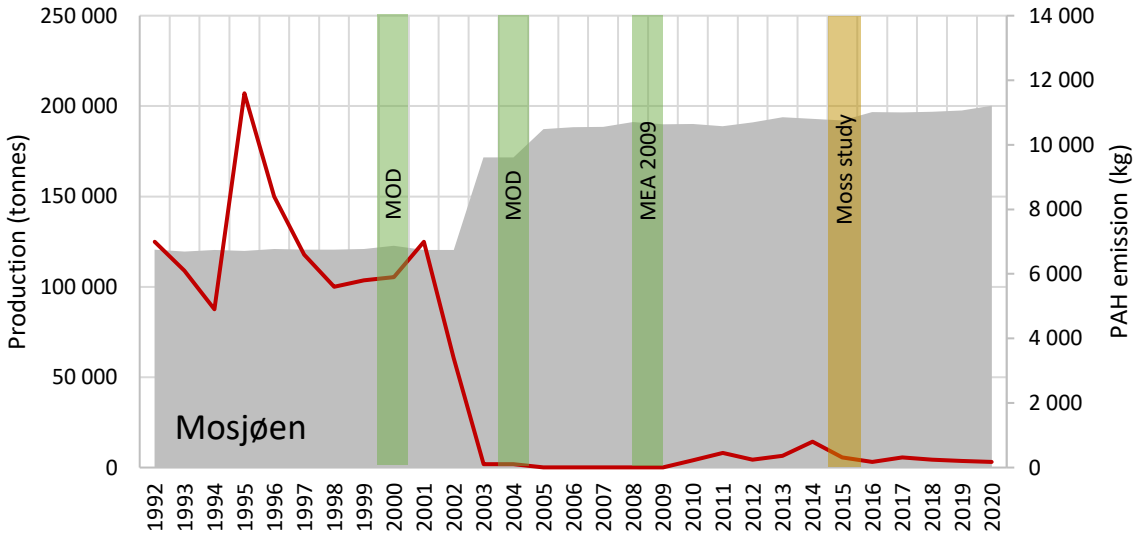


Figure 20: Emissions of PAHs (red line, unit: kg per year, right-hand y-axis) at Alcoa Mosjøen from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). The years measurement (MEA) and modelling (MOD) studies were carried out, are highlighted.

The ambient concentrations of PAHs (sum PAH, PAH16 and/or BaP) were assessed in two modelling studies and one measurement study in the period 1992 – 2020 (Grønskei and Gram, 2000; Tønnesen, 2004; Haugsbakk, 2010). The most recent measurements were carried out in the period November 2008 – November 2009 (Haugsbakk, 2010). The station (Helgelandskraft) was further away from the smelter than during previous PAH-studies. Average of the BaP measurements in Mosjøen was 0.41 ng/m^3, which is slightly below 50% of the target value. The average of PAH_{16} was 2.27 ng/m^3.

Measurements of PAHs in air carried out in winter and summer 1991 should be included in this overview although the measurement periods are before the period 1992 – 2020 considered here. Figure 21 shows concentrations of sum PAH, PAH_{16} and/or BaP measured and calculated in Mosjøen since 1991. Note that the number of PAHs included in sum PAH may have changed between the measurement campaigns and that also the measurement site has changed between 1991 and 2008/09. A significant decrease of both BaP and PAH_{16} (hardly visible in the figure) between 1991 and 2008/09 is observed. This is in line with the decrease in PAH-emissions due to technical conversions. Since 2003, PAH emissions at Mosjøen have been low. At Mosjøen, there is a tendency to slightly higher PAH values in summer than in winter, which is probably due to the greater frequency of wind up the valley in summer, because of the sea-breeze effect, and the fact that the aluminium plant is the main source of PAH in the area.

PAH measurements in 1991 (January – March 1991 (Hagen, 1991) and June – August 1991 (Hagen, 1992) were carried out in Mosjøen to follow up on corresponding measurements in the period 1980 – 1982 (Thrane, 1983b) after changes in the production conditions. In summer 1991, the averaged measured values in Mosjøen were 82% lower than in summer 1981. In winter 1991, total PAH was 61% lower than in winters 1980/81 and 1981/82. The PAH concentrations were higher in summer 1991 than in winter 1991. This is related to a higher frequency of wind into the fjords during summer due to the sea breeze effect. Due to the vicinity of the measurement station to the main road E6 through Mosjøen, vehicle traffic was found to have a pronounced contribution to PAH concentrations. The variations from sample to sample (day to day) were large. Reasons for this can be variations in the emissions and in meteorological conditions (wind direction, wind speed, stability).

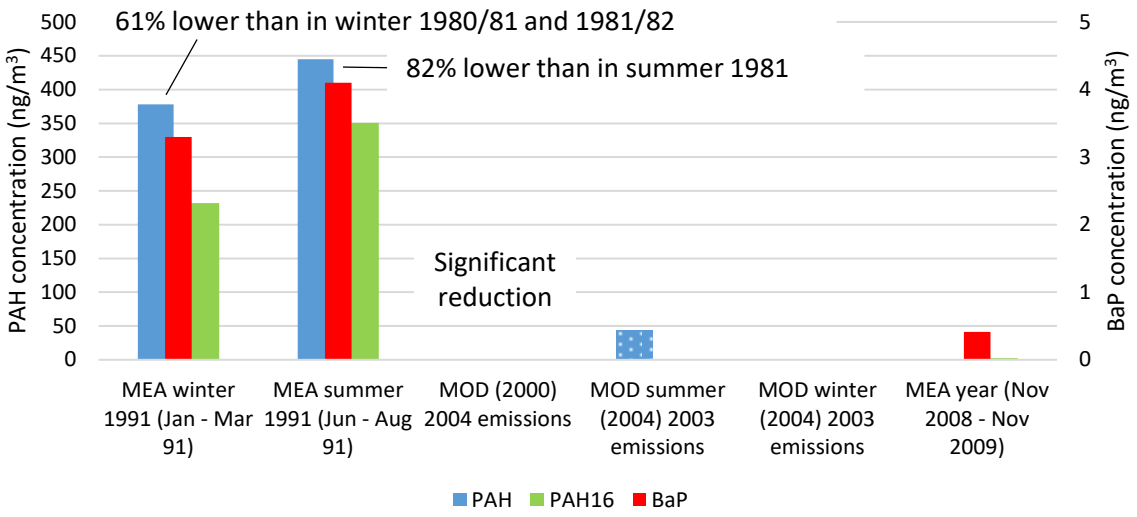


Figure 21: Average concentrations of sum PAH, PAH_{16} (left axis) and BaP (right axis) in Mosjøen, measured (1991, 2008-09) and calculated (2000, 2004), units: ng/m³.

In all measurement studies carried out in Mosjøen, i.e. 1980s, 1991 and 2009, daily average samples were taken once or twice a week (using NILU's PUR sampler, see Appendix A). In the 2009 study, eight daily samples were merged to monthly average samples. As the concentrations of PAHs can vary greatly from day to day, both due to variations in the emissions and the meteorological conditions (wind direction, wind speed, stability), the average values can be somewhat uncertain, and it can be difficult to give a correct assessment of the change in concentrations from one period to another. According to the results from the last measurement study in 2009 (BaP < 1 ng/m³) and low PAH emissions since 2003, the BaP limit value is not expected to be exceeded today.

By 2000, Elkem Aluminium Mosjøen was planning a major rebuild and expansion of the aluminium plant, replacing old electrolysis ovens with Söderberg electrodes to ovens with prebaked electrodes. Dispersion calculations of PAHs were carried out in order to map the effect of emissions to air before (emissions from 1999) and after (emission prognosis for 2004) the conversion on air quality in Mosjøen (Grønskei and Gram, 2000). The modernisation and development of the plant was calculated to lead to a significant reduction in the PAH concentrations in Mosjøen since the PAH emissions from the plant will cease.

By 2004, Elkem Aluminium Mosjøen was planning the construction and operation of a baking plant for prebaked anodes. Dispersion calculations were carried out in connection with this conversion to map the effect on the air quality in Mosjøen of emissions to air after the start-up of the baking plant (Tønnesen, 2004). The calculations showed that emissions of PAH from the anode baking would be very small, and that the impact on ambient concentrations would be low. The updated calculations show that the pollution load around the plant is lower than calculated in the previous report (Grønskei and Gram, 2000). The highest concentrations were calculated to be close to the plant, with large concentration gradients in the area.

Husnes

No PAH-emission data was available for Husnes. Since the plant uses prebake technology and imports anodes, there are practically no emissions of PAH.

No PAH measurement data was available for Husnes.

Høyanger

Figure 22 illustrates the development in production and PAH emissions at Hydro Høyanger from 1992 to 2020. The production had a dip in the early 1990s due to the market situation. The following increase during 1995 – 1998 was due to gradual restart of cells, followed by gradual increase in output per cell. This increase has continued after the shut-down of the Söderberg line in 2007. Since the plant now only uses prebake technology and imports anodes, there are practically no emissions of PAH after the closure of the Söderberg line. The historic air emissions (kg per year) were significant, however. Some reservations must be taken regarding the accuracy of the older PAH measurements.

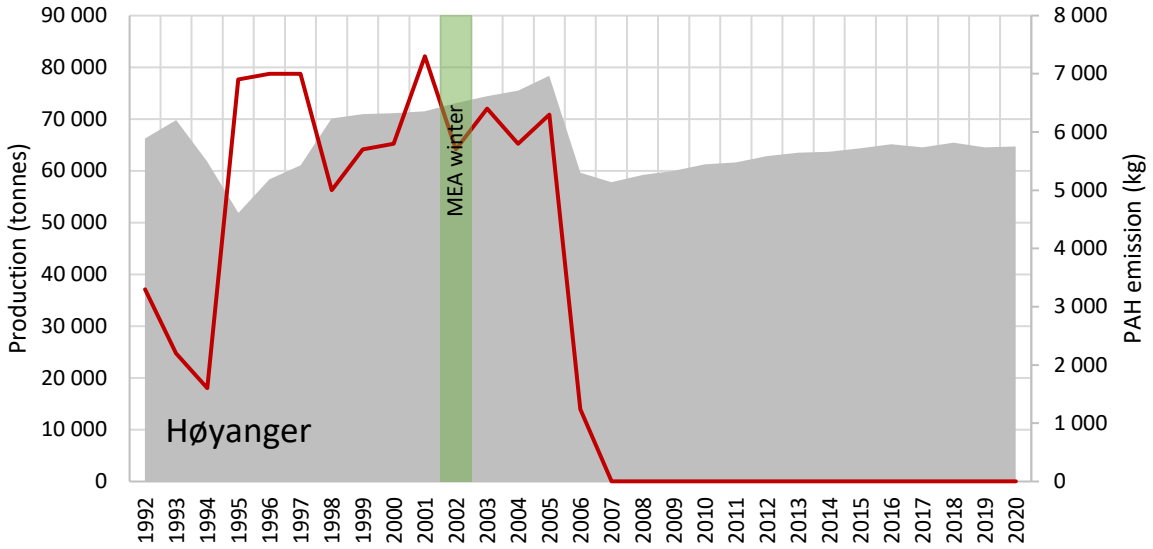


Figure 22: Emissions of PAHs (red line, unit: kg per year, right-hand y-axis) at Hydro Høyanger from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). In 2002, a measurement (MEA) study was carried out, as highlighted.

The ambient concentrations of PAHs (sum PAH, PAH_{16} and BaP) in Høyanger were assessed in one measurement study in the period 1992 – 2020 (Hagen, 2002), where measurements were carried out in winter 2001/02 at several aluminium smelters in Norway. Measurements of PAHs in air carried out in Høyanger in winter 1991 (Hagen, 1991) should be included in this overview although the measurement period is before the period 1992 – 2000 considered here. Figure 23 shows concentrations of sum PAH_{33}, PAH_{16} and BaP measured in Høyanger since 1991. In the studies in 1991 and 2002, measurements were carried out at the same site, with the same sampling and analysis method, with the same sampling frequency and in the same season. Concentrations of total PAH, PAH_{16} and BaP were clearly lower in 2002 compared to 1991. The average BaP concentration decreased by 73%. Both studies were carried out before the conversion from Söderberg to prebaked anodes, which took place in 2006 and is assumed to have led to a significant decrease in ambient PAH concentrations in Høyanger.

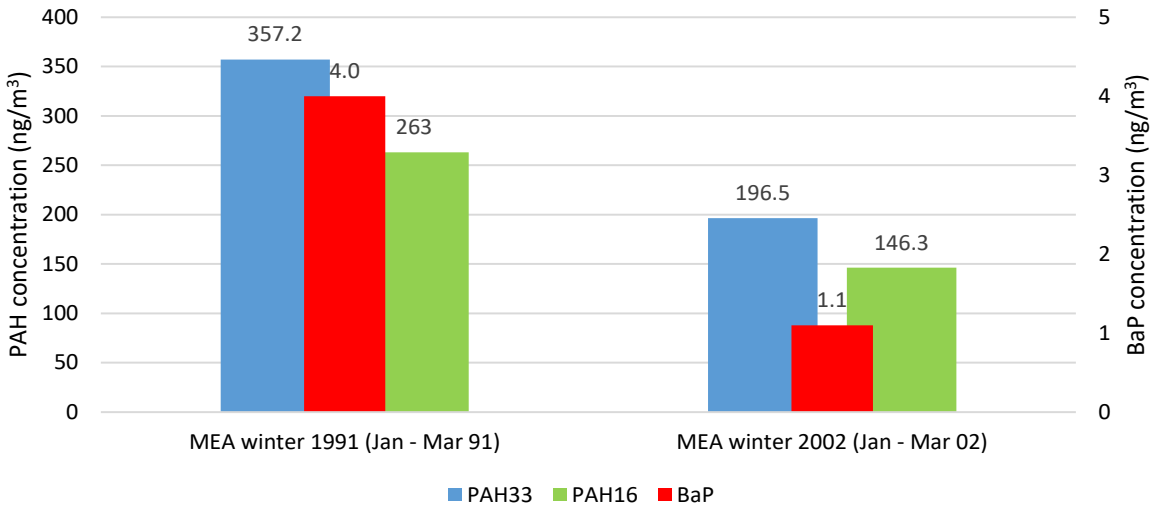


Figure 23: Average concentrations of sum PAH, PAH_{16} (left axis) and BaP (right axis) in Høyanger, measured in winter 1991 and winter 2002, units: ng/m³.

The PAH measurements at Høyanger in winter 1991 were carried out to control the levels ten years after corresponding measurements (October 1980 – February 1982, Thrane, 1983c, also based on daily samples once or twice a week), since production conditions had changed and emissions had been reduced. The measurements in 1980-82 showed a slightly higher PAH level in winter than in the rest of the year. The average PAH level in winter 1991 was clearly reduced to about 21% of the winter level of 1980/81 and 1981/82, indicating that emissions have been reduced significantly.

In all measurement studies carried out in Høyanger, i.e. 1980s, 1991 and 2002, daily average samples were taken once per week (using NILU's PUR sampler, see Appendix A). As the concentrations of PAHs can vary greatly from day to day, both due to variations in the emissions and the meteorological conditions (wind direction, wind speed, stability), the average values can be somewhat uncertain and it can be difficult to give a correct assessment of the change in concentrations from one period to another. The contribution to PAH from vehicle traffic is reported to be very small at the measurement station. Since BaP concentrations in 2002, before conversion to prebake, were already close to the AAQ limit, it is all reason to assume that current ambient levels are well below the target value.

Karmøy

Figure 24 illustrates the development in production and PAH emissions at Hydro Karmøy from 1992 to 2020. The production (tonnes per year) was close to the same level in 2017 as in the early 1990s, but around 100 000 tonnes lower than the peak in 2008. Since 2018, the production has increased after an expansion of the plant. For comparability, the figures for PAH to air (kg per year) are based on the NS-16 standard. Some reservations must be taken regarding the accuracy of the older PAH measurements, since the large variations cannot be explained from changes in the processes or treatment systems. Since the closure of the Söderberg lines in 2009, the PAH emissions have been practically eliminated.

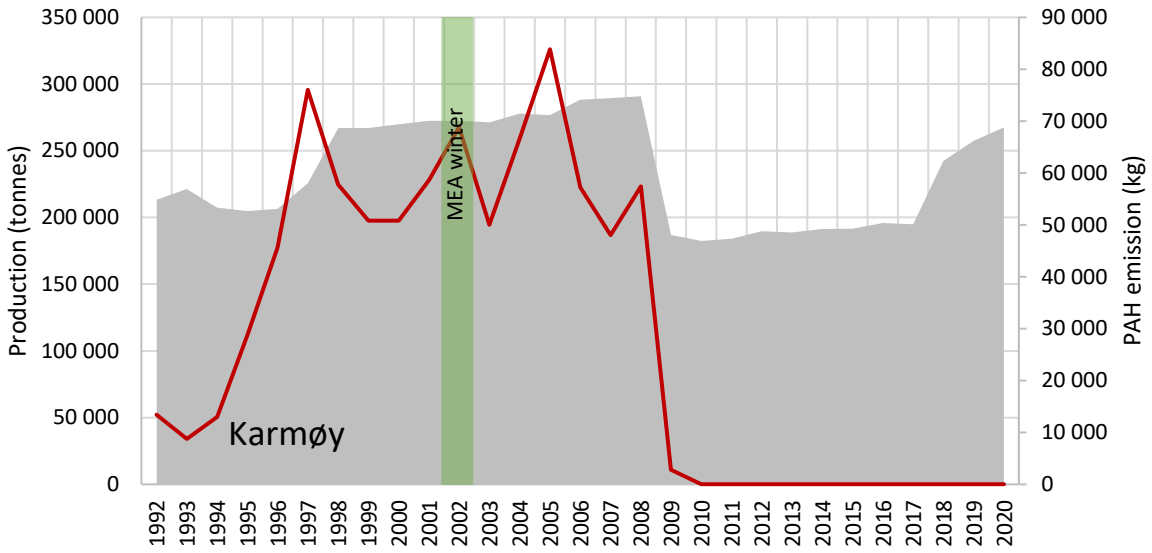


Figure 24: Emissions of PAHs (red line, unit: kg per year, right-hand y-axis) at Hydro Karmøy from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). In 2002, a measurement (MEA) study was carried out, as highlighted.

The ambient concentrations of PAHs (sum PAH, PAH_{16} and BaP) at Karmøy were assessed in one measurement study in the period 1992 – 2020 (Hagen, 2002), where measurements were carried out in winter 2001/02 at several aluminium smelters in Norway. Measurements of PAHs in air carried out at Karmøy in winter 1991 (Hagen, 1991) should be included in this overview although the measurement period is before the period 1992 – 2020 considered here. Figure 25 shows concentrations of sum PAH33, PAH_{16} and BaP measured at Karmøy since 1991. In the studies in 1991 and 2002, measurements were carried out at the same site, with the same sampling and analysis method, with the same sampling frequency, and late and early in the winter season. The concentrations of total PAH, PAH_{16} and BaP in 2001/02 were significantly reduced compared to 1991. The average BaP concentration decreased by 98%, the total PAH average decreased by 81%. Both studies were carried out before the conversion from Söderberg to prebaked anodes, which took place in 2009 and is assumed to have led to a significant decrease in ambient PAH concentrations at Karmøy. The 2-month averaged BaP concentration in winter 2001/02 was below the target value valid for annual averages.

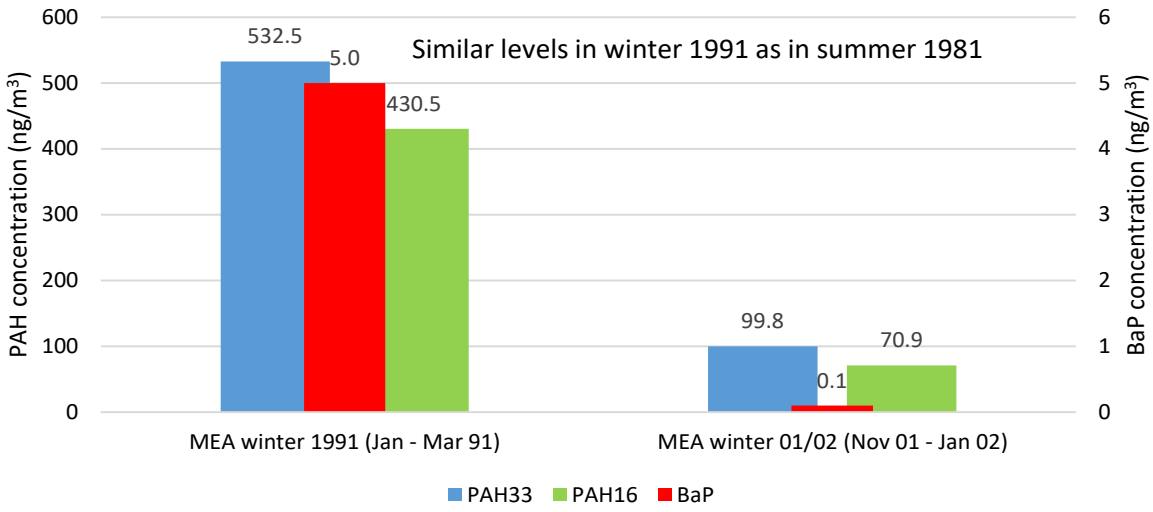


Figure 25: Average concentrations of sum PAH, PAH_{16} (left axis) and BaP (right axis) at Karmøy, measured in winter 1991 and winter 2001/02, units: ng/m³.

The PAH measurements at Karmøy in winter 1991 were carried out to check the levels ten years after corresponding measurements (June – September 1981, Thrane, 1985, also based on daily average samples once or twice a week, same location), since production conditions had changed and emissions had been reduced. The average PAH level in winter 1991 was reported to be similar to levels in summer 1981.

In all measurement studies carried out at Karmøy, i.e. 1981, 1991 and 2001/02, daily average samples were taken once per week (using NILU's PUR sampler, see Appendix A). As the concentrations of PAHs can vary greatly from day to day, both due to variations in emissions and in the meteorological conditions (wind direction, wind speed, stability), the average values can be somewhat uncertain, and it can be difficult to give a correct assessment of the change in the concentrations from one period to another.

Sunndal

Figure 26 illustrates the development in production and PAH emissions at Hydro Sunndal from 1992 to 2020. As a consequence of the expansion in 2002 – 2004, the production of aluminium increased. For PAH to air (kg per year), the figures before 2015 are recalculated to the EPA standard. For the oldest figures, this recalculation entails quite big uncertainty. With this reservation regarding the accuracy of early measurements, the figure indicated a 90-95% reduction in this period. Most of the reduction in PAH-emissions came as a result of the closure of the Söderberg potlines in 2003. The remaining emissions after 2004 are coming from the anode production.

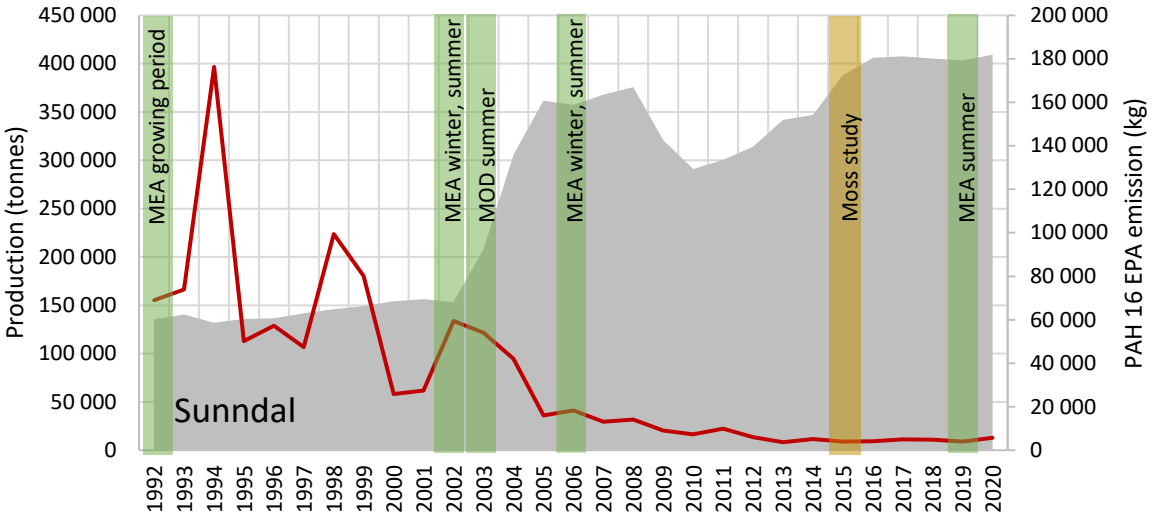


Figure 26: Emissions of PAHs (red line, unit: kg per year, right-hand y-axis) at Hydro Sunndal from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). The years measurement (MEA) or modelling (MOD) studies were carried out, are highlighted.

The most recent measurements in ambient air were carried out in summer 2019 (Hak, 2021a) at two stations, Pensjonistsenteret (in the centre of Sunndalsøra) and Vennevold (6 km up the valley). For comparing the results from 2019 to earlier measurements, several differences in the measurements have to be noted:

- In 2019, weekly samples were merged to monthly samples. In 2002 and 2006, daily samples (24 hours) were analysed. This means that the air volume sampled was much lower than in the monthly samples, which has an effect on the detection limits, i.e., lower detection limits for weekly and monthly samples compared to daily samples. The daily samples for the earlier studies were collected twice a week and this did not continuously cover the measurement periods. In addition, daily results are more sensitive to time variations in meteorology like wind direction, wind speed etc. and are not directly comparable to long-term mean values over 3 months.
- In 2019, particle-bound PAHs were analysed, while in 2002 and 2006, both particle-bound and gaseous PAHs were analysed. Some of the lighter PAHs are mainly gaseous (discussed in Section 1.1). The PAH-profiles from earlier studies will therefore differ from the PAH-profile from 2019.
- In 2019, PAH samples were analysed for 16 priority PAHs (EPA 16 PAHs). In 2002 and 2006, 33 PAHs were analysed. For comparison, the 16 priority PAHs were selected. Modelling results (Bøhler and Larsen, 1991) for the situation in 1990 and 1997 show the distribution of PAHs without indicating which compounds are included in the calculations.

In previous campaigns, PAHs were only sampled at Pensjonistsenteret.

Benzo(a)pyrene, which almost exclusively occurs in the particle phase, has decreased strongly over time. In summer 1991, the PAH-level at Sunndalsøra was reported to be 54% lower than in summer 1981 (Hagen, 1992). The benzo(a)pyrene concentration in the period June – August 1991 was 2.0 ng/m^3. As shown in Figure 27, the BaP concentration at Pensjonistsenteret was higher in summer 2002. After the technical conversion of the smelter in 2003/04, ambient PAH concentrations were strongly reduced. In summer 2006, a BaP-concentration of 0.16 ng/m^3 was measured at Pensjonistsenteret. In summer 2019, an even lower BaP concentration was measured, 0.009 ng/m^3.

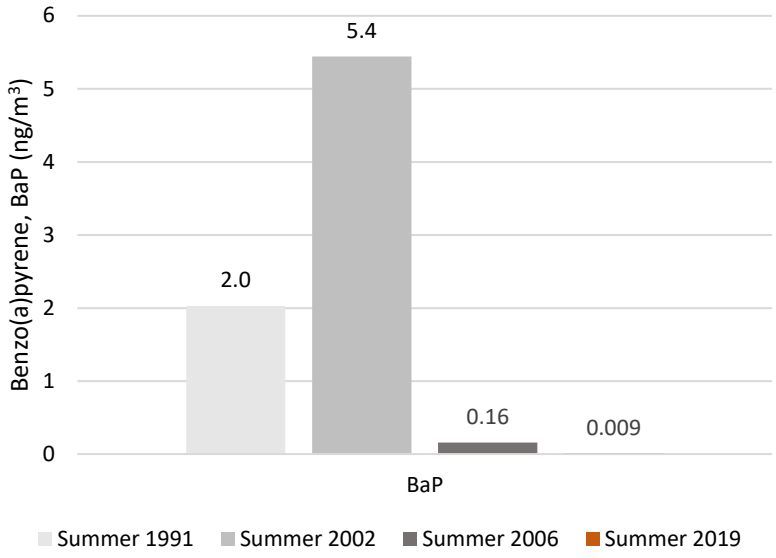


Figure 27: Average benzo(a)pyrene concentration in Sunndalsøra in summer 1991 (10 weeks), summer 2002 (10 weeks), summer 2006 (9 weeks) and summer 2019 (12 weeks).

Emissions of PAHs are reported to have decreased strongly, especially between 2002 and 2006, as a consequence of a change in production away from Söderberg technology, even though the production has more than doubled (see Figure 26). Söderberg technology was strongly associated with PAH emission due to the construction of the anode that consisted of coke and anthracite aggregates bound together with coal tar pitch. Meteorological conditions are supposed to have had a large effect on the decrease. PAH-emissions decreased further between 2006 and 2019. Further measurement results from Sunndal, especially PAH profiles, are discussed in more detail in Hak (2021a).

The ambient concentrations of PAHs (sum PAH, PAH_{16} and BaP) in Sunndalsøra were assessed in four measurement studies in the period 1992 – 2020 (Hagen, 2002; Hagen, 2003; Hagen, 2006; Hak, 2021a) and one modelling study (Gjerstad, 2003). Measurements of PAHs in air carried out in Sunndalsøra in 1991 (Hagen, 1991; Hagen, 1992) should be included in this overview although the measurement period is before the period 1992 – 2020 considered here. Figure 28 shows concentrations of sum PAH33, PAH_{16} and BaP measured in Sunndalsøra since 1991. In the studies in 1991, 2002 and 2006, measurements were carried out at the same site[21], with the same sampling and analysis method, with the same sampling frequency and in the same seasons. In 2019, only particle-bound PAHs were sampled and samples were analysed for PAH_{16}. As described above, the sampling frequency differed from the frequency of previous studies. Because of the sea breeze effect, leading to wind direction up the valley (and towards the measurement point) in summer, the concentrations in Sunndalsøra are higher in summer than in winter. In winter 2002, when Hydro Sunndal still had Söderberg technology, both PAH and BaP concentrations in ambient air were higher than ten years before, although the emissions had decreased. The concentrations of both PAH_{16} and BaP in summer 2019 were significantly reduced compared to earlier measurements. This is plausible since emissions continued decreasing after the conversion to prebake technology in 2002 – 2004. The levels in 2019 were so low that they are not visible in Figure 28 (BaP 0.009 ng/m^3, PAH_{16part} 0.2 ng/m^3). Sum PAH33 was not analysed in 2019. The target value for annual BaP averages is 1.0 ng/m^3.

[21] Only results from the station “Pensjonistsenteret” are shown. The station “Vennevold”, which was added in 2002, is located further away.

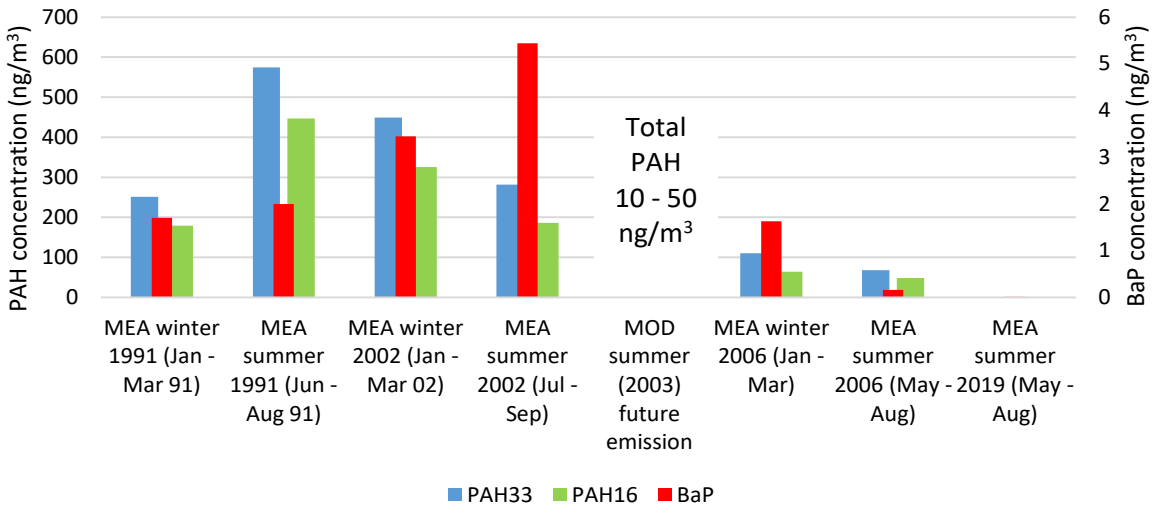


Figure 28: Average concentrations of sum PAH, PAH16 (left axis) and BaP (right axis) in Sunndalsøra, measured in winter and summer 1991, winter and summer 2002, winter and summer 2006 and summer 2019, as well as model results from 2003, units: ng/m³.

The PAH measurements in Sunndalsøra in 1991 were carried out to control the levels ten years after corresponding measurements (July – December 1981, Thrane, 1983d, also based on daily average samples once or twice a week, different location), since production conditions had changed and emissions had been reduced. The average PAH level in summer 1991 was reported to be 54% lower than in summer 1981. The average winter levels in 1991 were also lower than in winter 1981. This indicates that emissions have been significantly reduced during the period.

In all measurement studies carried out in Sunndalsøra (except 2019, see above), daily average samples were taken once to twice per week (using NILU's PUR sampler, see Appendix A). As the concentrations of PAHs can vary greatly from day to day, both due to variations in emissions and in the meteorological conditions (wind direction, wind speed, stability), the average values can be somewhat uncertain, and it can be difficult to give a correct assessment of the change in the concentrations from one period to another. In 2019, sampling was carried out continuously and monthly samples were analysed, covering the season evenly.

In addition to PAH measurements in ambient air, lettuce samples from several places up Sunndal valley were analysed for PAHs in summer 1989, summer 1990 and summer 1991 (July and September). PAH concentrations decreased with the distance from the aluminium plant, but even 30 km from the smelter, the levels were somewhat higher than in the Lillestrøm area (Mikalsen et al., 1994; Hagen, 1992). There were large gradients in the concentrations within the nearest 1 – 2 km from the plants. As reported in Hagen (2006), the plant still carried out yearly measurements of PAH in lettuce. By 2022, measurements in lettuce are not carried out any longer. It is not clear in which year the measurements ceased.

Øvre Årdal and Årdalstangen

Figure 29 illustrates the development in production and PAH emissions at Hydro Årdal and Årdalstangen from 1992 to 2020. The production of metal (tonnes per year) increased from 1995 to 2005, mainly as a result of expansions of the prebake lines. The Söderberg line was closed in 2007, but some of the lost capacity has been recovered through optimisation of the remaining prebake lines. The anode capacity has been expanded in several steps and is now nearly twice the level of the early 1990s. Emissions of PAHs to air show a large reduction from around 40 tonnes per year before 2006 to the present level of 1.3 tonnes per year (as NS-PAH16). During the years with Söderberg in

operation, about 2/3 of the PAH emissions to air came from the metal plant. After the closure of Söderberg, all measured emissions are from the carbon plant. The gas treatment system at the carbon plant has gradually been upgraded, so that the emissions at Tangen are down nearly 90% compared to the peak of 10-15 tonnes per year around year 2000. Some reservations must be taken regarding older figures and changes in the measurement methods.

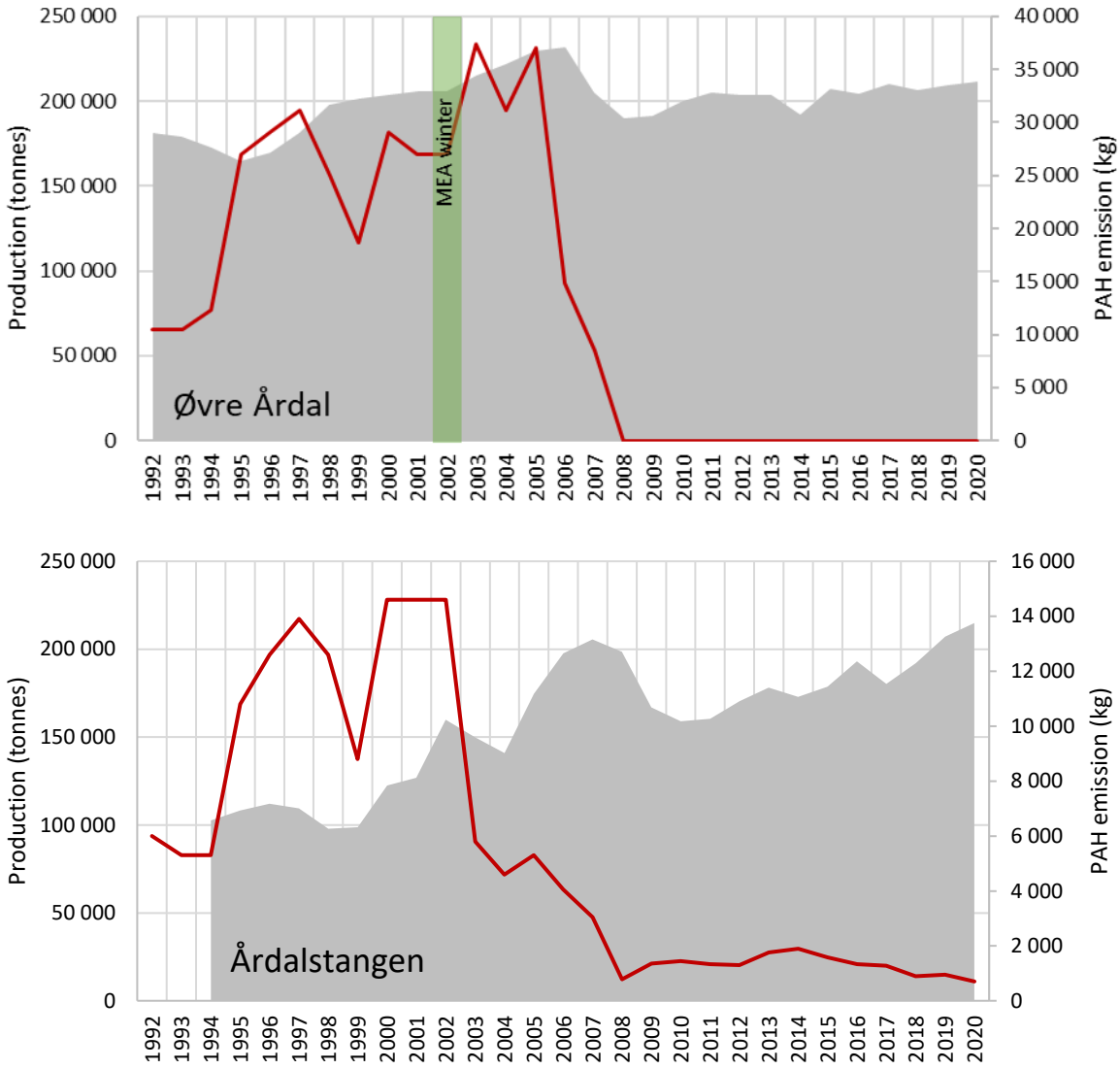


Figure 29: Emissions of PAHs (red line, unit: kg per year, right-hand y-axis) at Hydro Årdal and Årdalstangen from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). In 2002, a measurement (MEA) study was carried out at Øvre Årdal, as highlighted. No measurement or modelling data for Årdalstangen are available for the period 1992 – 2020.

The ambient concentrations of PAHs (sum PAH, PAH16 and BaP) in Øvre Årdal were assessed in one measurement study in the period 1992 – 2020 (Hagen, 2002). Measurements of PAHs in air carried out in Øvre Årdal and at Årdalstangen carried out in 1991 (Hagen, 1991; Hagen, 1992) should be included in this overview although the measurement period is before the period 1992 – 2020 considered here. Figure 30 shows concentrations of sum PAH33, PAH16 and BaP measured in Øvre Årdal since 1991. In all studies, measurements were carried out at the same site, with the same sampling and analysis method, with the same sampling frequency and in the same winter period. Measurements at one station at Årdalstangen in winter 1991 showed similar concentrations as

simultaneous measurements in Øvre Årdal. In winter 1991, gaseous and particle-bound PAHs were analysed separately in samples from Øvre Årdal and Årdalstangen. The split of 16 priority PAHs is shown in Section 1.1. Due to far better dispersion conditions in summer, PAH concentrations in Øvre Årdal are lower in summer than in winter. The way the plants and measuring stations are located in Øvre Årdal and Årdalstangen, the measuring stations will almost always be exposed to the emissions.

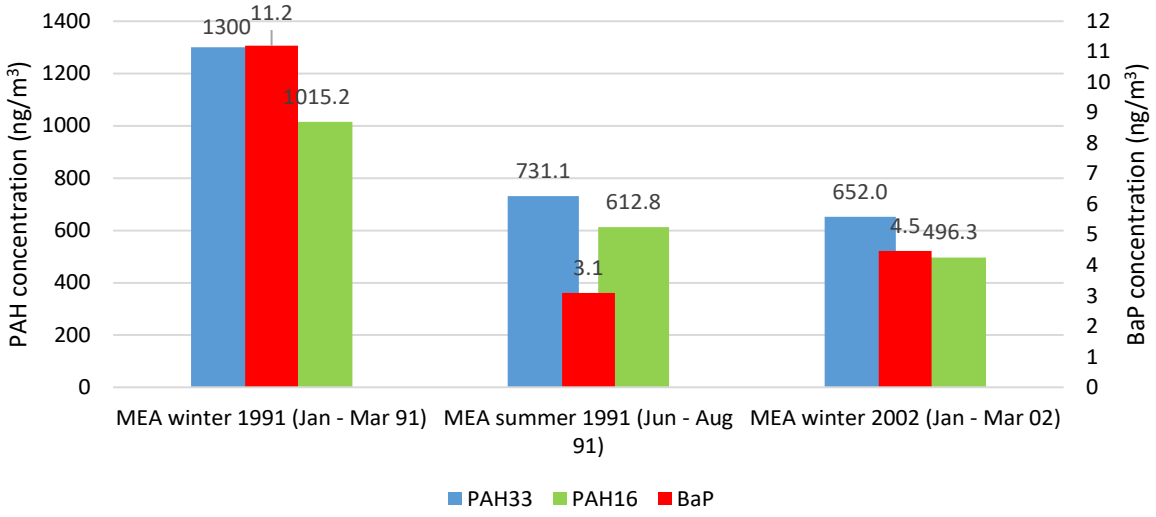


Figure 30: Average concentrations of sum PAH, PAH_{16} (left axis) and BaP (right axis) in Øvre Årdal, measured in winter and summer 1991 and winter 2002, units: ng/m³.

The PAH measurements in Øvre Årdal and Årdalstangen in winter 1991 were carried out to control the levels ten years after corresponding measurements (October 1980 – February 1982, Thrane, 1983e; Thrane, 1983f; Thrane, 1983a, also based on daily samples once or twice a week), since production conditions had changed and emissions had been reduced. The average PAH level in winter 1991 is reported to be significantly reduced compared to winters in the early 1980s (23% reduction in Øvre Årdal, 30% reduction at Årdalstangen), even though levels in winter 1991 were higher than in the two previous winters. In winter 1990, the level in Øvre Årdal was only 8% of the level ten years earlier, i.e. 92% reduction. Levels in Øvre Årdal are strongly dependent on the dispersion conditions. The PAH summer levels in 1991 in Øvre Årdal were 22% lower than in summer 1981.

In all measurement studies carried out in Øvre Årdal and Årdalstangen, daily average samples were taken once per week (using NILU's PUR sampler, see Appendix A). As the concentrations of PAHs can vary greatly from day to day, both due to variations in emissions and in the meteorological conditions (wind direction, wind speed, stability), the average values can be somewhat uncertain, and it can be difficult to give a correct assessment of the change in the concentrations from one period to another.

In addition to PAH measurements in ambient air, lettuce samples were collected in Årdal in summer 1991. There were large gradients in the concentrations within the nearest 1-2 km from the plant (Hagen, 1992).

All studies were carried out before the conversion from Söderberg to prebaked anodes, which took place in 2007 and is assumed to have led to a significant decrease in ambient PAH concentrations in Øvre Årdal. Also reduction of emissions from Årdalstangen led to decreasing ambient concentrations.

Kubal

Figure 31 illustrates the development in production and tar (PAH) emissions at Kubal from 1992 to 2020. Different measurement methods have been used for air emissions of tar and PAH during the

period, but tar is shown in the graph, since this parameter has the longest history of measurement. As can be seen, there have been some significant variations with some peaks up to 3 times the "normal" level. However, since the conversion from Söderberg to prebake in 2009, the tar (and PAH) emissions have been eliminated.

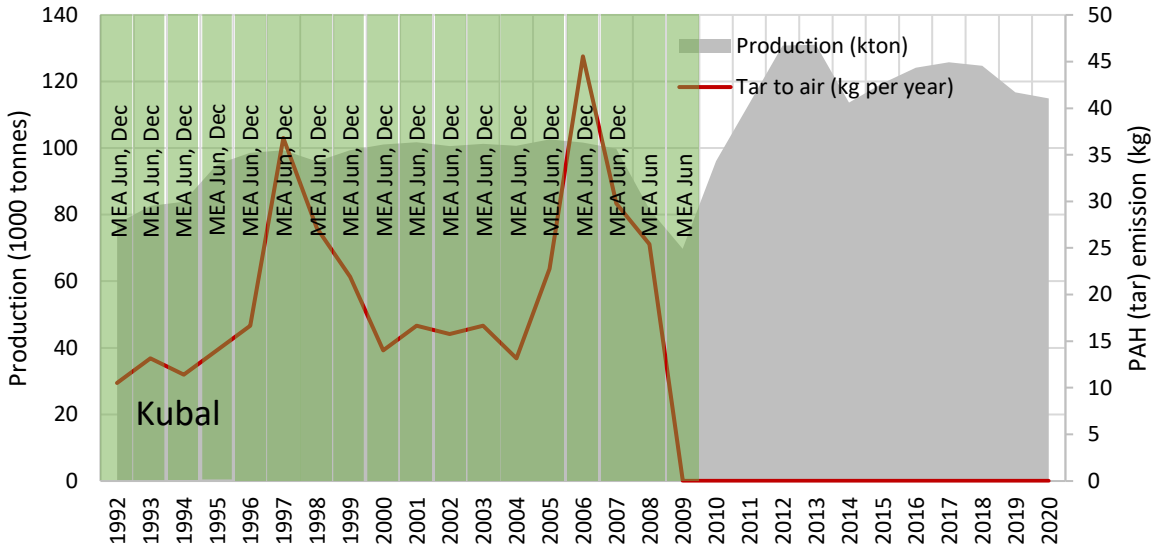


Figure 31: Emissions of PAHs, here: tar, (red line, unit: kg per year, right-hand y-axis) at Kubal from 1992 to 2020. Development of production (grey background, unit: 1000 tonnes per year, left-hand y-axis). Measurements (MEA) were carried out in summer and winter until 2009, as highlighted.

Kubikenborg Aluminium AB has been measuring PAH in Sundsvall for a long time (data since 1985 are available). The emissions from the smelter were large and the ambient PAH levels in Sundsvall were high. In the period 2007/2008, a conversion of Kubal's plant 2 was carried out (see Section 1.4.9), which ceased PAH emission from the aluminium smelter and thus entailed sharply reduced levels of PAHs in central Sundsvall (Sundsvall municipality, 2010). Between 1985 and 2009, PAHs[22] were measured at Villa Marieberg (Haga) and at Kubikenborg, twice a year (continuous daily average measurements every weekday in June and December). The method is described in Appendix A. The temporal development of benzo(a)pyrene concentrations from these measurements is shown in Figure 32. Measurements of BaP in June 2009 indicate that levels have decreased to 0.47 ng/m^3 at Kubikenborgsskolan and 0.15 ng/m^3 next to Villa Marieberg (Haga). For comparison, the average of summer measurements (June) during the period 1985 – 2008 showed levels of 3.45 ng/m^3 at Kubikenborgsskolan and 2.46 ng/m^3 next to Villa Marieberg (Haga). After Kubal's ambient PAH measurements stopped in 2009, Sundsvall municipality carried out BaP measurements in central Sundsvall in the period November 2011 to April 2012. The concentration of BaP was reported to be low and at the level that can be expected in an urban environment affected by traffic (Sundsvall municipality, 2013). The BaP average during the period was 0.07 ng/m^3.

[22] Data for benzo(a)pyrene, coronene, benzo(a)anthracene, chrysene and benzo(b)fluoranthene are available.

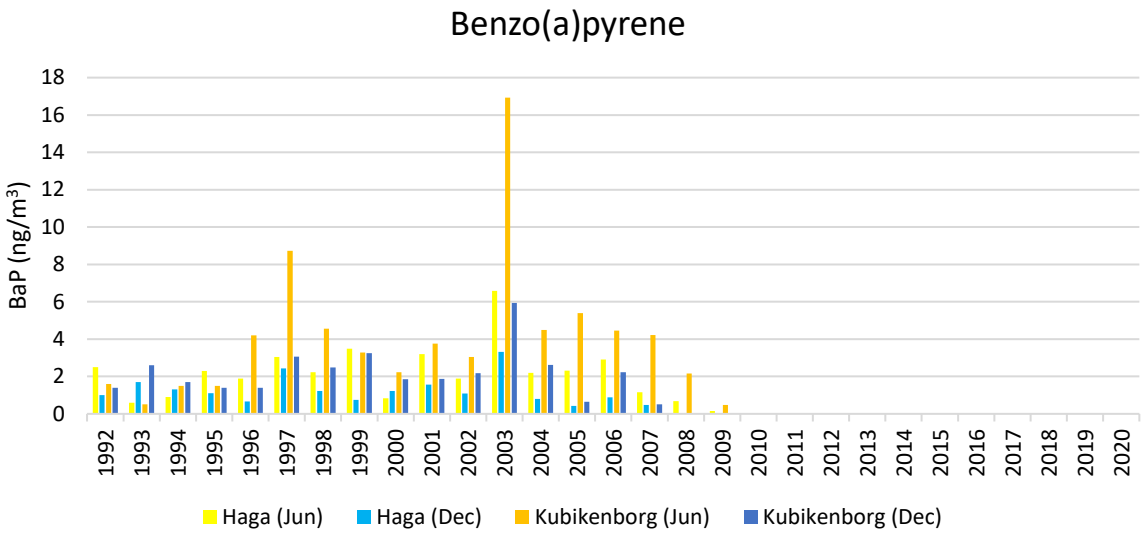


Figure 32: Concentrations of benzo(a)pyrene (BaP) in summer (Jun) and winter (Dec) from sampling at two stations in Sundsvall in the period 1992 – 2009.

ISAL

PAH emission data from ISAL were not available for the study. The plant has no anode production, and hence has practically no emissions of PAH to air. A small amount of PAH is released from leakage from the seaside landfill of spent potlining.

No PAH measurement data were available for ISAL.

2.2 Fluorides

The evolution of fluoride emissions (tonnes/year) for the individual plants in the period 1992 – 2020 are shown in Section 2.2.2, together with the yearly production (tonnes) and results from measurement and modelling studies.

2.2.1 Background concentrations

Fluorides have not been measured at Norwegian background sites.

2.2.2 Emissions and ambient concentrations

Fjarðaál

Figure 33 illustrates the development in production and fluoride emissions at Fjarðaál in the period 2007 – 2020. Emissions of fluoride have mainly followed the production curve, but increased in the period 2017 – 2020.

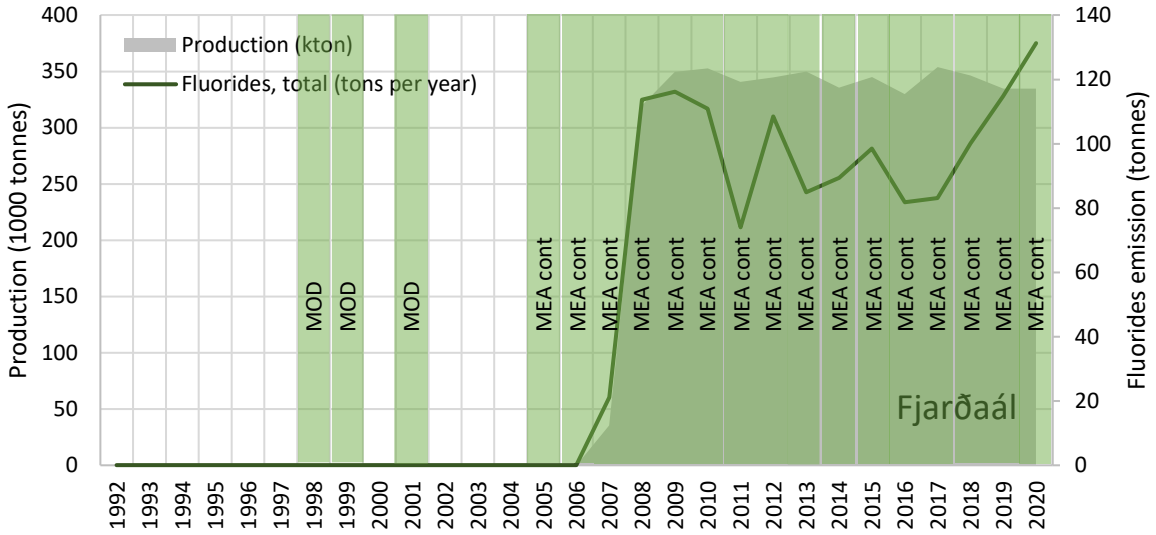


Figure 33: Emissions of fluorides (green line, unit: tonnes per year, right-hand y-axis) at Alcoa Fjarðaál from 2007 to 2020. Development of production (grey background, unit: 1000 tonnes per year, left-hand y-axis). The years modelling (MOD) studies were carried out, are highlighted. Measurements (MEA) have been carried out continuously since 2005.

The Alcoa Fjarðaál smelter was launched in April 2007. Continuous fluoride measurements have been carried out since 2005/2011 at four stations around the smelter (see Section 1.4.1). Annual average concentrations of gaseous fluorine and fluorine in PM in the period 2005/2011 – 2020 are shown in Figure 34. The ambient concentrations were highest in 2018/2019.

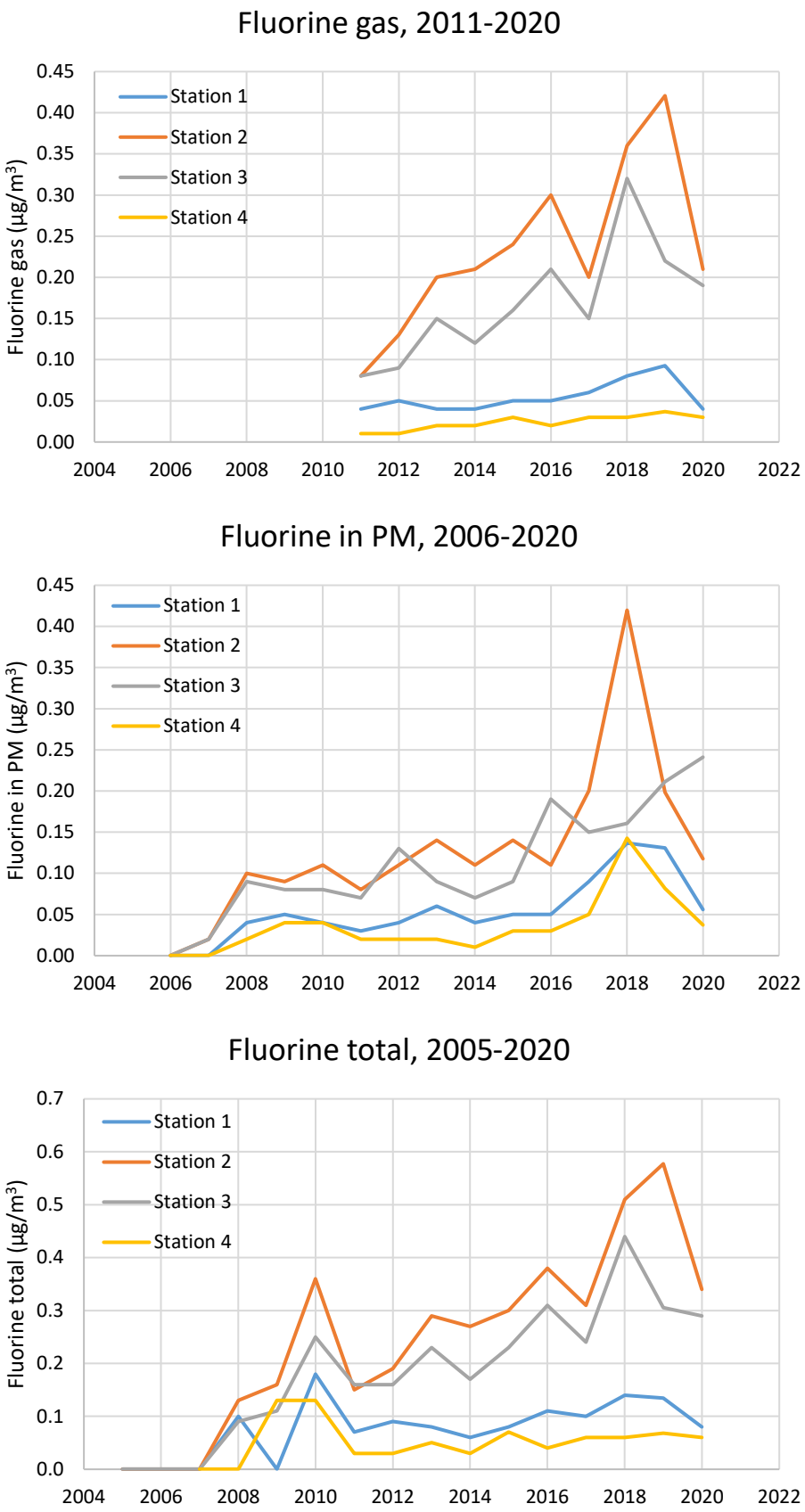


Figure 34: Average annual concentrations of fluorides (µg/m³) in the years 2006/2011 – 2020 at the four monitoring stations around Alcoa Fjarðaál. Please note different scales.

Model calculations and an impact assessment for fluoride emissions to air from the (then) planned aluminium smelter Fjarðaál were published in the years 1998, 1999 and 2001 (Guerreiro et al., 2001; Guerreiro, 1999; Guerreiro and Tshukudu, 1998a; Guerreiro and Tshukudu, 1998b).

Lista

Figure 35 illustrates the development in production and fluoride emissions from 1992 to 2020, as reported by Alcoa Lista[23]. Fluoride emissions (tonnes per year) went down about 30% compared to the early 1990s.

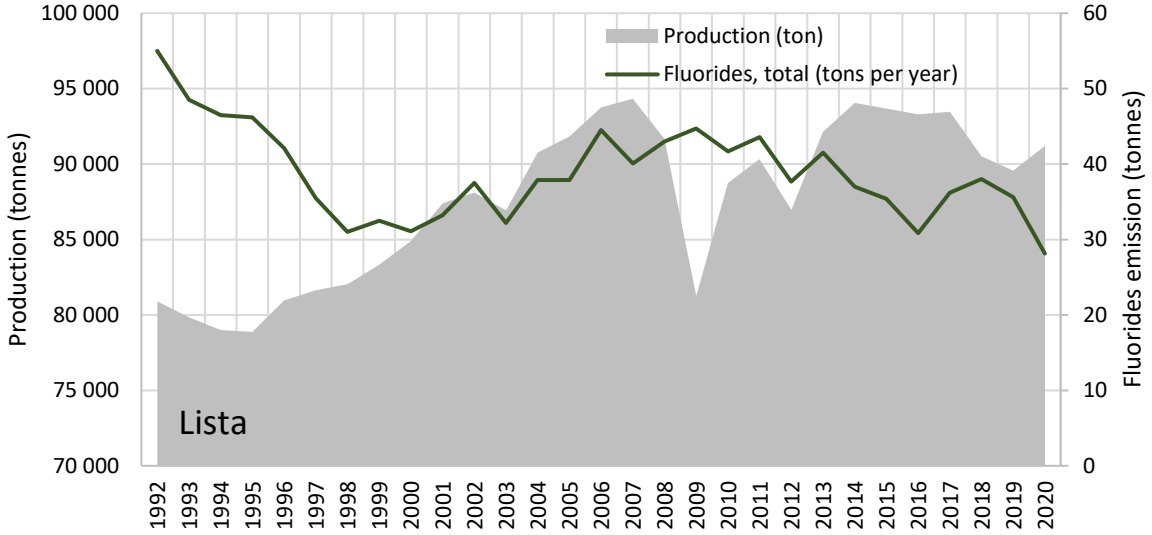


Figure 35: Emissions of fluorides (green line, unit: tonnes per year, right-hand y-axis) at Alcoa Lista from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). No measurement or modelling data are available for the period 1992 – 2020.

There are no recent measurements of fluorides in ambient air around Lista.

Mosjøen

Figure 36 illustrates the development in production and fluoride emissions at Alcoa Mosjøen from 1992 to 2020. The production (tonnes per year) has increased by 2/3 in the period, while fluoride emissions (tonnes per year) are approximately at the same level as in the early 1990s. There are hardly any other sources of fluoride than the aluminium plant in Mosjøen.

[23] https://www.norskeutslipp.no/no/Diverse/Virksomhet/?CompanyID=5310

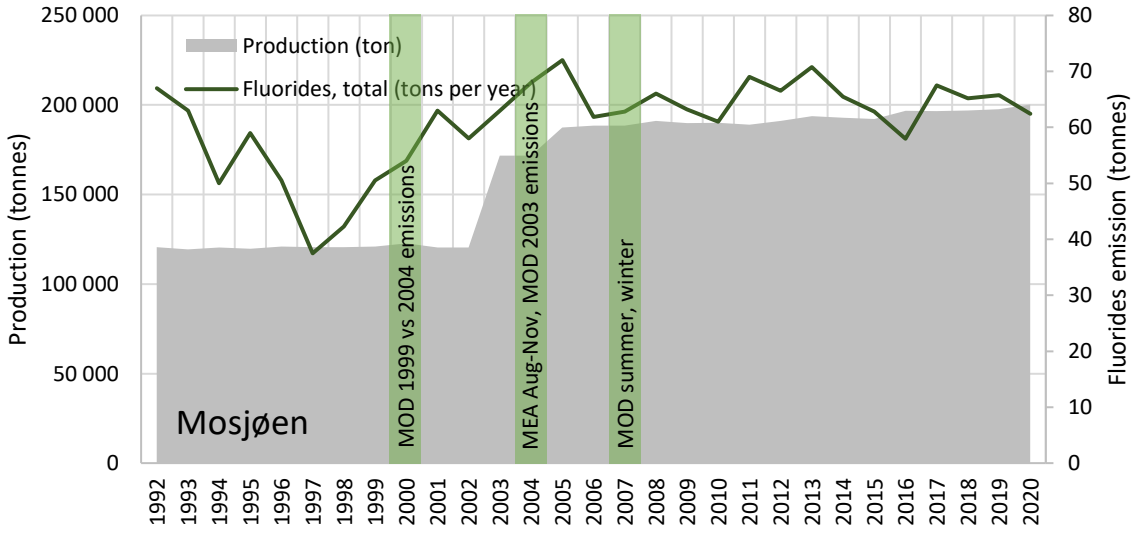


Figure 36: Emissions of fluorides (green line, unit: tonnes per year, right-hand y-axis) at Alcoa Mosjøen from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). The years measurement (MEA) or modelling (MOD) studies were carried out, are highlighted.

The ambient concentrations of fluorides (gaseous, particle phase and/or total) were assessed in three modelling studies (Grønskei and Gram, 2000; Tønnesen, 2004; Tønnesen, 2007) and one measurement study (Hagen, 2005) in the period 1992 – 2020. Measurements of fluorides in gaseous and particulate phase in autumn 2004 were carried out in Finnskoggata (see Section 1.4.3). NILU's "EK sampler" was used for sampling fluorides both in gaseous and particulate phase (see Appendix A). The samples were taken over 24 hours. The gaseous part was on average only approx. 1.5% of total fluoride (0.02 µg/m^3 and 1.3 µg/m^3). Although the formerly recommended air quality criteria were low (see Section 1.2), the measurement results from autumn 2004 indicated that the criteria would be met with a relatively good margin. In the period November 1980 – February 1982, measurements were made once a week of total[24] fluoride at a station located between the station in Finnskoggata and the former SO_2 station at Mosjøen gymnas (Thrane, 1983b). These measurements showed average values of particulate fluoride of 0.25 µg/m^3 autumn and winter, 1 µg/m^3 in spring and 1.5 µg/m^3 in summer. This difference is due to the difference in the wind frequency distribution throughout the year, with the highest frequency of wind from the plant towards the city in the summer months. Compared with other places with aluminium industry in Norway, the fluoride level measured at Mosjøen in the 1980s was low.

The measurements in autumn 2004 (Hagen, 2005) showed lower concentrations than the dispersion calculations carried out earlier in 2004 (Tønnesen, 2004). The measured level was similar to previous measurements for fluoride (1980 – 1982). The concentrations of the measured substances can vary greatly from day to day both due to variations in the emissions and in the meteorological conditions (wind direction, wind speed, stability). It was concluded to be probable that measurements throughout an entire summer season could have given a higher level than that measured in the period August – November 2004 (Hagen, 2005).

By 2000, Elkem Aluminium Mosjøen was planning a major rebuild and expansion of the aluminium plant, replacing old electrolysis ovens with Söderberg electrodes to ovens with prebaked electrodes. Dispersion calculations of gaseous fluoride were carried out in order to map the effect of emissions to air before (emissions from 1999) and after (emission prognosis for 2004) the conversion on air quality in Mosjøen (Grønskei and Gram, 2000). The modernisation and development of the plant was

[24] Total fluoride: gaseous and particulate fluorides

calculated to lead to higher emissions and concentrations of gaseous fluorine. The calculations indicated that there may be exceedances of recommended air quality criteria for fluorine and particles, where the highest contributions come from untreated hall gas. The highest concentrations were calculated to be close to the plant, with large concentration gradients in the area.

By 2004, Elkem Aluminium Mosjøen was planning the construction and operation of a baking plant for prebaked anodes. Dispersion calculations were carried out in connection with this conversion to map the effect on the air quality in Mosjøen of emissions to air after the start-up of the baking plant (Tønnesen, 2004). The updated calculations showed that the pollution load around the plant was projected to be lower than calculated in the previous report by Grønskei and Gram (2000). By now, the model calculations are outdated and results are not shown here.

Husnes

Figure 37 illustrates the development in production and fluoride emissions from 1992 to 2020. The production capacity (tonnes per year) had not been fully utilised in the early 1990s due to the market situation. The following increase during 1992 – 2003 was due to gradual restart of cells. However, in 2009, potroom B was shut down as a consequence of the finance crisis. The fluoride emissions (tonnes per year) increased during the production increase and fell when the production was reduced. In 2017, they were approximately 25% lower than in the early 1990s. Re-start of potroom B will result in increased emissions, more or less in proportion to the increase in production. The production in 1998 was not reported[25].

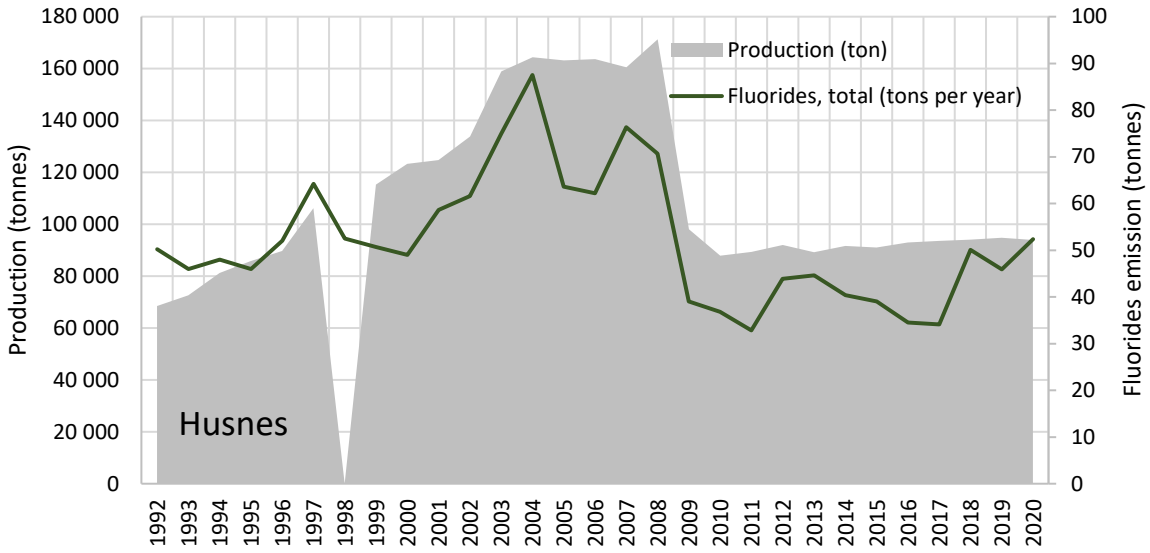


Figure 37: Emissions of fluorides (green line, unit: tonnes per year, right-hand y-axis) at Hydro Husnes from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). No measurement or modelling data are available for the period 1992 – 2020.

No ambient fluoride measurement data from Husnes are available.

25 https://www.norskeutslipp.no/Templates/NorskeUtslipp/Pages/company.aspx?id=61&CompanyID=6256&epslanguage=no&SectorID=600

Høyanger

Figure 38 illustrates the development in production and fluoride emissions at Hydro Høyanger from 1992 to 2020. The fluoride emissions (tonnes per year) were reduced by 2/3 when the Söderberg line was closed in 2006.

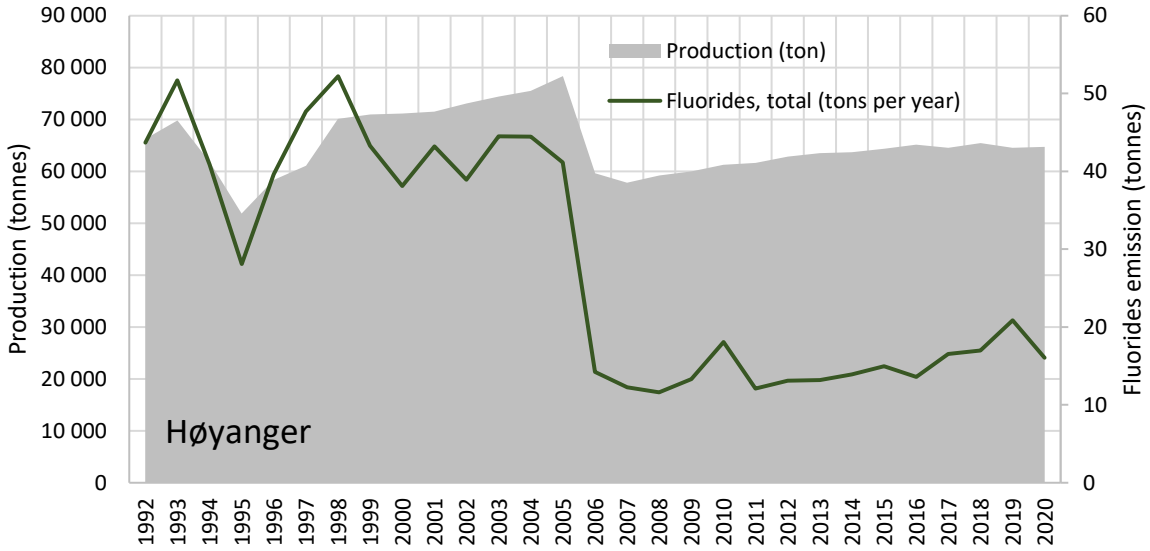


Figure 38: Emissions of fluorides (green line, unit: tonnes per year, right-hand y-axis) at Hydro Høyanger from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). No measurement or modelling data are available for the period 1992 – 2020.

There are no recent measurements of fluorides in ambient air around Høyanger.

Karmøy

Figure 39 illustrates the development in production and fluoride emissions at Hydro Karmøy from 1992 to 2020. After a recent increase in production, fluoride emissions (tonnes per year) are higher than in the early 1990s.

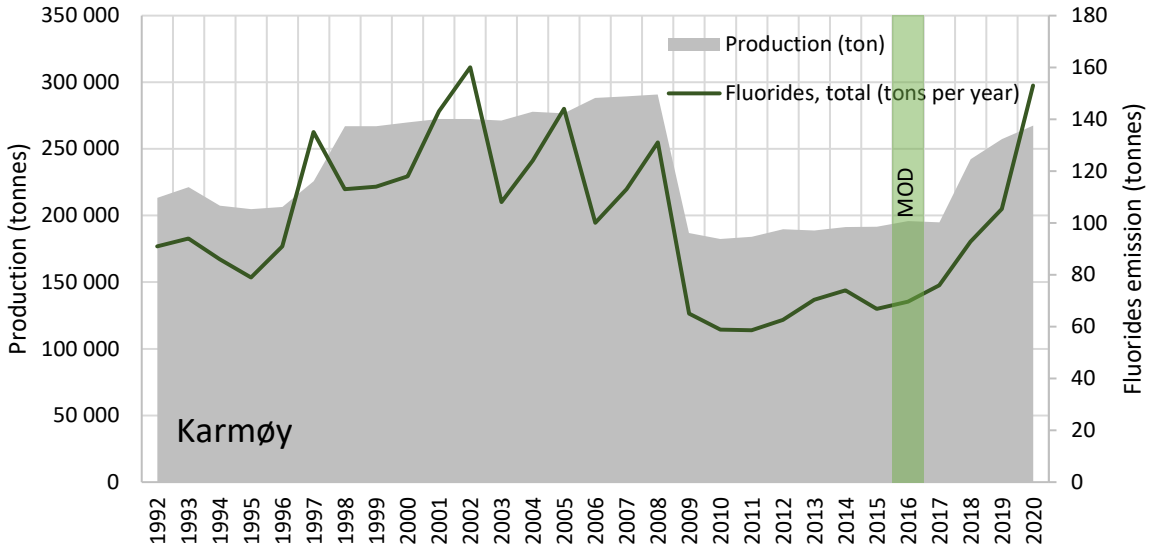


Figure 39: Emissions of fluorides (green line, unit: tonnes per year, right-hand y-axis) at Hydro Karmøy from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). A modelling (MOD) study was carried out in 2016, as highlighted.

No recent measurement data of air pollutants in the surroundings of Hydro Karmøy are available. In 2016, model calculations of the dispersion of emissions from an increased production after a planned expansion have been performed for the Karmøy aluminium smelter (Tønnesen, 2016). In connection with the planned expansion, the emission permit required Hydro Karmøy to carry out dispersion calculations for the fully developed plant to verify the assumed stack heights. As can be seen in Figure 39, the expansion was finalised in 2018 and production went up. The calculations were performed for, a.o. hydrogen fluoride (HF) and particulate fluorine.

The maximum annual average calculated for the fully developed plant over land outside the factory area was 1.5 µg/m^3 for hydrogen fluoride and 0.9 µg/m^3 for fluorine (assumed to be particulate fluorine), occurring northwest of the plant between the plant and RV 47. The background concentration was assumed to be 0. The recommended criterion for health (10 µg/m^3 for half-year averages), which is not in force today, was complied with by a good margin. However, the recommended criterion for the effect of fluorides on vegetation of 1 µg/m^3 (average over 24 hours), which also is not in force today, was calculated to be exceeded up to 1 km from the border of the factory area. Changes in the design and height of the gas treatment plants in the new development were calculated to affect the extent of the exceedance insignificantly. Emissions from the roof of the production hall contributed 95% of the total concentration within the area of exceedance. The dispersion conditions which give the largest overall contribution are wind along the plant's longitudinal axis (northeast – southwest) with a wind speed of 4-6 m/s. The occurrence of such wind conditions is less than 3% of the time on an annual basis for the wind sector with dispersion towards in land (towards Austevik).

Sunndal

Figure 40 illustrates the development in production and fluoride emissions from 1992 to 2020. The production (tonnes per year) at Hydro Sunndal has increased almost threefold in the period 1992 – 2020, while total fluoride emissions (tonnes per year) have not changed markedly compared to the early 1990s, due to conversion to prebake technology and more efficient fume-treatment plants removing fluorides.

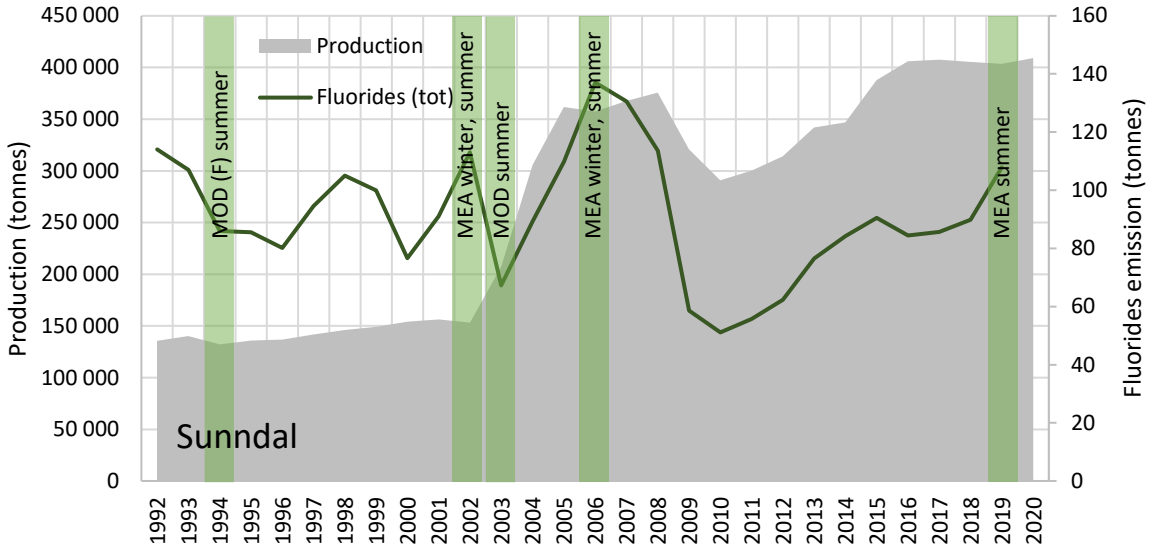


Figure 40: Emissions of fluorides (green line, unit: tonnes per year, right-hand y-axis) at Hydro Sunndal from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). The years measurement (MEA) or modelling (MOD) studies were carried out, are highlighted.

The most recent measurements in ambient air were carried out in summer 2019 (Hak, 2021a) at two stations, Pensjonistsenteret (in the centre of Sunndalsøra) and Vennevold (6 km up the valley). The 3-month average concentration of particle-bound fluorides was 0.37 µg/m^3 at Pensjonistsenteret and 0.13 µg/m^3 at Vennevold. These levels are 24% and 42%, respectively, lower than levels of particle-bound fluorides reported for 2006 (see Figure 41). The emissions of total fluorides and the PM-emissions are reported to have decreased between 2006 and 2019, even though the production has increased. The sampling method used was the same as in 2002 and 2006 and the same analysis principle was used. In 2002 and 2006, measurements were carried out on 20 days distributed over 3 months. These results are more sensitive to time variations than weekly samples.

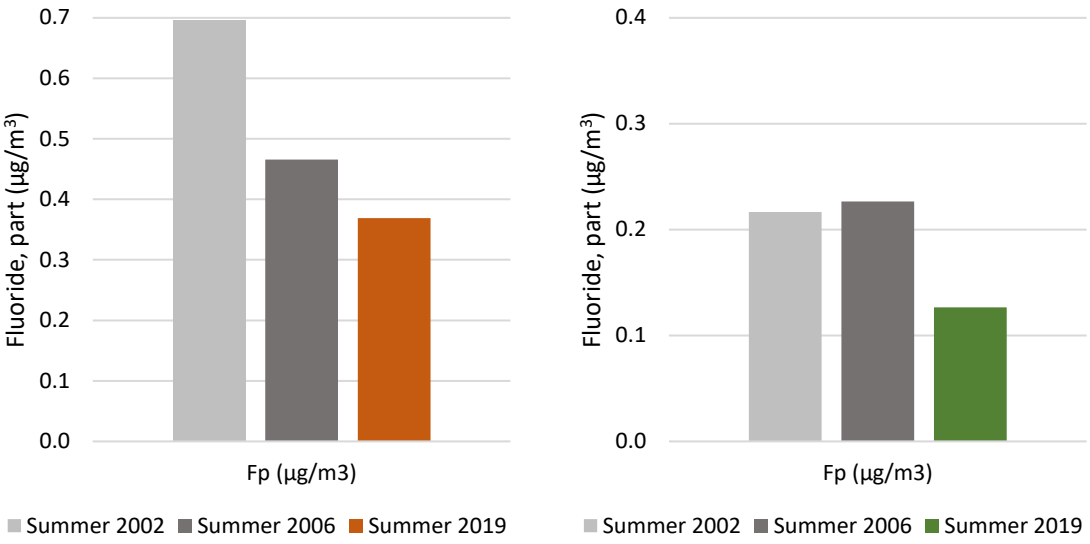


Figure 41: Average concentration of particle-bound fluoride in summer 2002 (10 weeks), summer 2006 (9 weeks) and summer 2019 (12 weeks) at Pensjonistsenteret (left-hand panel) and at Vennevold (right-hand panel). Note different scales.

For comparison, results from dispersion calculations for summer 1990 and summer 1997 are presented in the modelling study by Bøhler and Larsen (1991). In the centre of Sunndalsøra, a half-year average over summer 1990 of around 3-5 µg/m^3 is shown for total fluoride concentrations. A summer average of ca. 0.4 µg/m^3 several km up the valley (area around Vennevold) is shown for summer 1990. After the expansion of the smelter, a reduction of the total fluoride emissions by 30% (compared to 1990) was estimated. Dispersion calculations for total fluoride for summer 1997 showed 1-3 µg/m^3 in the centre of Sunndalsøra and around 0.4 µg/m^3 several km up the valley. The expansion of SU4 and the closure of SU1/2 was estimated to lead to small changes in fluoride emissions. Emissions via the roof of SU1 and SU2 were estimated as the largest fluoride emissions at Hydro Sunndal in 1990. For the dispersion calculations it is assumed that the particles have a diameter less than 10-15 µm. If a substantial share of the particles has a diameter 30-50 µm, those will deposit close to the smelter and increase the gradient around the smelter.

The 3-month average concentration of gaseous fluorides was 0.40 µg/m^3 at Pensjonistsenteret and 0.19 µg/m^3 at Vennevold. These levels are markedly lower than levels of gaseous fluorides reported for 2006 (see Figure 42) and little lower than in 2002.

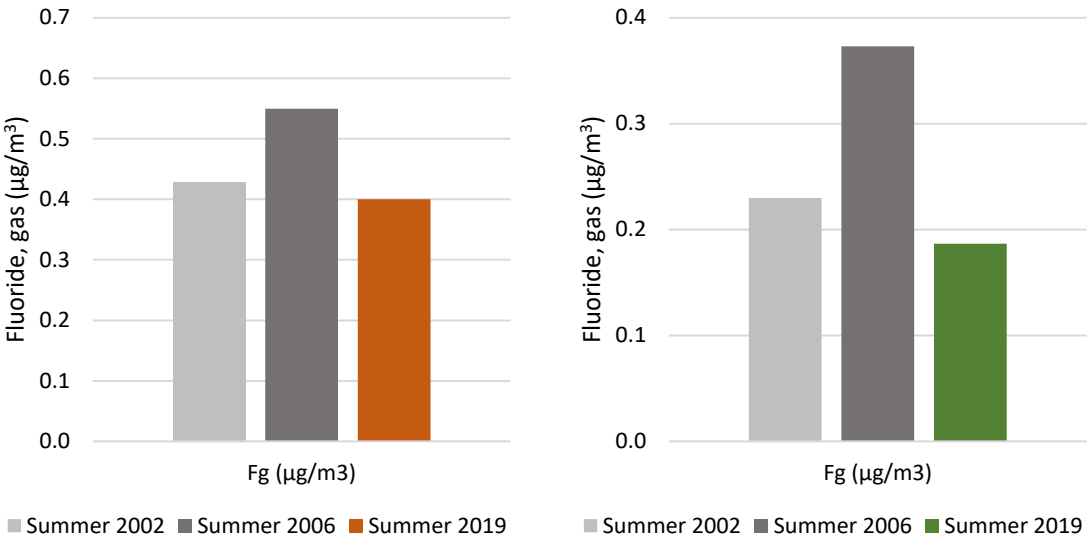


Figure 42: Average concentration of gaseous fluoride in summer 2002 (10 weeks), summer 2006 (9 weeks) and summer 2019 (12 weeks) at Pensjonistsenteret (left-hand panel) and at Vennevold (right-hand panel). Note different scales.

Dispersion calculations for fluorides in Sunndalen were carried out by Bøhler et al. (1994) in order to calculate the uptake of fluorides in plants as well as the wet deposition of fluorides in Sunndalen (using the same emission data as Bøhler and Larsen (1991)). The calculated uptake is largest in July (32 mg/m^2 month at Sunndalsøra) compared to the entire year and varies depending on the vegetation type. Uptake calculated for areas around Vennevold was about half of that. Monthly average concentrations of fluoride in air calculated for the receptor Sunndalsøra for 1991 were 2.4 µg/m^3 in May, 1.94 µg/m^3 in June, 2.33 µg/m^3 in July and 2.07 µg/m^3 in August. Concentrations up towards Sunndalen calculated for July were 0.93 µg/m^3 at Furu and 0.54 µg/m^3 at Hoås. The receptors Furu (3.5 km from the smelter) and Hoås (10 km from the smelter) further up Sunndalen may represent the situation at Vennevold.

Øvre Årdal and Årdalstangen

Figure 43 illustrates the development in production and fluoride emissions at Hydro Årdal and Årdalstangen from 1992 to 2020. The fluoride emissions (tonnes per year) increased slightly during the production increase and fell when the Söderberg line was closed. In 2020, the emissions were approximately 15% lower than in the early 1990s. Nearly all the fluoride emissions come from the metal plant of which ca. 76% of the fluoride emissions come from the halls, according to data received from Årdal Metallverk.

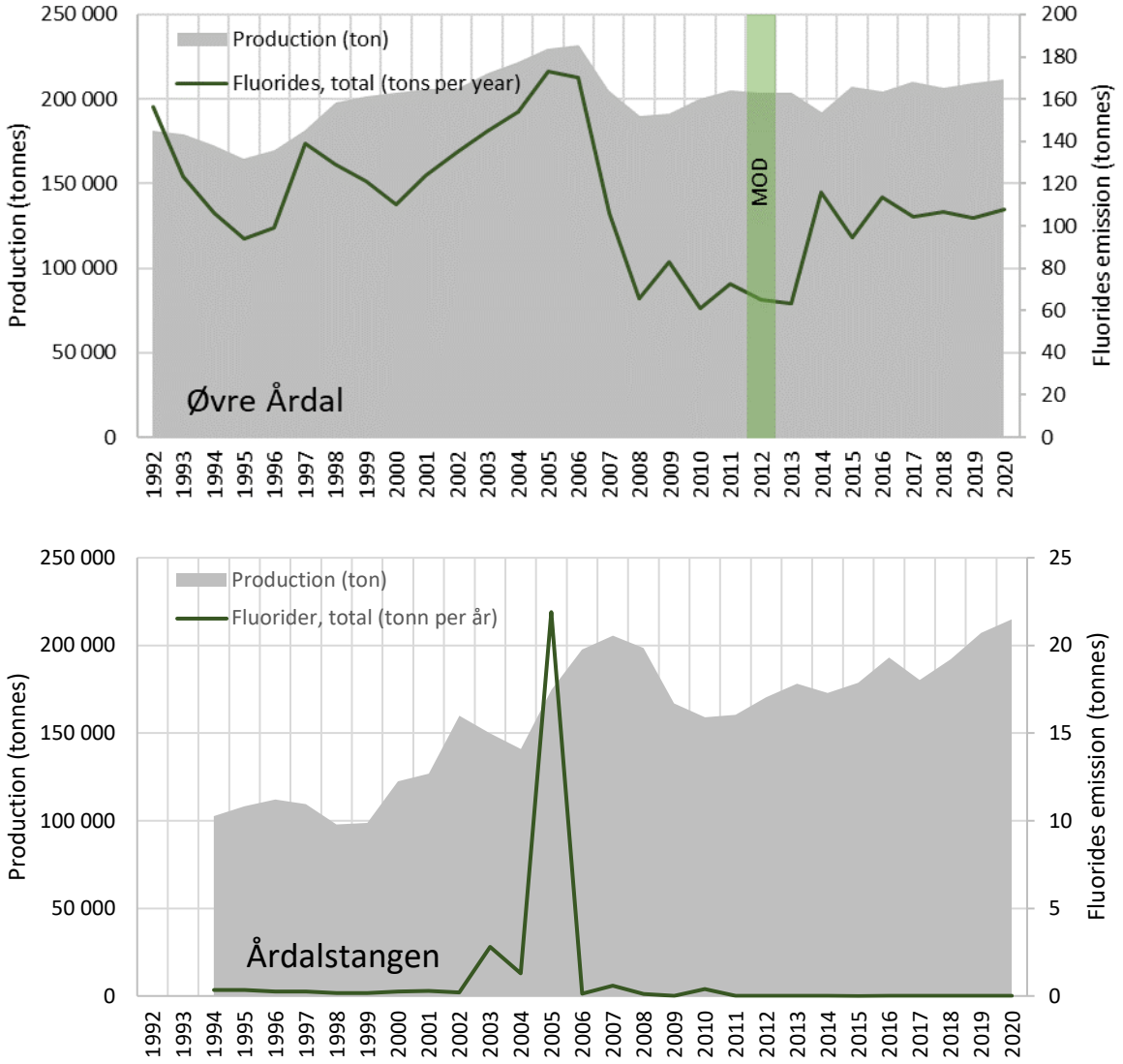


Figure 43: Emissions of fluorides (green line, unit: tonnes per year, right-hand y-axis) at Hydro Årdal[26] and Årdalstangen from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). A modelling (MOD) study for Øvre Årdal was carried out in 2012, as highlighted.

Dispersion calculations for SO_2, fluorides, particulate matter and heavy metals at Øvre Årdal were carried out in 2012 (Hak and Castell, 2012b) to map the effect on air quality in Øvre Årdal of emissions to air under normal operating conditions, using meteorology from 2010. Dispersion calculations of SO_2 were used as a basis for calculating the dispersion of fluoride, particulate matter and heavy metals. The calculated annual average concentration of gaseous fluoride was a maximum of 5 µg/m^3, while Klif's[27] recommended air quality criterion at that time was 10 µg/m^3 for half-yearly average. Maximum annual average calculated for total fluoride was 8 µg/m^3.

[26] https://www.norskeutslipp.no/no/Diverse/Virksomhet/?CompanyID=6258 and https://www.norskeutslipp.no/no/Diverse/Virksomhet/?CompanyID=6259

[27] Klif: Klima- og forurensningsdirektoratet, now: Miljødirektoratet

Kubal

Figure 44 illustrates the development in production and fluoride emissions from 1992 to 2020. While production (in 1000 tonnes per year) has increased more than 50%, fluoride emissions (tonnes per year) are close to the same level as in the early 1990s.

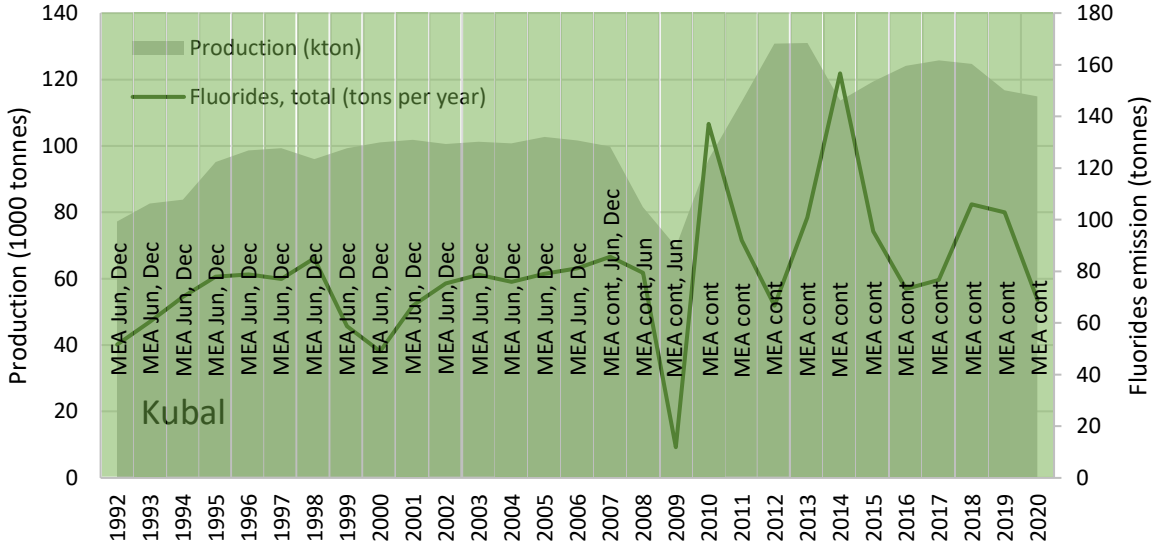


Figure 44: Emissions of fluorides (green line, unit: tonnes per year, right-hand y-axis) at Kubal from 1992 to 2020. Development of production (grey background, unit: 1000 tonnes per year, left-hand y-axis). Measurements (MEA) were carried out over the entire period 1992 – 2020, continuously (cont) and season wise (Jun, Dec), as highlighted.

Kubikenborg Aluminium AB has been measuring fluorides in Sundsvall for a long time (data since 1985 are available). Between 1985 and 2009, fluorides were measured at Villa Marieberg (Haga), 3.3 km northwest of the smelter, and at Kubikenborg right west from the smelter, twice a year (continuous daily average measurements every weekday in June and December). The method is described in Appendix A. The temporal development of fluoride concentrations from these measurements is shown in Figure 45. Fluorides have been measured continuously (daily average samples once per week) at 2-3 sites in Sundsvall since 2007 (see Figure 46). In the period 1992 – 2020, ambient concentrations of fluorides in Sundsvall have been varying in time with emissions. As a matter of course, levels were highest at Kubikenborg, which is located adjacent to the smelter.

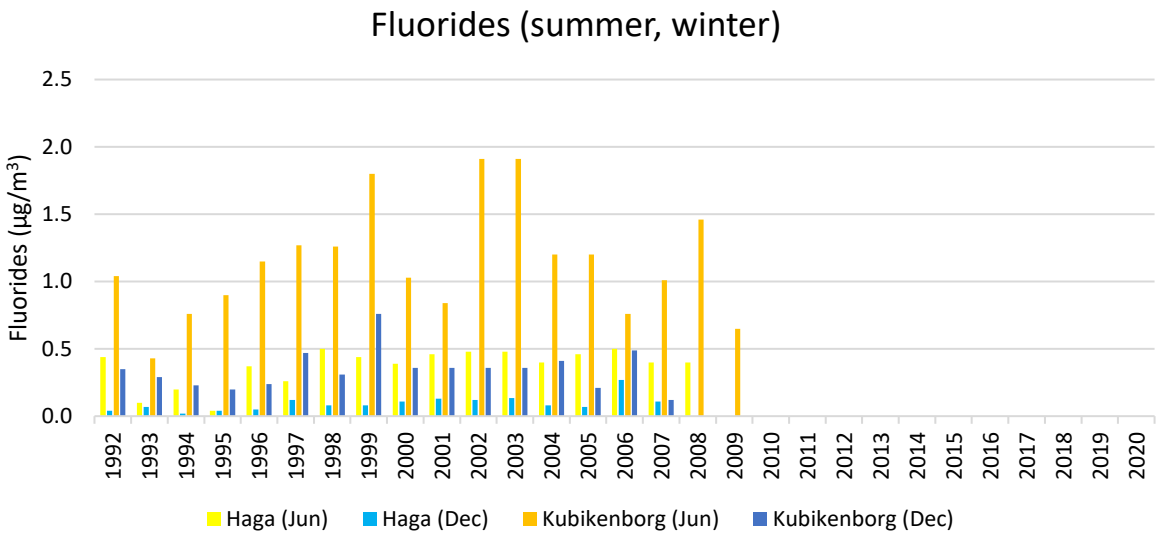


Figure 45: Concentrations of fluorides in summer (Jun) and winter (Dec) from sampling at two stations in Sundsvall in the period 1992 – 2009. Unit: µg/m³.

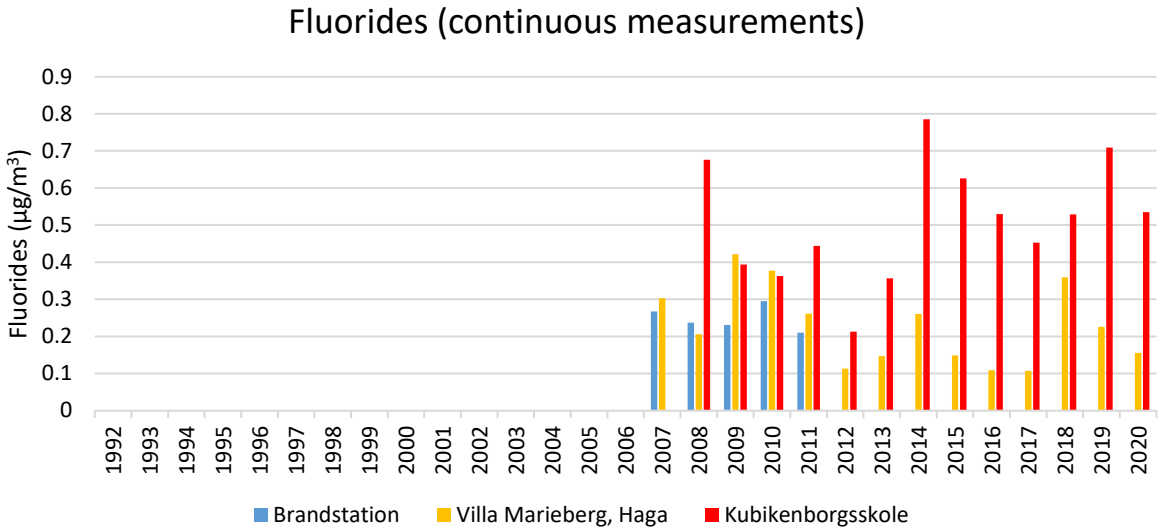


Figure 46: Annual average concentrations of fluorides from continuous measurements at 2-3 stations in Sundsvall in the period 2007 – 2020. Unit: µg/m³.

KUBAL carried out short measurement campaigns for HF in July 2012, September 2018, September 2019 and May/June 2021. The same method was used in all four campaigns (but different from the method mentioned above). The measurements cover four consecutive 24-hour samples for each of the campaigns. As shown in Figure 47, ambient HF concentrations at three sites close to KUBAL increased from 2012 to 2021. The purpose of the campaign measurements was to see the effect of changing from stack-led emissions to roof ventilators in Plant 2. Roof ventilators were installed in Plant 2 in 2013. The increase of ambient fluoride concentrations indicates that the roof ventilators increase the concentration in close proximity to the plant and have possibly more effect on the surrounding area. This was expected since the emissions are no longer emitted through chimneys nor diluted and dispersed like before. Unfortunately, the campaign measurements 2018, 2019 and 2021 (four daily samples, as mentioned above) have been carried out when the emissions have been higher than normal. As shown in Figure 46, the trend is not as clear in the weekly measurements.

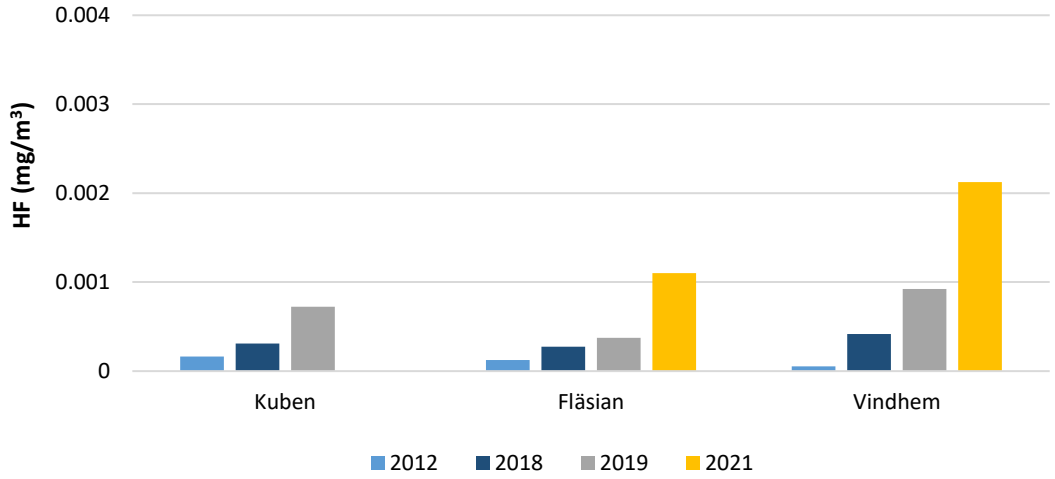


Figure 47: HF average over campaign measurements at Kuben, Fläsian and Vindhem carried out over four days each in 2012, 2018, 2019 and 2021. Note that the concentrations are shown in mg/m³.

ISAL

Figure 48 illustrates the development in production and fluoride emissions from 1992 to 2020. Production (1000 tonnes per year) more than doubled in the period, while fluoride emissions (tonnes per year) are approximately at the same level as in the early 1990s.

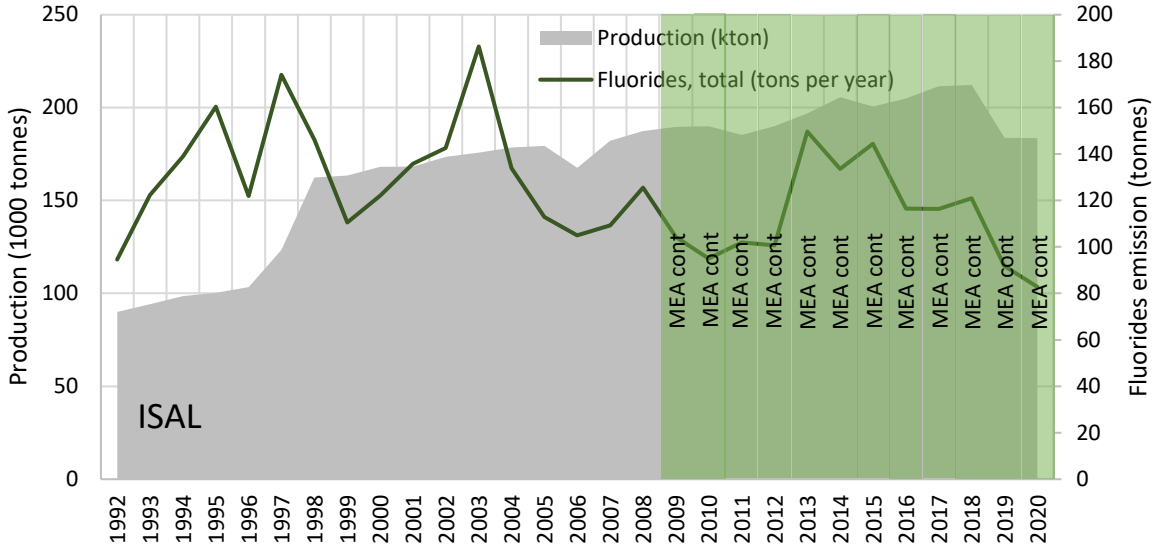


Figure 48: Emissions of fluorides (green line, unit: tonnes per year, right-hand y-axis) at ISAL from 1992 to 2020. Development of production (grey background, unit: 1000 tonnes per year, left-hand y-axis). Measurements (MEA) have been carried out since 1994. Continuous data from 2009 were available for the report, as highlighted.

A measurement programme to monitor air quality parameters has been carried out at Hvaleyrarholt, ca. 2 km northeast of the smelter, since 1994. Data from 2009 were available for this report. Gaseous and particulate fluoride is sampled on filters. Annual average concentrations of gaseous fluorides and particulate fluorides are shown in Figure 49. The ambient concentrations of fluorides in the particle

phase have been decreasing in recent years and are well below relevant criteria for protection of vegetation and animals.

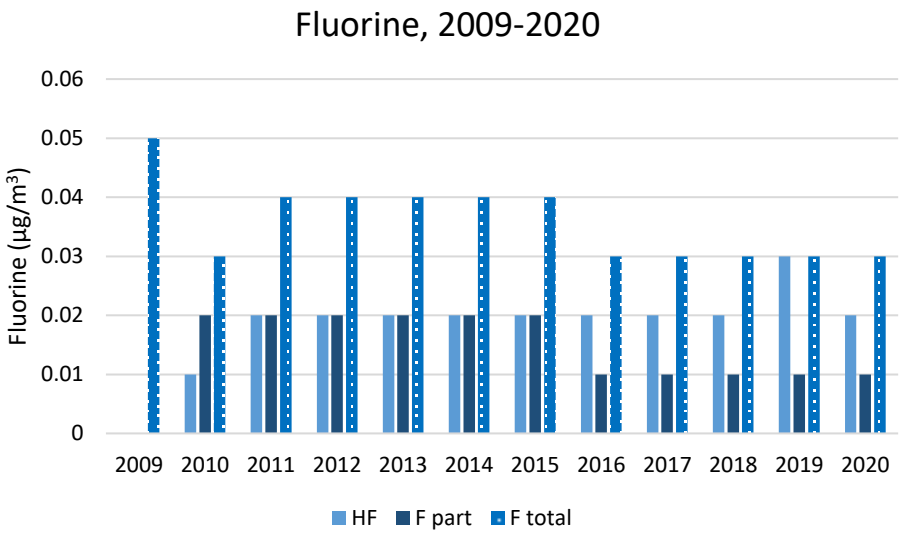


Figure 49: Annual average concentrations of fluorine in the years 2009/10 – 2020 at Hvaleyrarholt, 2 km northeast of ISAL.

2.3 Sulphur dioxide

2.3.1 Background concentrations

At the background stations Birkenes, Hurdal, Kårvatn, Tustervatn and Zeppelin, SO_2 has been measured for several decades (Aas et al., 2021). Figure 50 shows how SO_2 concentrations at Norwegian background sites have developed over the last decades, showing a decreasing trend especially at Birkenes, which is most influenced by long-range transport from the European continent. Aas et al. (2021) report strongly decreasing SO_2-trends in the period 1990 – 2019 at all regional background stations, as indicated in Figure 50.

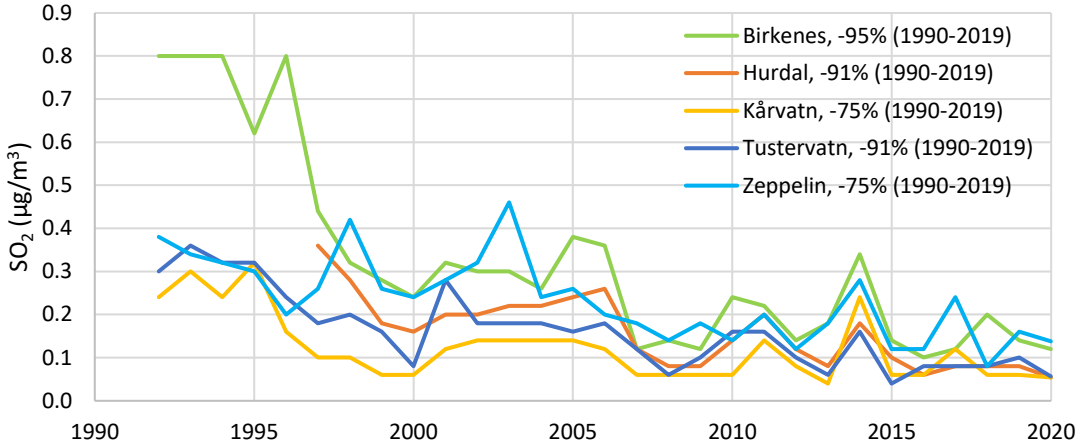


Figure 50: Variation of sulphur dioxide concentration (µg/m³)[28] at Norwegian background sites in the period 1992 – 2020.

2.3.2 Emissions and ambient concentrations

The Icelandic smelters do not have wet scrubbers due to less sensitive terrestrial environment and relatively good dispersion conditions.

Fjarðaál

Figure 51 illustrates the development in production and SO_2 emissions in the period 2007 – 2020. Emissions of SO_2 continued to rise from 2008 to 2013 due to increased sulphur content in anodes. After this, SO_2 emissions have been slightly reduced again.

[28] Aas et al. (2021) report SO_2 levels in µg S/m³. 1 µg S/m³ corresponds to 2 µg/m³ SO_2. Here levels are converted to µg/m³.

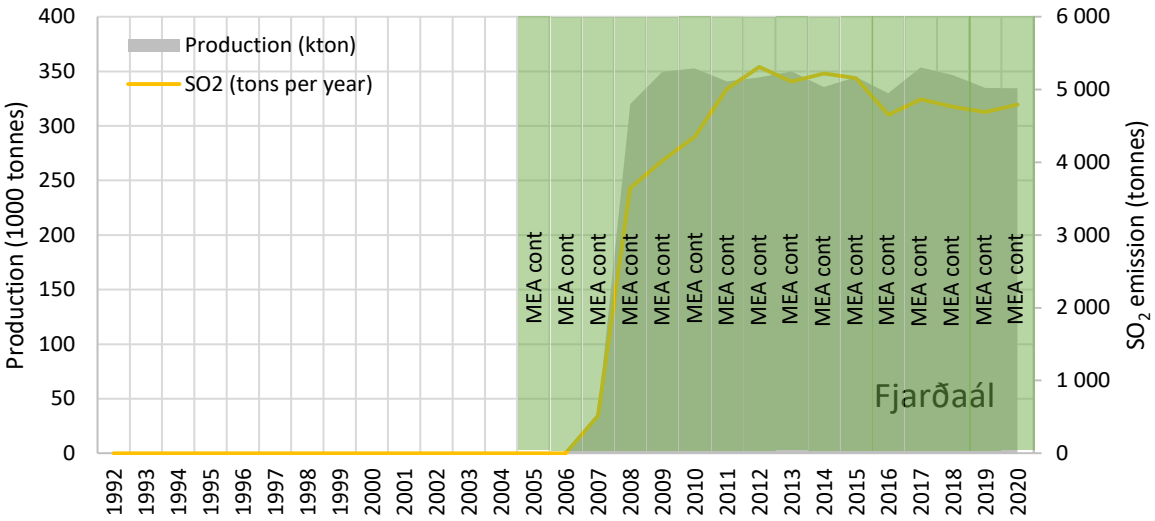


Figure 51: Emissions of sulphur dioxide (yellow line, unit: tonnes per year, right-hand y-axis) at Alcoa Fjarðaál from 1992 to 2020. Development of production (grey background, unit: 1000 tonnes per year, left-hand y-axis). Measurements (MEA) have been carried out continuously since 2005, as highlighted.

The Alcoa Fjarðaál smelter was launched in April 2007. Continuous SO_2 measurements have been carried out by Náttúrustofa Austurlands since 2005 at four stations around the smelter (see Section 1.4.1). Annual averages of SO_2 concentrations in the period 2005 – 2020 are shown in Figure 52. Production and emissions have been rather constant since the smelter started operation. The ambient concentrations measured were also rather constant. Highest concentrations were measured in 2014 as a consequence of the eruption in Holuhraun in the Northeastern Region of Iceland (29. August 2014 – 27. February 2015).

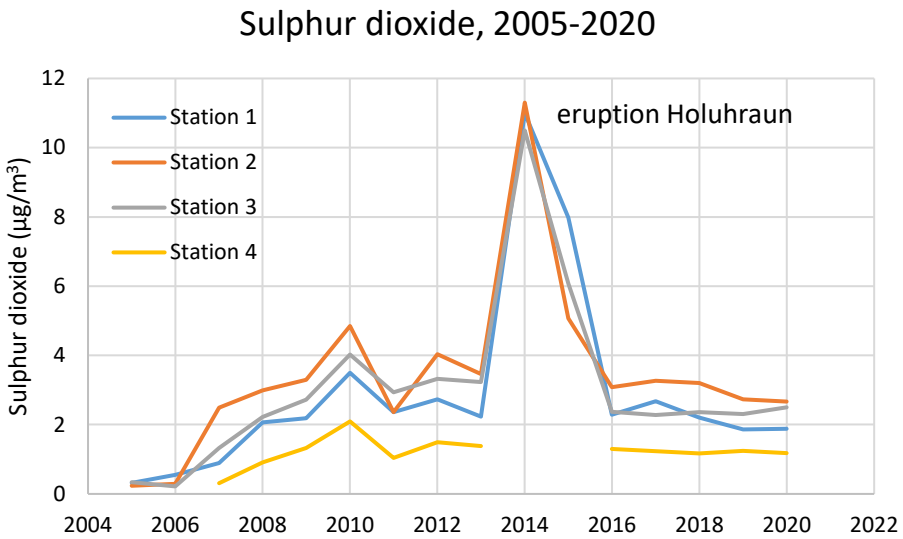


Figure 52: Annual average concentrations of sulphur dioxide in the years 2005 – 2020 at the four monitoring stations around Alcoa Fjarðaál. Unit: µg/m³.

Model calculations and an impact assessment for SO_2 emissions to air from the planned aluminium smelter Fjarðaál were published in the years 1998, 1999 and 2001 (Guerreiro et al., 2001; Guerreiro, 2001; Guerreiro, 1999; Guerreiro and Tshukudu, 1998a; Guerreiro and Tshukudu, 1998b).

Lista

Figure 53 illustrates the development in production and SO_2 emissions from 1992 to 2020, as reported by Alcoa Lista[29]. SO_2 emissions (tonnes per year) are reduced ca. 75% compared to the early 1990s. However, some of the reduction for SO_2 after 2011 may be related to a change in sampling procedure, hence the reduction is more likely 65% for SO_2.

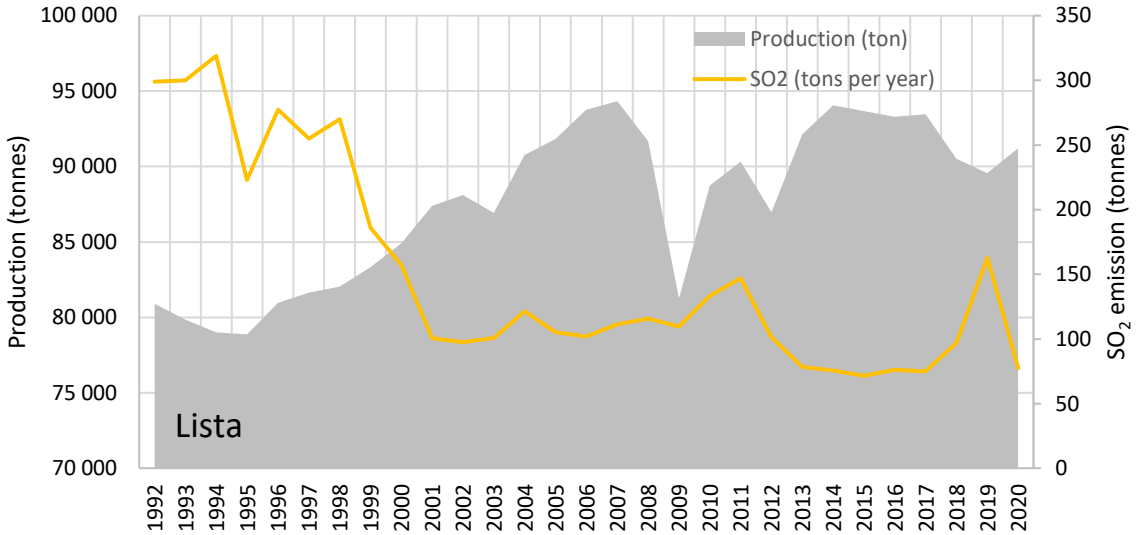


Figure 53: Emissions of sulphur dioxide (yellow line, unit: tonnes per year, right-hand y-axis) at Alcoa Lista from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). No measurement or modelling data are available for the period 1992 – 2020.

There are no recent measurements of SO_2 in ambient air around Lista.

Mosjøen

Figure 54 illustrates the development in production and SO_2 emissions from 1992 to 2020. SO_2-emissions (tonnes per year) are reduced by about 70%. The peak emissions for SO_2 in 2005 – 2007 were due to construction of new gas treatment plants while the old ones were phased out, in accordance with a dispensation from the authorities.

[29] https://www.norskeutslipp.no/no/Diverse/Virksomhet/?CompanyID=5310

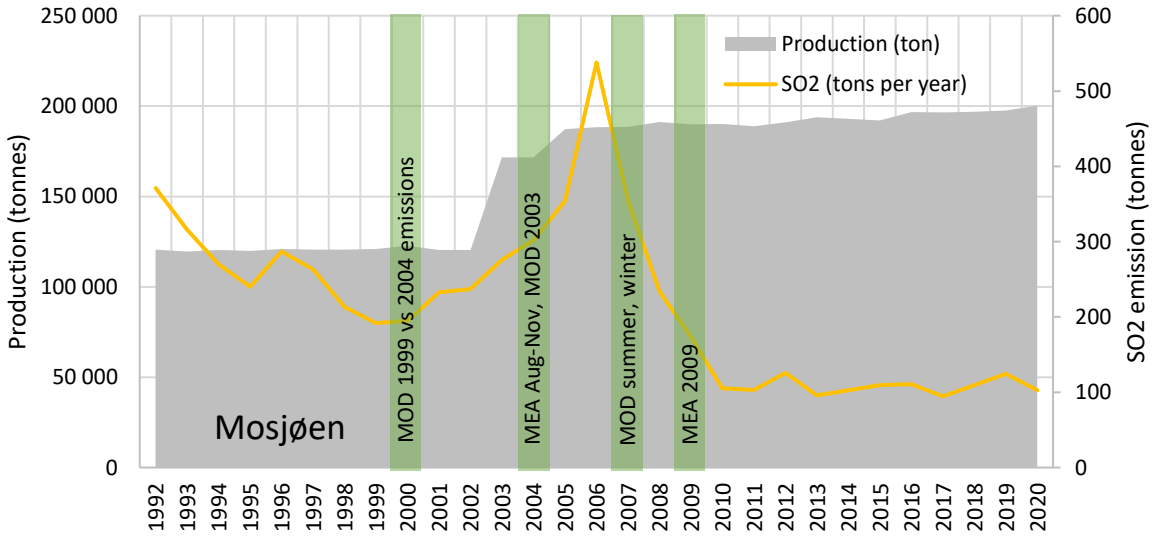


Figure 54: Emissions of sulphur dioxide (yellow line, unit: tonnes per year, right-hand y-axis) at Alcoa Mosjøen from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). The years measurement (MEA) or modelling (MOD) studies were carried out, are highlighted.

The ambient concentrations of SO_2 were assessed in three modelling studies (Grønskei and Gram, 2000; Tønnesen, 2004; Tønnesen, 2007) and two measurement studies (Hagen, 2005; Haugsbakk, 2010) in the period 1992 – 2000. Figure 55 shows concentrations of SO_2 measured and calculated in Mosjøen since 1992.

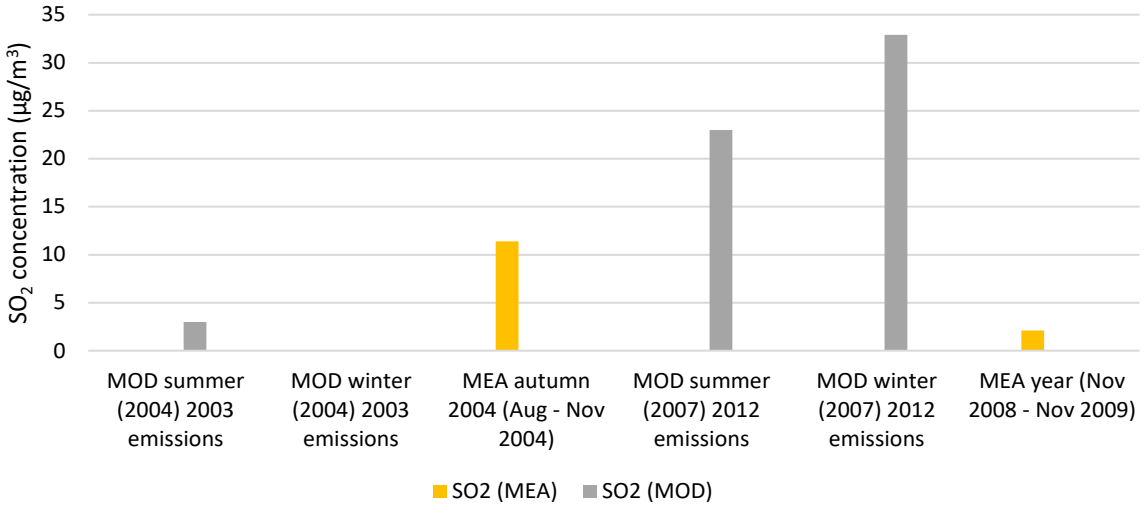


Figure 55: SO_2 concentrations ($\mu g/m^3$) in the area around Mosjøen from several modelling studies and two measurement studies.

The most recent measurements were carried out for a year (November 2008 – November 2009) at one station (Helgelandskraft, located further away from the smelter than the station used in 2004). Continuous measurements (hourly data) were carried out. Thus, the measurements are more representative than earlier measurements where one 24-hour sample per week was collected. The average SO_2 concentration over the entire period was 2.1 $\mu g/m^3$ and no exceedances of limit values were registered. After 2009, SO_2 emissions continued decreasing and have been rather stable since

2010. Long-range transport of SO_2 is not considered significant compared to local sources. Any other local emissions of SO_2, including small emissions from vehicle traffic, are also very small.

Measurements of SO_2 in autumn 2004 (Hagen, 2005) were carried out in Finnskoggata (see Section 1.4.3). NILU's "EK sampler" was used for sampling (see Appendix A). The samples were taken over 24 hours. The measured level was higher than previous measurements for SO_2 (1974 – 1976). These showed values of approx. 10-15 µg/m^3 as a winter average and due to the low values, the measurements in Mosjøen were stopped at the end of the 1970s. However, the measurement station used in 2004 was closer to the smelter than the measurement stations used in the 1970s (see Section 1.4.3). The concentrations of the measured substances can vary greatly from day to day both due to variations in the emissions and in the meteorological conditions (wind direction, wind speed, stability). The average concentration measured in the period August – November 2004 was 11.4 µg/m^3, with three days exceeding the 24-hour limit value of 125 µg/m^3. Since previous wind data from Mosjøen show that wind from northwest and north (i.e. from the smelter towards the measurement site) occur far more often in spring and summer than in autumn (Thrane, 1983b), measurements over an entire calendar year could give considerably more days with high concentrations than was measured in autumn 2004. It is therefore probable that the limit value for daily averages of SO_2 was exceeded by a good margin in Mosjøen in 2004.

The measurements in autumn 2004 showed higher SO_2 concentrations than the dispersion calculations carried out earlier in 2004 (Tønnesen, 2004). These calculations showed a half-year average value for the summer half-year of approx. 3 µg/m^3 in the area by the measuring station in Finnskoggata, i.e. somewhat lower than what the measurements showed in autumn 2004 (11 µg/m^3).

By 2000, Elkem Aluminium Mosjøen was planning a major rebuild and expansion of the aluminium plant, replacing old electrolysis ovens with Söderberg electrodes to ovens with prebaked electrodes. Dispersion calculations of SO_2 were carried out in order to map the effect of emissions to air before (emissions from 1999) and after (emission prognosis for 2004) the conversion on air quality in Mosjøen (Grønskei and Gram, 2000). The modernisation and development of the plant was calculated to lead to higher emissions and concentrations of SO_2, especially in pollution episodes (week winds and poor vertical mixing conditions). The calculations indicated that there may be exceedances of recommended air quality criteria for SO_2, where diffuse hall emissions dominate over point sources. Higher concentrations are calculated for winter than for summer.

By 2004, Elkem Aluminium Mosjøen was planning the construction and operation of a baking plant for prebaked anodes. Dispersion calculations were carried out in connection with this conversion to predict the effect on the air quality in Mosjøen of emissions to air after the start-up of the baking plant (Tønnesen, 2004). The updated calculations show that the pollution load is lower than calculated in the previous report by Grønskei and Gram (2000). Concentrations of SO_2 above the limit value for ecosystems (annual average value) will occur, but such concentrations occur over the fjord.

Husnes

Figure 56 illustrates the development in production and SO_2 emissions at Hydro Husnes from 1992 to 2020. The SO_2 emissions (tonnes per year) have been reduced by about 50%. The production in 1998 was not reported[30].

30

https://www.norskeutslipp.no/Templates/NorskeUtslipp/Pages/company.aspx?id=61&CompanyID=6256&epslanguage=no&SectorID=600

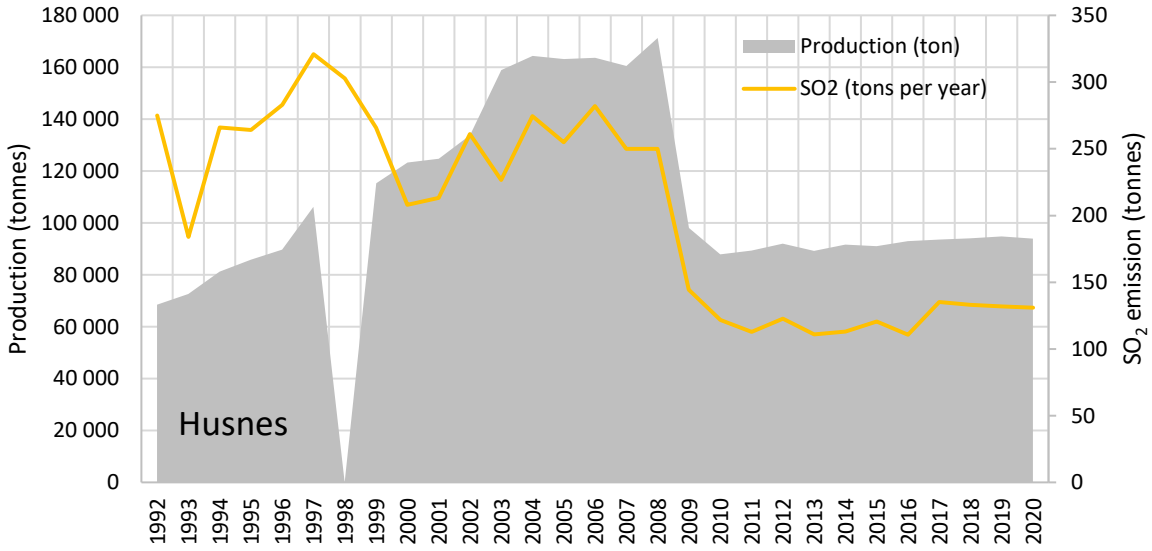


Figure 56: Emissions of sulphur dioxide (yellow line, unit: tonnes per year, right-hand y-axis) at Hydro Husnes from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). No measurement or modelling data are available for the period 1992 – 2020.

No SO_2 measurement data was available for Husnes.

Høyanger

Figure 57 illustrates the development in production and SO_2 emissions at Hydro Høyanger from 1992 to 2020[31]. SO_2-emissions (tonnes per year) have been reduced by about 30%.

[31] https://www.norskeutslipp.no/no/Diverse/Virksomhet/?CompanyID=5261

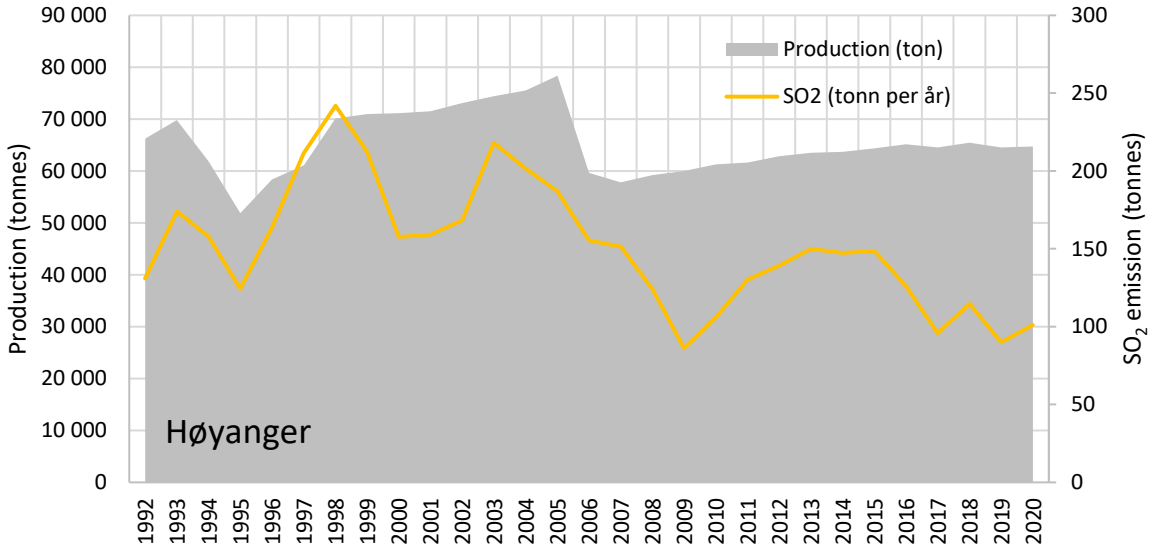


Figure 57: Emissions of sulphur dioxide (yellow line, unit: tonnes per year, right-hand y-axis) at Hydro Høyanger from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). No measurement or modelling data are available for the period 1992 – 2020.

There are no recent measurements of SO_2 in ambient air around Høyanger.

Karmøy

Figure 58 illustrates the development in production and SO_2 emissions at Hydro Karmøy from 1992 to 2020. SO_2-emissions (tonnes per year) are reduced by about 40%.

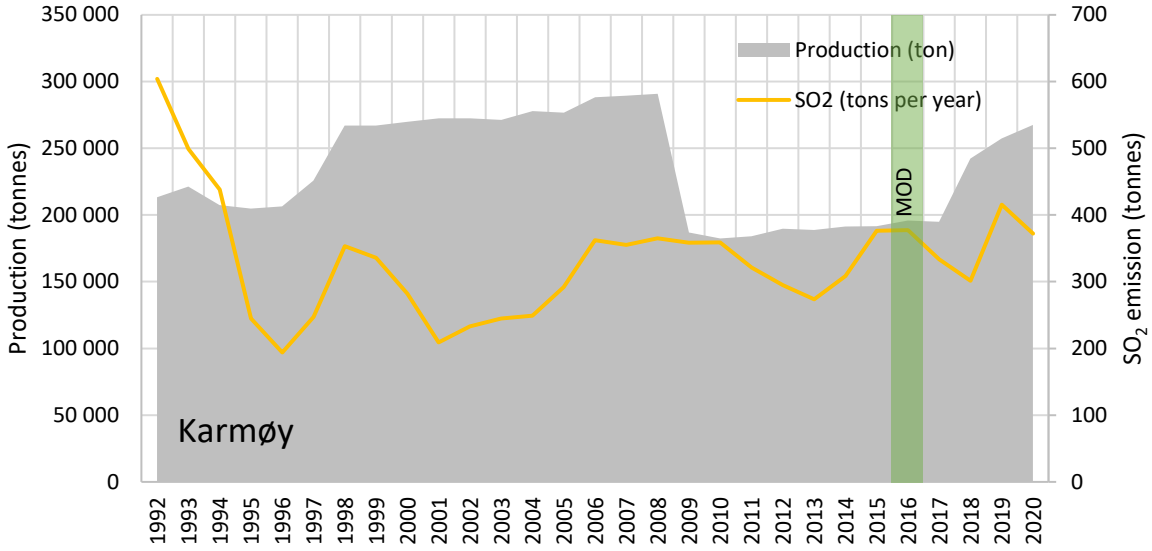


Figure 58: Emissions of sulphur dioxide (yellow line, unit: tonnes per year, right-hand y-axis) at Hydro Karmøy from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). A modelling (MOD) study was carried out in 2016, as highlighted.

No recent measurement data of air pollutants in the surroundings of Hydro Karmøy are available. In 2016, model calculations of the dispersion of emissions from an expanded production have been performed for the Karmøy aluminium smelter (Tønnesen, 2016). Hydro aluminium Karmøy was

preparing an expansion of its aluminium plant on Karmøy. In connection with the planned expansion, the emission permit required Hydro Karmøy to carry out dispersion calculations for the fully developed plant to verify the assumed stack heights. As can be seen in Figure 39, the first phase of the expansion was finalised in 2018. The calculations were performed for a.o. sulphur dioxide (SO_2).

The maximum annual average calculated for the fully developed plant (projected capacity twice the current level) over land outside the factory area was 4.2 µg/m^3 for SO_2, occurring northwest of the plant between the plant and road RV47. Typical background concentrations of SO_2 in Norway are low, between 0.16 µg/m^3 at Tustervatn and 0.32 µg/m^3 at Birkenes II as annual averages (Figure 50). All assessment criteria for short-term concentrations of SO_2 are complied with by a good margin. The model results showed that the impact was in compliance with the SO_2 limit values for ambient air. The dispersion conditions which give the largest overall contribution are wind along the plant's longitudinal axis (northeast – southwest) with a wind speed of 4-6 m/s. The occurrence of such wind conditions is less than 3% of the time on an annual basis for the wind sector with dispersion towards in land (towards Austevik).

Sunndal

Figure 59 illustrates the development in production and SO_2 emissions[32] in the period 1992 – 2020. SO_2 emissions (tonnes per year) have been reduced about 60% compared to the early 1990s. Since about 2010, the SO_2 emissions vary in line with the production.

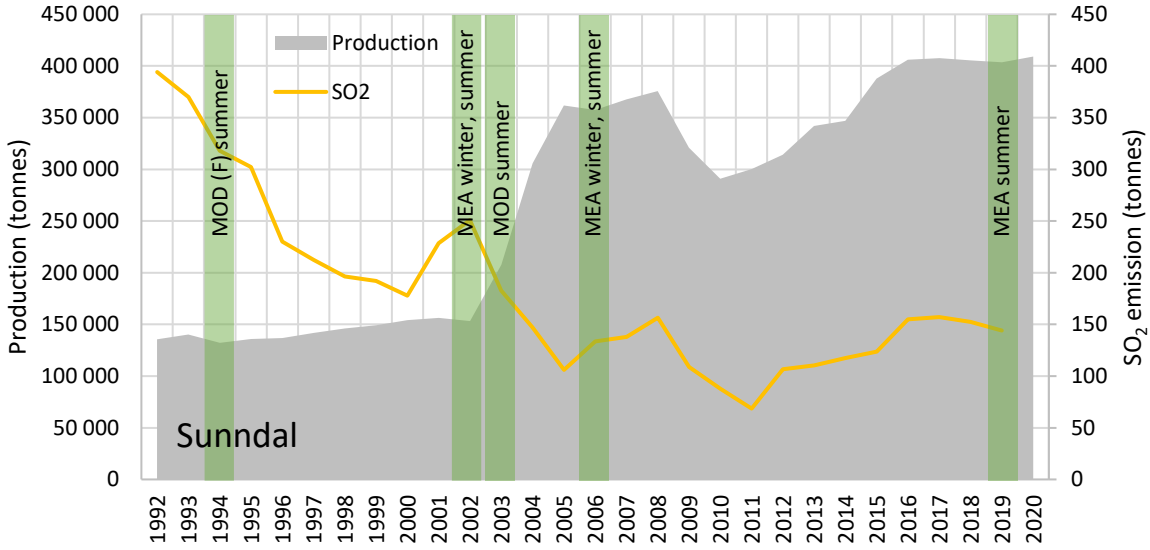


Figure 59: Emissions of sulphur dioxide (yellow line, unit: tonnes per year, right-hand y-axis) at Hydro Sunndal from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). The years measurement (MEA) or modelling (MOD) studies were carried out, are highlighted.

The most recent measurements in ambient air were carried out in summer 2019 (Hak, 2021a) at two stations, Pensjonistsenteret (in the centre of Sunndalsøra) and Vennevold (6 km up the valley). The 3-month average concentration of SO_2 was 1.2 µg/m^3 at Pensjonistsenteret and 0.5 µg/m^3 at Vennevold. SO_2-levels have decreased between 2002 and 2006 and between 2006 and 2019 (see Figure 60). The emissions of SO_2 are reported to have decreased, especially between 2002 and 2006, even though the production has increased (see Figure 59). The sampling method used was the same as in 2002 and 2006 and the same analysis principle was used. In 2002 and 2006, measurements

[32] https://www.norskeutslipp.no/no/Diverse/Virksomhet/?CompanyID=5309

were carried out on 20 days distributed over 3 months. These results are more sensitive to time variations than weekly samples.

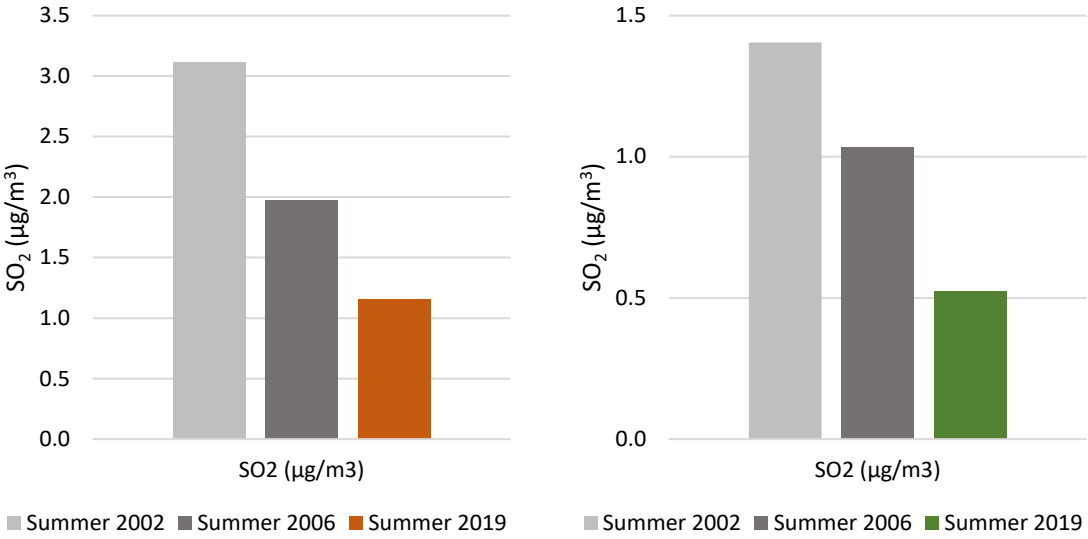


Figure 60: Average concentration of sulphur dioxide in summer 2002 (10 weeks), summer 2006 (9 weeks) and summer 2019 (12 weeks) at Pensjonistsenteret and at Vennevold. Please note different scales.

For comparison, in an earlier modelling study (Bøhler and Larsen, 1991) results from dispersion calculations for summer 1990 and summer 1997 (after a planned expansion, closing down SU1 and SU2 and opening two new oven halls SU4) for the centre of Sunndalsøra showed around 10 µg/m^3 as a half-year average over summer 1990 and 5-10 µg/m^3 in summer 1997. The expansion of the smelter was estimated to lead to a little increase of total SO_2-emissions (but roof emissions were estimated to be reduced compared to 1990-emissions) and to a broader distribution of concentrations close to the smelter in 1997. In 1990, the largest SO_2 emissions were estimated to arise from the cleaning facilities for SU1/2 and SU3. The largest SO_2 emissions over the roof were estimated to come from SU1/2. The expansion was carried out (with some modifications of the original plan) in the period 2002 – 2004.

Øvre Årdal and Årdalstangen

Figure 61 illustrates the development in production and SO_2 emissions at Hydro Årdal from 1992 to 2020. The metal plant originally did not have any SO_2 abatement, until wet scrubbers were installed in 1992/93, giving an 80% reduction. The emission level has fluctuated around 350-400 tonnes per year since then. About 80% of the SO_2 emissions comes from the metal plant. According to data received from Årdal Metallverk, ca. 90% of the sulphur emissions come from stacks.

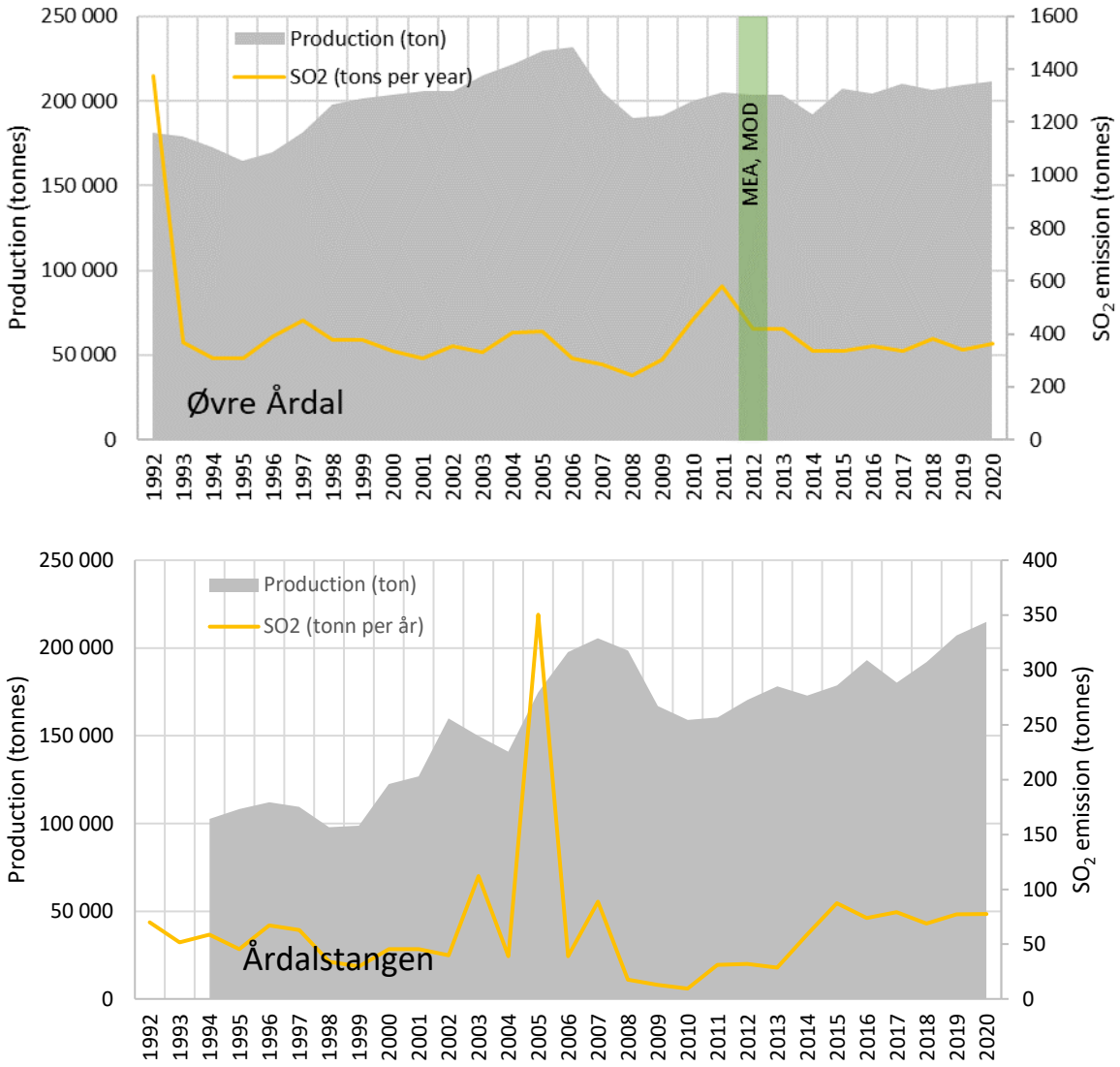


Figure 61: Emissions of sulphur dioxide (yellow line, unit: tonnes per year, right-hand y-axis) at Hydro Årdal and Årdalstangen from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). The years measurement (MEA) or modelling (MOD) studies were carried out, are highlighted.

The most recent SO_2 measurements were carried out in May – October 2012 using passive samplers while Hydro Årdal was renovating the treatment towers for exhaust gas from electrolysis (Hak and Castell, 2012a). The purpose of the measurements was to map the effect on air quality in Øvre Årdal of emissions to air during the conversion of the smelter. Passive samplers were distributed at 20 sampling points in Øvre Årdal (exposure time one week over the whole period). The highest weekly SO_2 concentration was 23 µg/m^3, observed near the plant. The half-year concentration varied between 11.1 µg/m^3 north of the aluminium plant and 14.9 µg/m^3 in the immediate vicinity of the plant. At all sampling points, the half-year averages were well below Klif's recommended air quality criterion (40 µg/m^3) and below the EU limit value for ecosystems (20 µg/m^3). SO_2 is mainly emitted from stacks at greater heights and will therefore have a dispersion pattern that does not give equally high ground-level concentrations close to the plant.

In the same time period as the measurements took place at Øvre Årdal, dispersion calculations (Hak and Castell, 2012b) were carried out for SO_2, fluorides, particulate matter and heavy metals. Calculations were carried out for normal operating conditions for the reference period 2010.

Dispersion calculations of SO_2 were used as a basis for calculating the dispersion of fluoride, particulate matter and heavy metals. Annual average concentrations of SO_2 were highest near the smelter and significantly lower a few km from the source. The highest annual average was 8 µg/m^3, well below the EU limit value for annual average concentrations (20 µg/m^3). It is not assumed that there are other local sources that have significant emissions of SO_2.

Kubal

Figure 62 illustrates the development in production and SO_2 emissions at Kubal from 1992 to 2020. SO_2 emissions have been reduced by 40-50%.

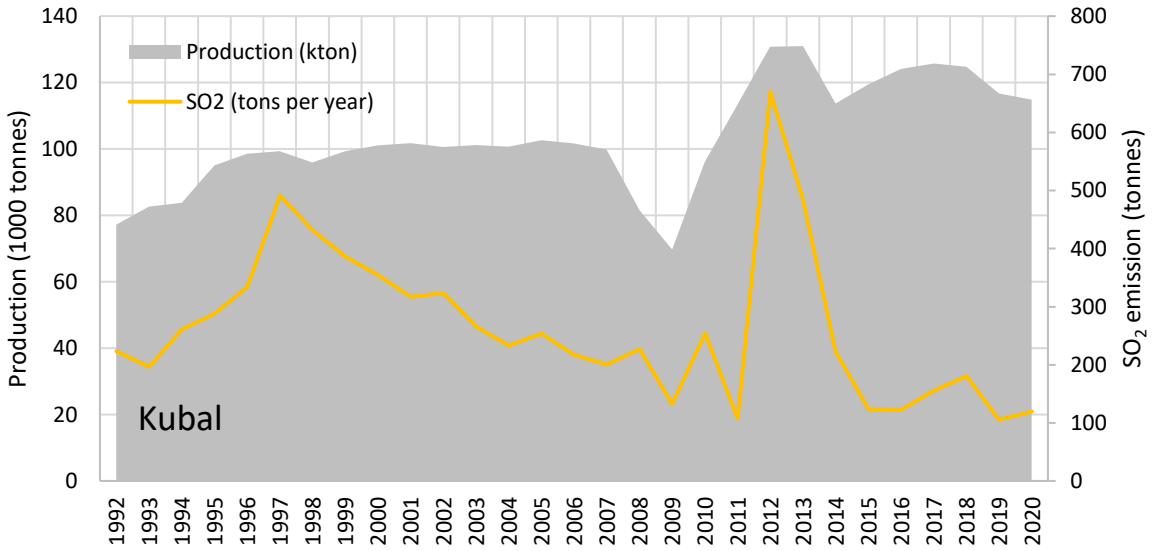


Figure 62: Emissions of sulphur dioxide (yellow line, unit: tonnes per year, right-hand y-axis) at Kubal from 1992 to 2020. Development of production (grey background, unit: 1000 tonnes per year, left-hand y-axis). No measurement or modelling data are available for the period 1992 – 2020.

No SO_2 measurement data were available for Kubal.

Sundsvall municipality has been measuring SO_2 in central Sundsvall (first using Opsis remote sensing on roof-top level, since 2006 passive samplers have been used). Concentrations have been decreasing since the 1980s as a result of the expansion of district heating and reduced industrial emissions (Sundsvall municipality, 2010).

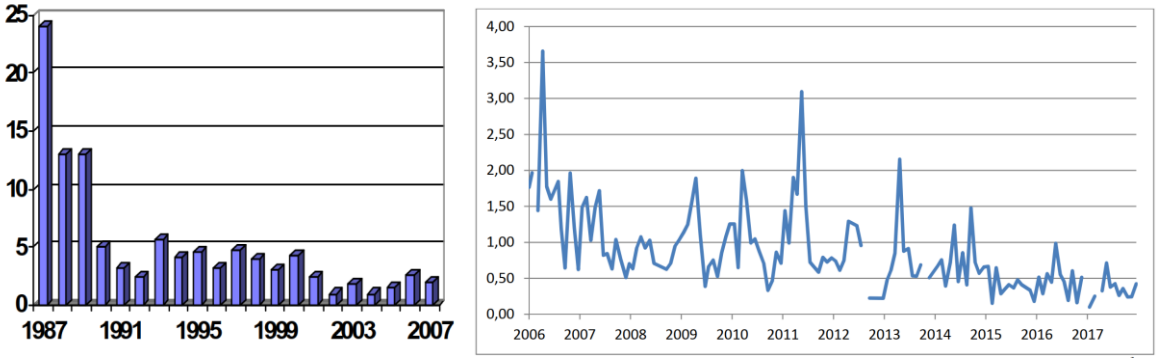


Figure 63: Left: Annual average concentrations of SO_2 in the period 1987 – 2007 (Opsis measurements, µg/m³). Source: Sundsvall municipality (2010). Right: Monthly average concentrations of SO_2 from Stadshuset in Sundsvall in the period 2006 – 2016 (passive samplers, µg/m³). Source: Sundsvall municipality (2018)

KUBAL carried out short measurement campaigns for SO_2 in July 2012, September 2018, September 2019 and May/June 2021. The same method was used in all four campaigns. The measurements cover four consecutive 24-hour samples for each of the campaigns. As shown in Figure 64, ambient SO_2 concentrations at three sites close to KUBAL were significantly lower in 2018, 2019 and 2021 than in 2012. The purpose of the campaign measurements was to see the effect of changing from stack-led emissions to roof ventilators in Plant 2. Roof ventilators were installed in Plant 2 in 2013. The strong decrease of ambient SO_2 concentrations since 2012 indicates that the technical changes resulted in lower effect of emissions on ambient concentrations in the surroundings and that other sources than KUBAL have a larger influence on SO_2-concentrations at the three sampling points.

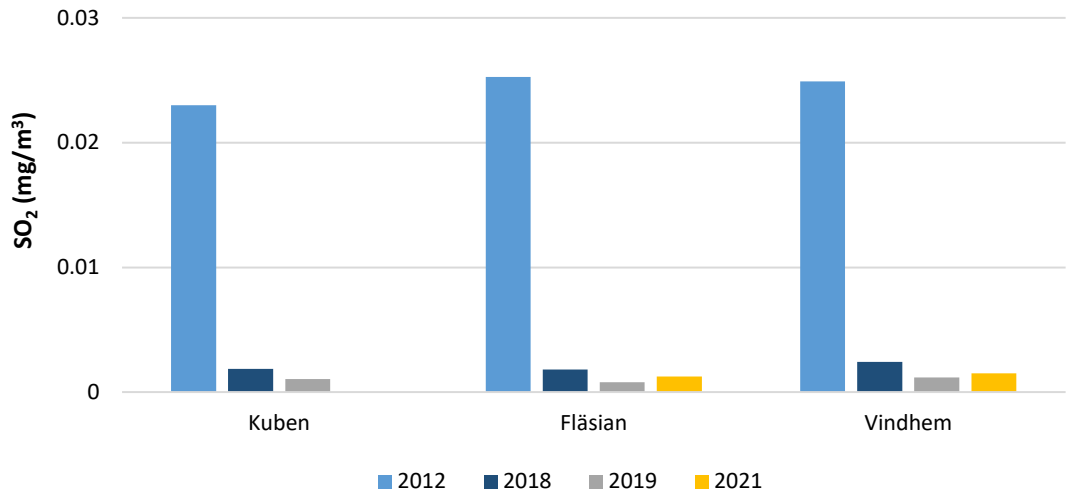


Figure 64: SO_2 average over campaign measurements at Kuben, Fläsian and Vindhem carried out over four days each in 2012, 2018, 2019 and 2021. Note that the concentrations are shown in mg/m³.

ISAL

Figure 65 illustrates the development in production and SO_2 emissions at ISAL from 1992 to 2020. The SO_2 emissions (tonnes per year) have increased nearly in proportion to the production, since the plant has no wet scrubbers.

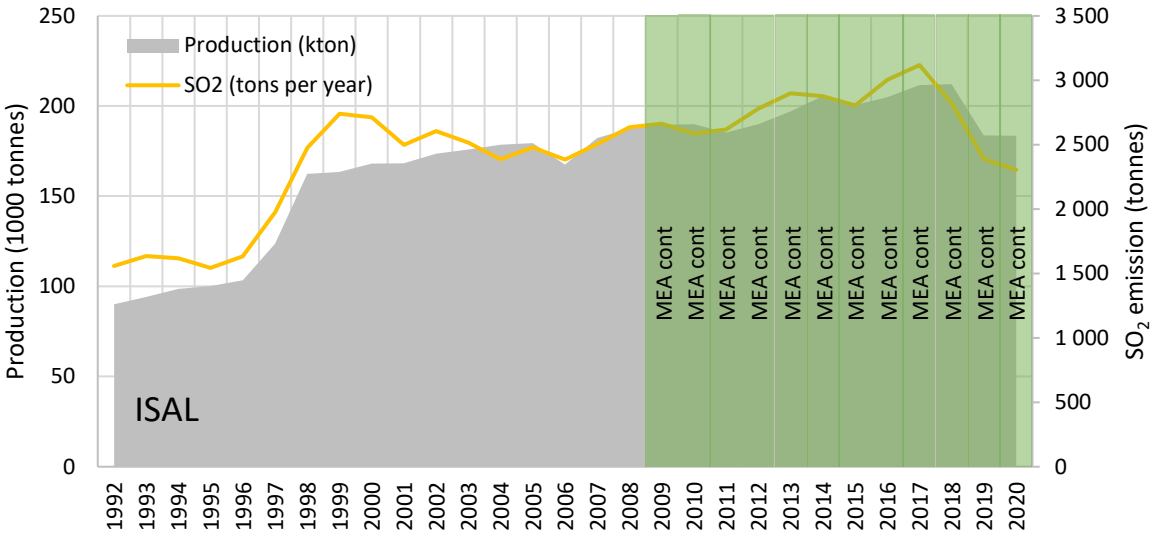


Figure 65: Emissions of sulphur dioxide (yellow line, unit: tonnes per year, right-hand y-axis) at ISAL from 1992 to 2020. Development of production (grey background, unit: 1000 tonnes per year, left-hand y-axis). Measurements (MEA) have been carried out since 1994. Continuous data from 2009 were available for the report, as highlighted.

A measurement programme to monitor air quality parameters has been carried out at Hvaleyrarholt, ca. 2 km northeast from the smelter, since 1994. Data from 2009 were available for this report. SO_2 is measured continuously using an SO_2-monitor. Annual average concentrations of SO_2 are shown in Figure 66. The ambient concentrations of SO_2 have been nearly unchanged over the past 3 decades. The highest annual average was measured in 2014, after the eruption in Holuhraun in the Northeastern Region of Iceland.

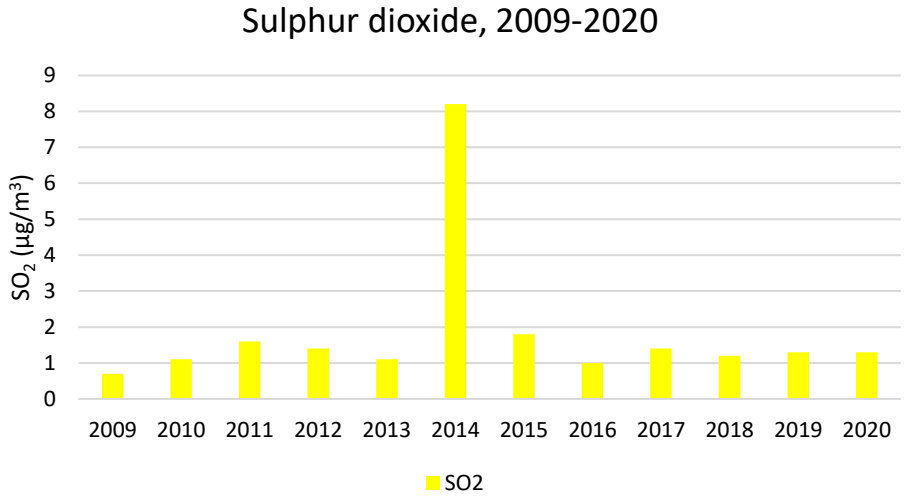


Figure 66: Annual average concentration of SO_2 in the years 2009 – 2020 at Hvaleyrarholt, 2 km northeast of ISAL.

2.4 Particulate matter (PM)

2.4.1 Background concentrations

PM_{10} and $PM_{2.5}$ have been measured at the background stations Birkenes, Hurdal and Kårvatn since 2000 and 2010, respectively. Figure 67 and Figure 68 show how PM_{10} and $PM_{2.5}$ concentrations at Norwegian background sites have developed over the last decades, showing a decreasing trend at all sites. Aas et al. (2021) report PM-trends of –35 % at Birkenes for PM_{10} in the period 2000 – 2020 and –51 % for $PM_{2.5}$ in the same period. The $PM_{2.5}$-trend at Hurdal was –43 % in the period 2010 – 2020, all numbers elaborated using Mann-Kendall test and Sen slope estimates (significant level 0.05).

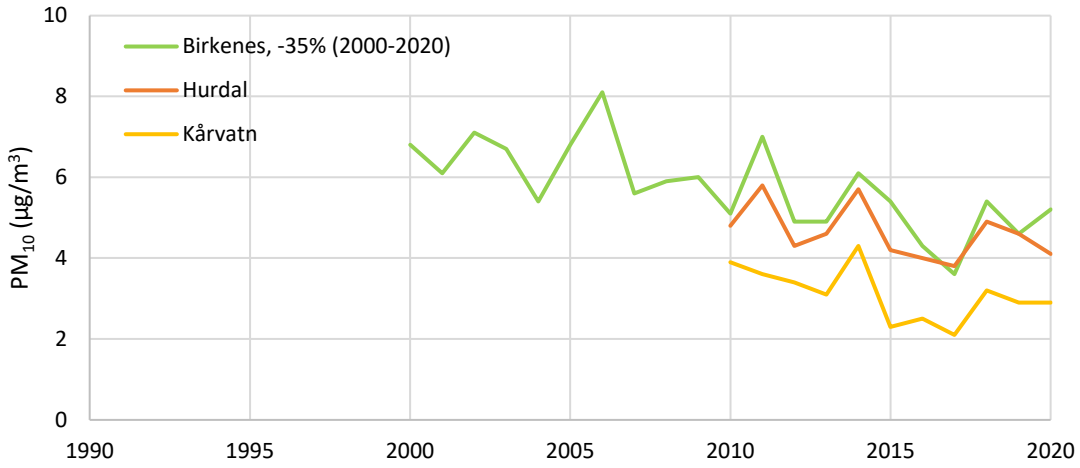


Figure 67: Variation of PM_{10} concentration (µg/m^3) at Norwegian background sites in the period 2000 – 2020.

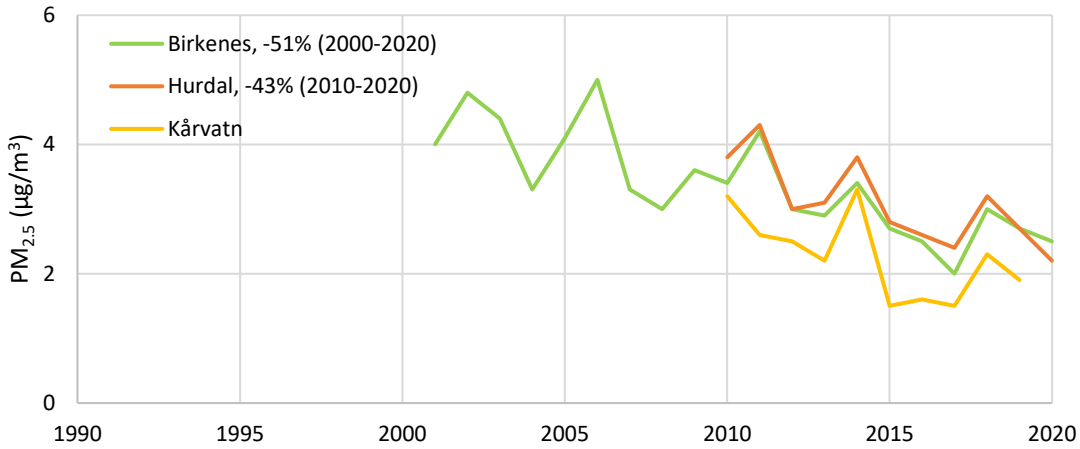


Figure 68: Variation of $PM_{2.5}$ concentration (µg/m^3) at Norwegian background sites in the period 2001 – 2020.

2.4.2 Emissions and ambient concentrations

Fjarðaál

Figure 69 illustrates the development in production and PM emissions at Alcoa Fjarðaál in the period 2007 – 2020. Emissions of PM have mainly fluctuated between 100 and 150 tonnes per year with no clear trend.

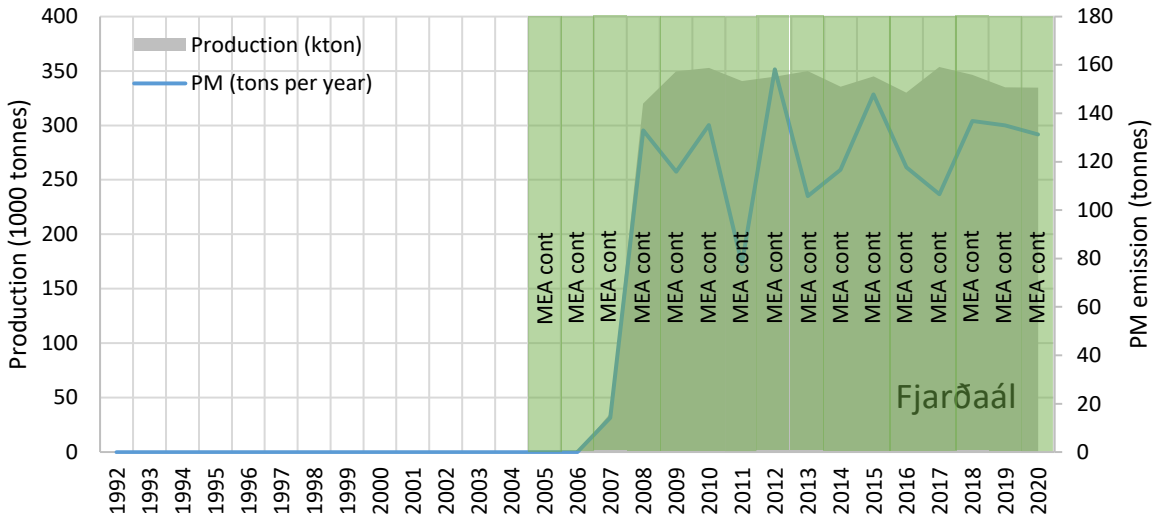


Figure 69: Emissions of particulate matter (blue line, unit: tonnes per year, right-hand y-axis) at Alcoa Fjarðaál from 1992 to 2020. Development of production (grey background, unit: 1000 tonnes per year, left-hand y-axis). Measurements (MEA) of PM_{10} have been carried out continuously since 2005, as highlighted.

The Alcoa Fjarðaál smelter was launched in April 2007. Continuous PM measurements have been carried out since 2005 at four stations around the smelter (see Section 1.4.1). Annual averages of PM_{10} concentrations in the period 2005 – 2020 are shown in Figure 70. Measurements before the smelter activities started are supposed to reflect the natural background, e.g. sea salt. The ambient PM concentrations measured were highest in 2007 when the production started. There were further concentration peaks in 2014 (Holuhraun?) and 2018. Annual PM_{10} averages are mostly below 10 µg/m^3.

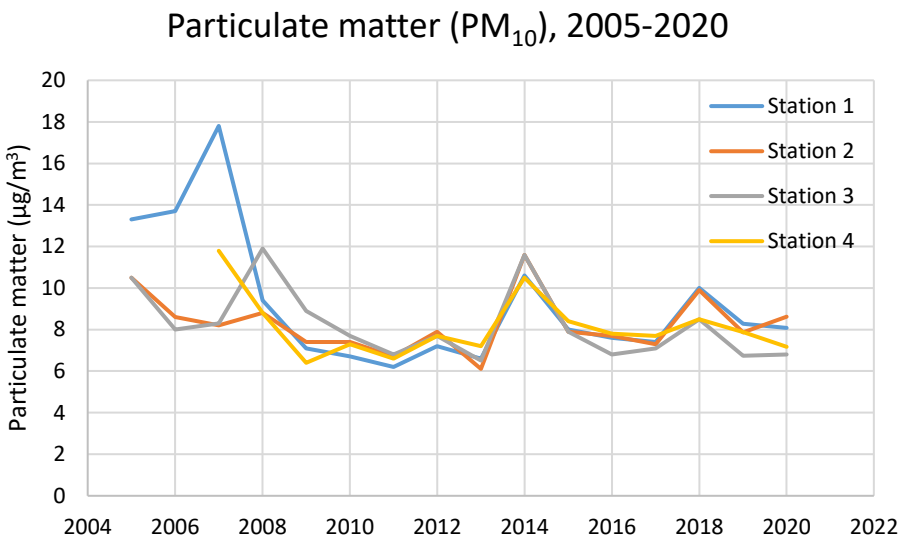


Figure 70: Annual average concentrations of PM_{10} in the years 2005 – 2020 at the four monitoring stations around Alcoa Fjarðaál.

Model calculations and an impact assessment for PM emissions to air from the planned aluminium smelter in Reyðarfjörður were published in 1999 and 2001 (Guerreiro, 1999; Guerreiro et al., 2001). The findings are not discussed here.

Lista

Figure 71 illustrates the development in production and PM emissions from 1992 to 2020, as reported by Alcoa Lista (www.norskeutslipp.no). PM emissions (tonnes per year) are reduced ca. 50% compared to the early 1990s. For PM, the reporting did not include fugitive sources (ship unloading etc.) before 2001. For comparability, the graph only includes measured dust emissions.

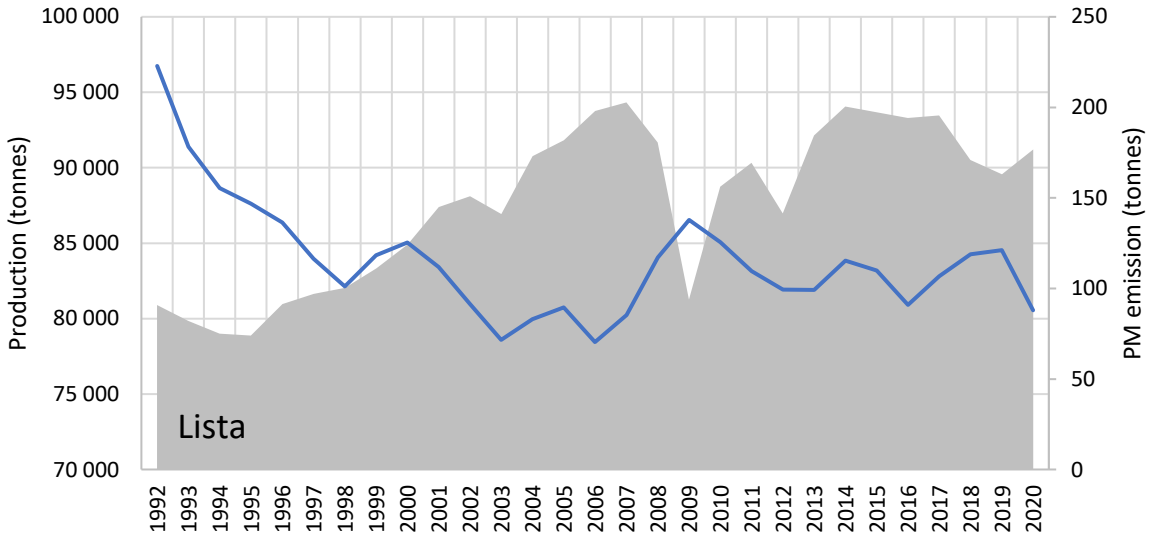


Figure 71: Emissions of particulate matter (blue line, unit: tonnes per year, right-hand y-axis) at Alcoa Lista from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). No measurement or modelling data are available for the period 1992 – 2020.

There are no recent measurements of particulate matter in ambient air around Lista.

Mosjøen

Figure 72 illustrates the development in production and PM emissions at Alcoa Mosjøen from 1992 to 2020. PM-emissions (tonnes per year) are reduced by about 50%.

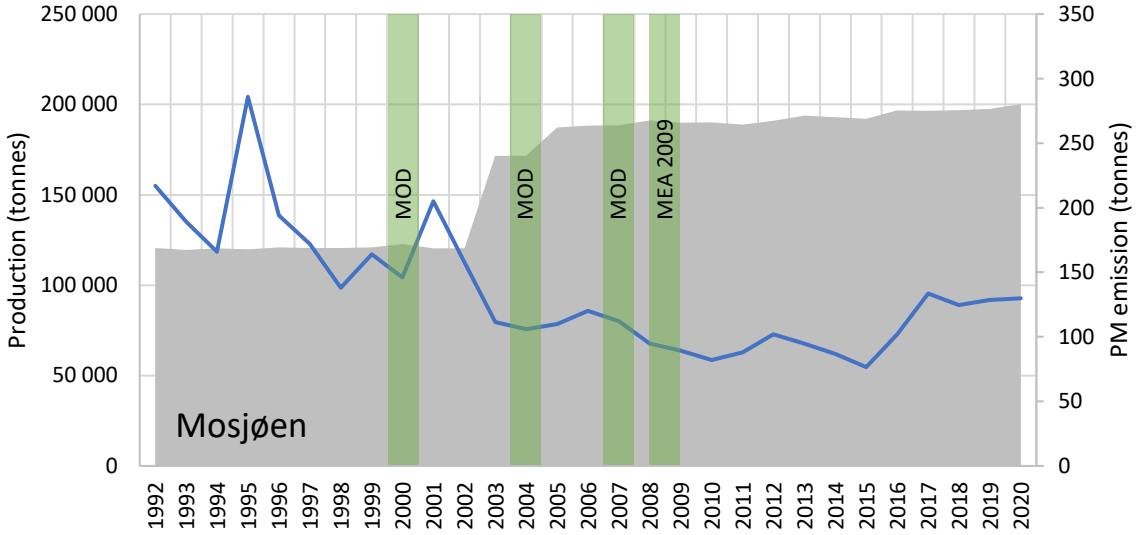


Figure 72: Emissions of particulate matter (blue line, unit: tonnes per year, right-hand y-axis) at Alcoa Mosjøen from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). The years measurement (MEA) or modelling (MOD) studies were carried out, are highlighted.

The ambient concentration of particulate matter was assessed in three modelling studies (Grønskei and Gram, 2000; Tønnesen, 2004; Tønnesen, 2007) and one measurement study (Haugsbakk, 2010) in the period 1992 – 2020. The most recent study concerns measurements carried out in the period November 2008 – November 2009 (Haugsbakk, 2010). At the station Helgelandskraft, PM_{10} was measured continuously on an hourly basis. Also SO_2 and PAH measurements were carried out. The PM_{10} average over the entire period was 13.1 µg/m^3 (6 exceedances of the daily limit value, 35 exceedances of national target, of 7 allowed). PM_{10} concentrations in the summer months were higher than in the winter months.

By 2000, Elkem Aluminium Mosjøen was planning a major rebuild and expansion of the aluminium plant, replacing old electrolysis ovens with Söderberg electrodes to ovens with prebaked electrodes. Dispersion calculations of particles were carried out in order to map the effect of emissions to air before (emissions from 1999) and after (emission prognosis for 2004) the conversion on air quality in Mosjøen (Grønskei and Gram, 2000). The modernisation and development of the plant was calculated to lead to a somewhat lower dust load, most likely due lower emission after the conversion to prebake technology. The dispersion calculations indicated that there may be exceedances of recommended air quality criteria for particles, where fugitive hall emissions dominate over point sources. In order to be able to distinguish between size fractions, Molab AS has investigated the composition of the dust in the halls at several measuring points (Røssvoll, 2000). The study indicated that the dust consists essentially of Al_2O_3. There were large gaps in the measurement results, but an average of the values showed that 84% of the particulate mass was present as PM_{10} of which 34% was present as $PM_{2.5}$.

By 2004, Elkem Aluminium Mosjøen was planning the construction and operation of a baking plant for prebaked anodes. Dispersion calculations were carried out in connection with this conversion to map the effect on the air quality in Mosjøen of emissions to air after the start-up of the baking plant

(Tønnesen, 2004). The updated dispersion calculations show that the pollution load around the plant is lower than calculated in the previous report by Grønskei and Gram (2000). Analyses from hall 5 and hall 6 showed that 90% of the particle mass was present as PM_{10} and 30% as $PM_{2.5}$ (Tønnesen, 2004).

Husnes

Figure 73 illustrates the development in production and PM emissions at Hydro Husnes from 1992 to 2020. The PM emissions (tonnes per year) have been reduced by about 60%.

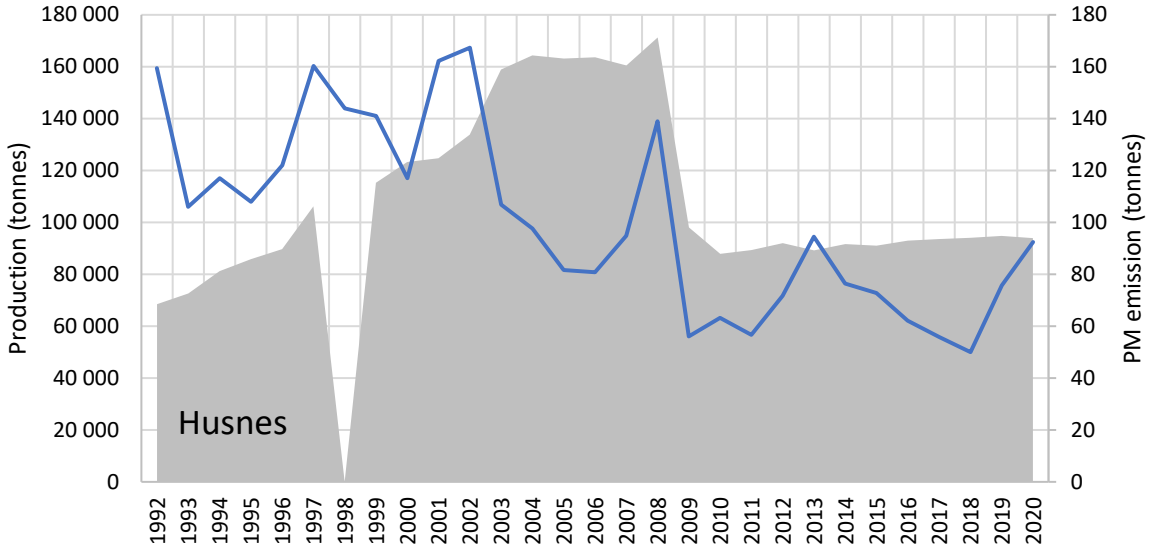


Figure 73: Emissions of particulate matter (blue line, unit: tonnes per year, right-hand y-axis) at Hydro Husnes from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). No measurement or modelling data are available for the period 1992 – 2020.

No measurement or modelling studies on PM have been found for Husnes.

Høyanger

Figure 74 illustrates the development in production and PM emissions at Hydro Høyanger from 1992 to 2020. PM-emissions (tonnes per year) have been reduced by about 80%.

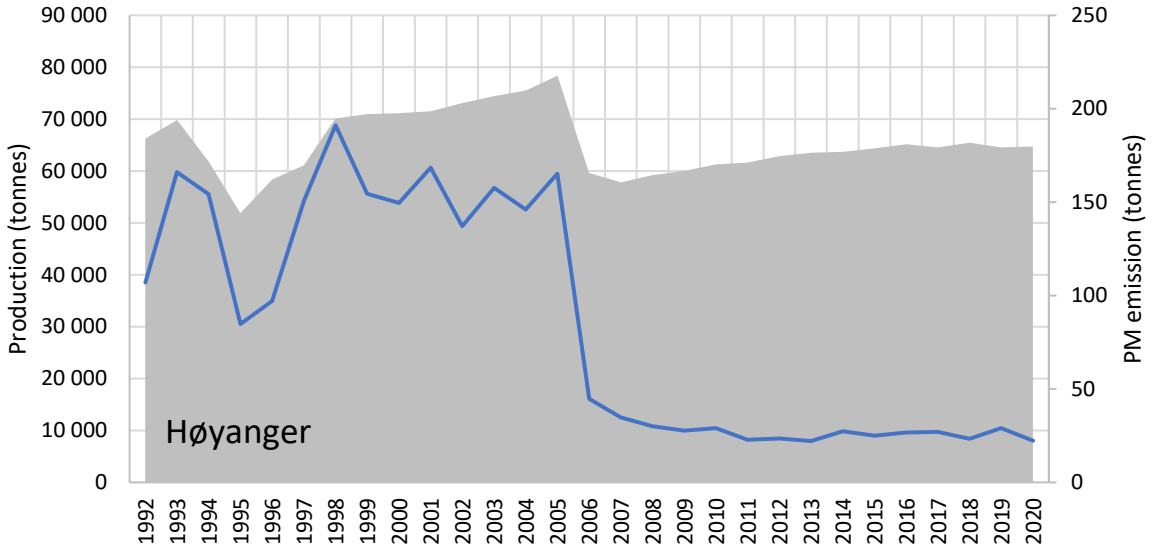


Figure 74: Emissions of particulate matter (blue line, unit: tonnes per year, right-hand y-axis) at Hydro Høyanger from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). No measurement or modelling data are available for the period 1992 – 2020.

There are no recent measurements of particulate matter in ambient air around Høyanger.

Karmøy

Figure 75 illustrates the development in production and PM emissions at Hydro Karmøy from 1992 to 2020. PM-emissions (tonnes per year) are reduced by about 50%.

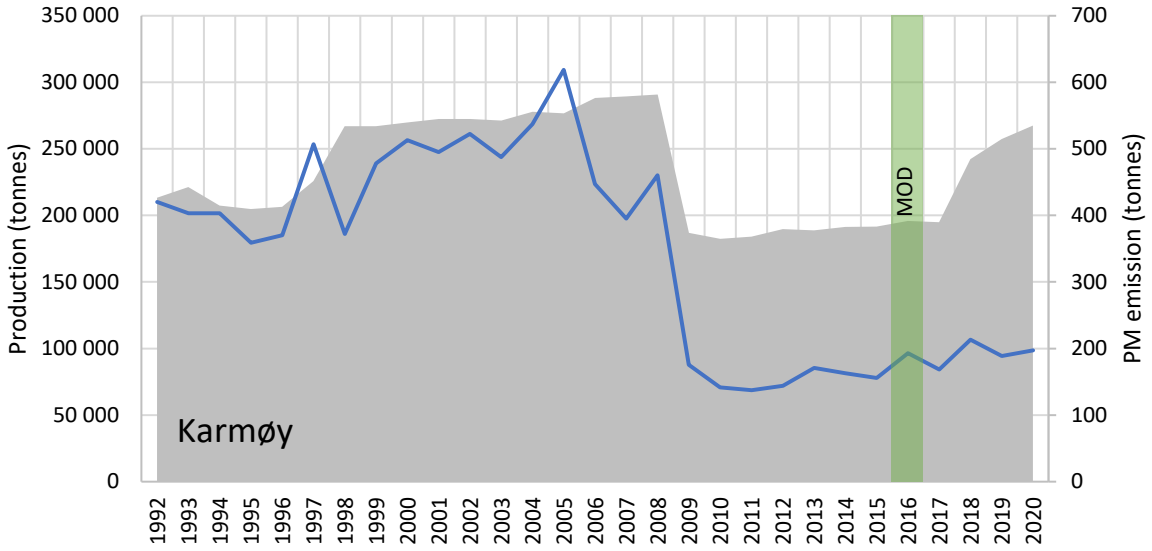


Figure 75: Emissions of particulate matter (blue line, unit: tonnes per year, right-hand y-axis) at Hydro Karmøy from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). A modelling (MOD) study was carried out in 2016, as highlighted.

No recent measurement data of air pollutants in the surroundings of Hydro Karmøy are available. In 2016, model calculations of the dispersion of emissions from an expanded production have been

performed for the Karmøy aluminium smelter (Tønnesen, 2016). Hydro aluminium Karmøy was preparing an expansion of its aluminium plant on Karmøy. In connection with the planned expansion, the emission permit required Hydro Karmøy to carry out dispersion calculations for the fully developed plant to verify the assumed stack heights. As can be seen in Figure 39, the first stage of the expansion was finalised in 2018. The calculations were performed a.o. for particulate matter (PM_{10}).

The maximum annual average calculated for the fully developed plant over land outside the factory area was 6.1 µg/m^3, occurring northwest of the plant between the plant and road Riksvei 47. The typical background concentration in rural areas is 1-10 µg/m^3. The recommended criterion for health (20 µg/m^3 for annual averages) was complied with by a good margin. The dispersion conditions which give the largest overall contribution are wind along the plant's longitudinal axis (northeast – southwest) with a wind speed of 4-6 m/s. The occurrence of such wind conditions is less than 3% of the time on an annual basis for the wind sector with dispersion towards in land (towards Austevik). The total load/contribution of pollutants is the sum of background concentrations and local contribution.

Sunndal

Figure 76 illustrates the development in production and PM emissions at Hydro Sunndal from 1992 to 2020. PM emissions (tonnes per year) have been reduced about 60%. For comparability, the PM figures do not include fugitive emissions, since these have not been reported through the whole period, and the basis of reporting has been changed.

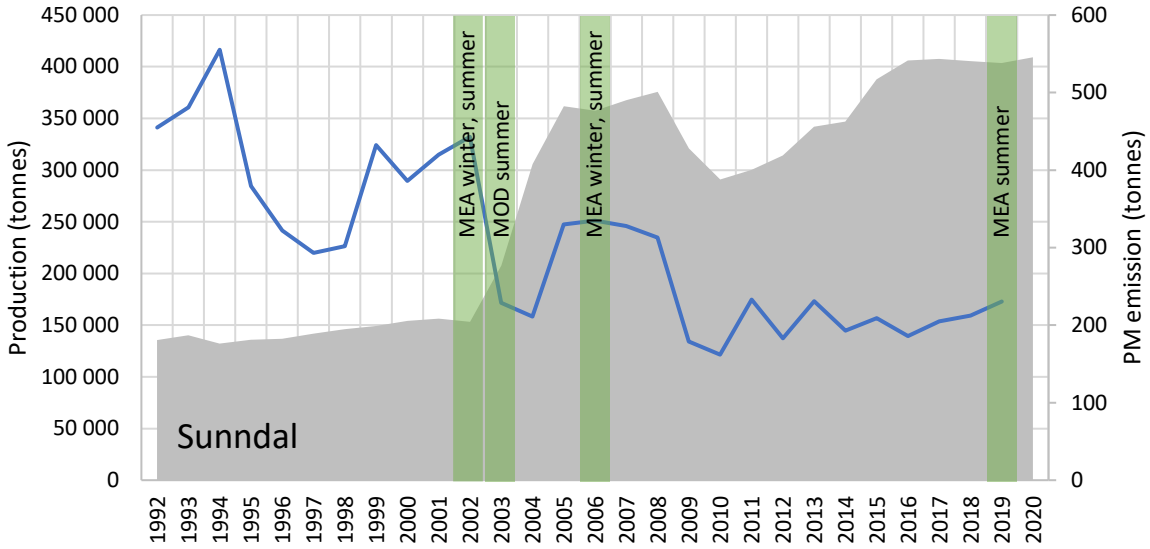


Figure 76: Emissions of particulate matter (blue line, unit: tonnes per year, right-hand y-axis) at Hydro Sunndal from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). The years measurement (MEA) or modelling (MOD) studies were carried out, are highlighted.

The most recent measurements in ambient air were carried out in summer 2019 (Hak, 2021a) at two stations, Pensjonistsenteret (in the centre of Sunndalsøra) and Vennevold (6 km up the valley). PM_{10} was also included in measurement studies in 2002 and 2006 and in a modelling study in 2003 (Hagen, 2003; Hagen, 2006; Gjerstad, 2003). In Figure 77, PM_{10}-levels from summer 2019 are compared to PM_{10}-levels in summer 2002 and summer 2006. Due to different meteorological patterns in winter, the results from the winter seasons in 2002 and 2006 are not included in the comparison. In summer

2019, PM_{10} at Pensjonistsenteret was about 50% lower than in summer 2006. PM was not measured at Kårvatn before 2010, thus no background levels are available for 2002 and 2006.

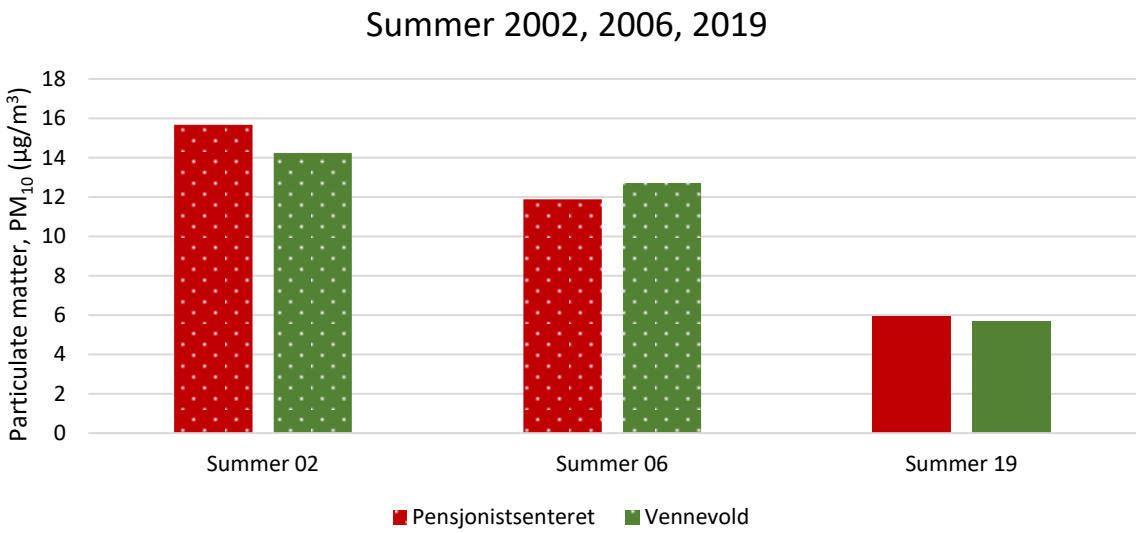


Figure 77: Average concentration of PM_{10} in summer 2002 (10 weeks), summer 2006 (9 weeks) and summer 2019 (12 weeks) at Pensjonistsenteret and at Vennevold. $PM_{2.5}$ was not measured at Sunndal in 2002 and 2006.

Emissions of particulate matter from Hydro Sunndal have decreased from 2002 to 2006 and further to 2019 (see Figure 76). The PM_{10}-levels measured during the three summer campaigns varied in a similar level as the PM emission. In 2002 and 2006, measurements were carried out on 20 days distributed over 3 months. These results are more sensitive to time variations and not directly comparable to long-term mean values over 3 months.

For comparison, an earlier modelling study (Bøhler and Larsen, 1991) calculated dispersion of pollution for the summers of 1990 and 1997 (i.e., after an expansion planned for 1997, consisting of building two new halls, SU4, at the same time as SU1/2 is closed). Dispersion calculations for summer 1990 (assuming particles below 10-15 µm in diameter) showed PM concentration around 10-20 µg/m^3 in the centre of Sunndalsøra (half-year average over summer) and below 3 µg/m^3 several km up the valley. Closing SU1/2, which was the main PM-source, was assumed to result in a 50% reduction of dust emissions. The calculations show that summer averages in the range 5-10 µg/m^3 can appear in the centre of Sunndalsøra after the expansion. The expansion was realised (with some modifications of the original plan) in the period 2002 – 2004.

Øvre Årdal and Årdalstangen

Figure 78 illustrates the development in production and PM emissions at Hydro Årdal and Årdalstangen from 1992 to 2020. PM emissions (tonnes per year) increased between 1994 and 2006, but were significantly reduced when the Söderberg line was closed. The level in 2017 is about ⅓ of the level in 1992-94, and about ¼ of the peak level in 2006. More than 95% of the measured dust emissions come from the metal plant, but there are some fugitive emissions related to unloading and transport of coke and alumina at the Årdalstangen harbour which are not included in the graphs. According to data received from Årdal Metallverk, ca. 80% of the dust emissions come from the halls.

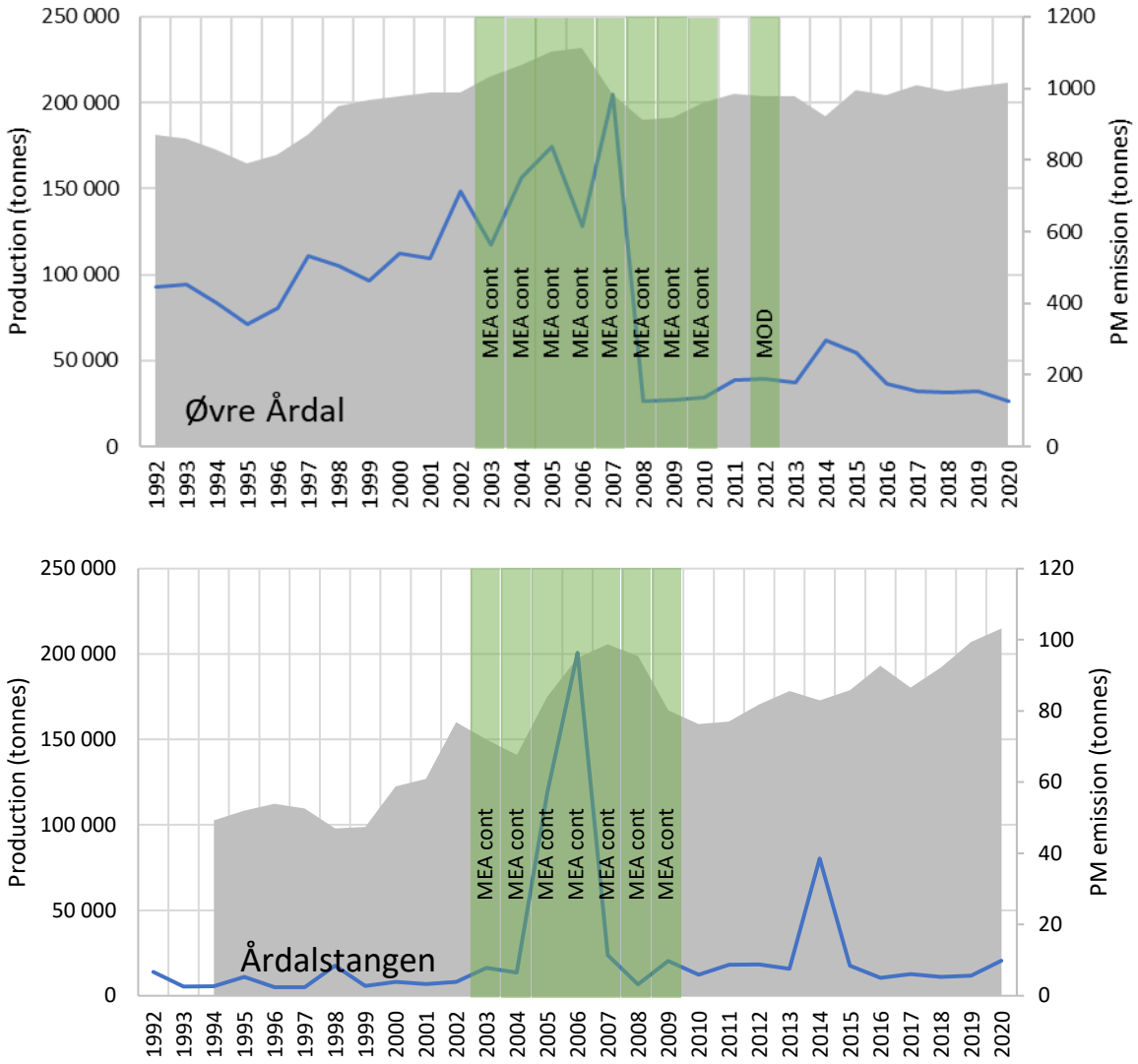


Figure 78: Emissions of particulate matter (blue line, unit: tonnes per year, right-hand y-axis) at Hydro Årdal and Årdalstangen from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). The years measurement (MEA) or modelling (MOD) studies were carried out, are highlighted.

The most recent measurements of particulate matter at Årdal were carried out in the period 2003 – 2009, when PM_{10} was measured rather continuously in Øvre Årdal and at Årdalstangen (24-hour average samples). Annual averages are shown in Figure 79. The results have not been published in a report. While the annual averages showed a decreasing tendency, the measurements showed a period of exceedances of the daily average in summer and autumn 2008. Dust emissions decreased significantly from 2007 to 2008, from 984 tonnes to 128 tonnes annually. Concentrations in 2009 seemed to be lower than concentrations in 2007, however, measurements did not cover the full year.

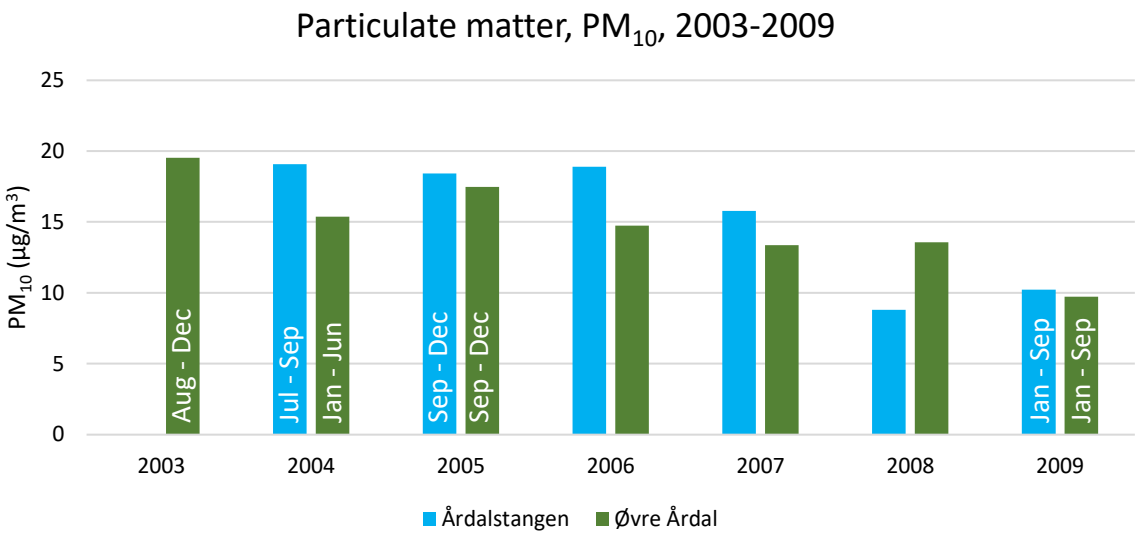


Figure 79: Annual average concentrations of PM_{10} at Årdalstangen and Øvre Årdal in the period 2003 – 2009 (µg/m³). For some years, measurements did not cover the full year.

Dispersion calculations for SO_2, fluorides, particulate matter and heavy metals at Øvre Årdal were carried out in 2012 (Hak and Castell, 2012b) to map the effect on air quality in Øvre Årdal of emissions to air under normal operating conditions, using meteorology from 2010. Dispersion calculations of SO_2 were used as a basis for calculating the dispersion of fluoride, particulate matter and heavy metals. The annual average contribution of particulate matter from the smelter in Øvre Årdal was calculated to be 13 µg/m³ for 2010 conditions. With an added background concentrations of 2-4 µg/m³, the airborne dust level calculated for the model area was far below the limit values for annual averages at that time for $PM_{2.5}$ (25 µg/m³) and PM_{10} (40 µg/m³).

Kubal

Figure 80 illustrates the development in production and PM emissions from 1992 to 2020. PM emissions have been reduced by 40-50%.

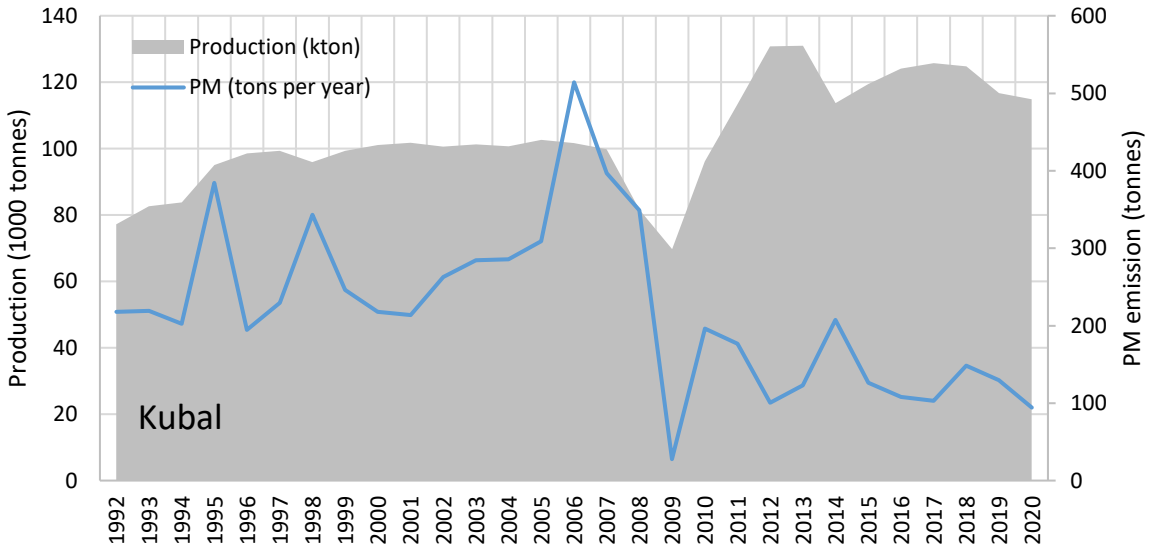


Figure 80: Emissions of particulate matter (blue line, unit: tonnes per year, right-hand y-axis) at Kubal from 1992 to 2020. Development of production (grey background, unit: 1000 tonnes per year, left-hand y-axis). No measurement or modelling data are available for the period 1992 – 2020.

No measurements of particulate matter in ambient air from Kubikenborg Aluminium AB are available. Sundsvall municipality has been monitoring PM at traffic related measurement stations. These data are not considered relevant for the present study.

ISAL

Figure 81 illustrates the development in production and PM emissions from 1992 to 2020. For PM, the emissions (tonnes per year) increased when the third potroom was started, but they have since been reduced by about 35%.

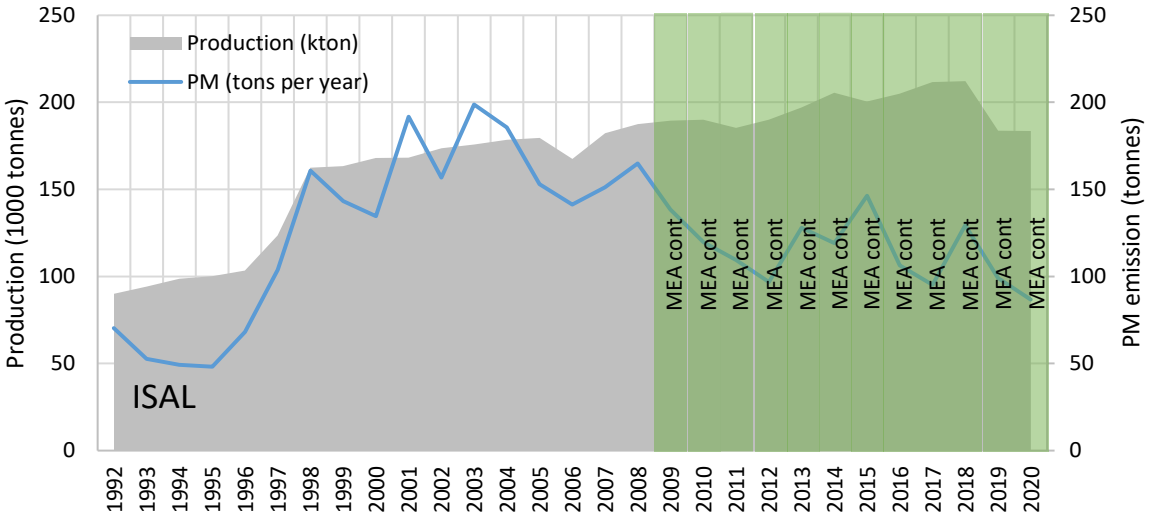


Figure 81: Emissions of particulate matter (blue line, unit: tonnes per year, right-hand y-axis) at ISAL from 1992 to 2020. Development of production (grey background, unit: 1000 tonnes per year, left-hand y-axis). Measurement (MEA) of PM_{10} and $PM_{2.5}$ have been carried out since 1994. Continuous data from 2009 were available for this report, as highlighted.

A measurement programme to monitor air quality parameters has been carried out at Hvaleyrarholt, ca. 2 km northeast of the smelter, since 1994. Data from 2009 were available for this report. Annual average concentrations of particulate matter (PM_{10}, $PM_{2.5}$) are shown in Figure 82. The ambient concentrations of PM have not changed significantly over the past 10 years.

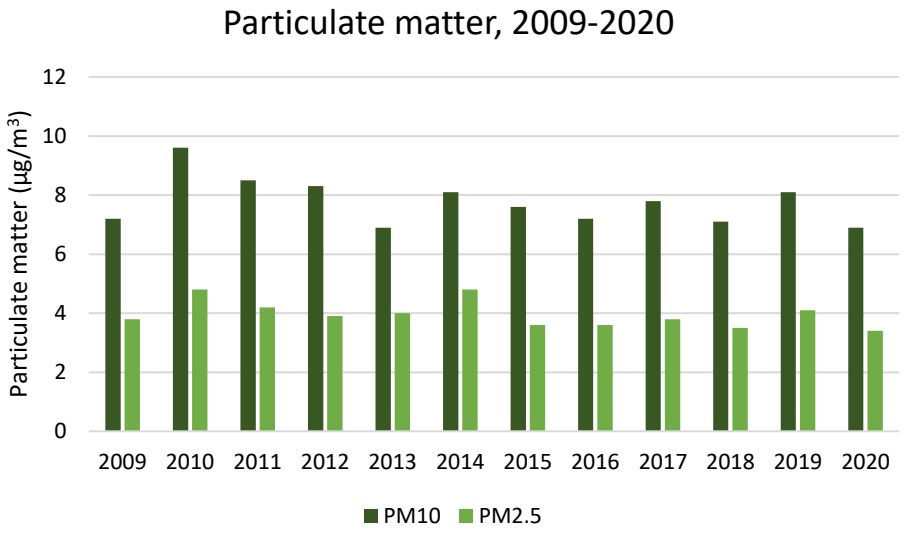


Figure 82: Annual average concentrations of PM_{10} and $PM_{2.5}$ in the years 2009 – 2020 at Hvaleyrarholt, 2 km northeast of ISAL.

2.5 Heavy metals (HM)

2.5.1 Background concentrations

Background measurements of selected heavy metals[33] in air are/have been carried out at Birkenes, Zeppelin and Andøya. Figure 83 shows how metal concentrations at Norwegian background sites have developed over the last decades. Bohlin Nizzetto et al. (2021) report strongly decreasing trends for metal concentrations since the beginning of the 1990s, as indicated in Figure 83.

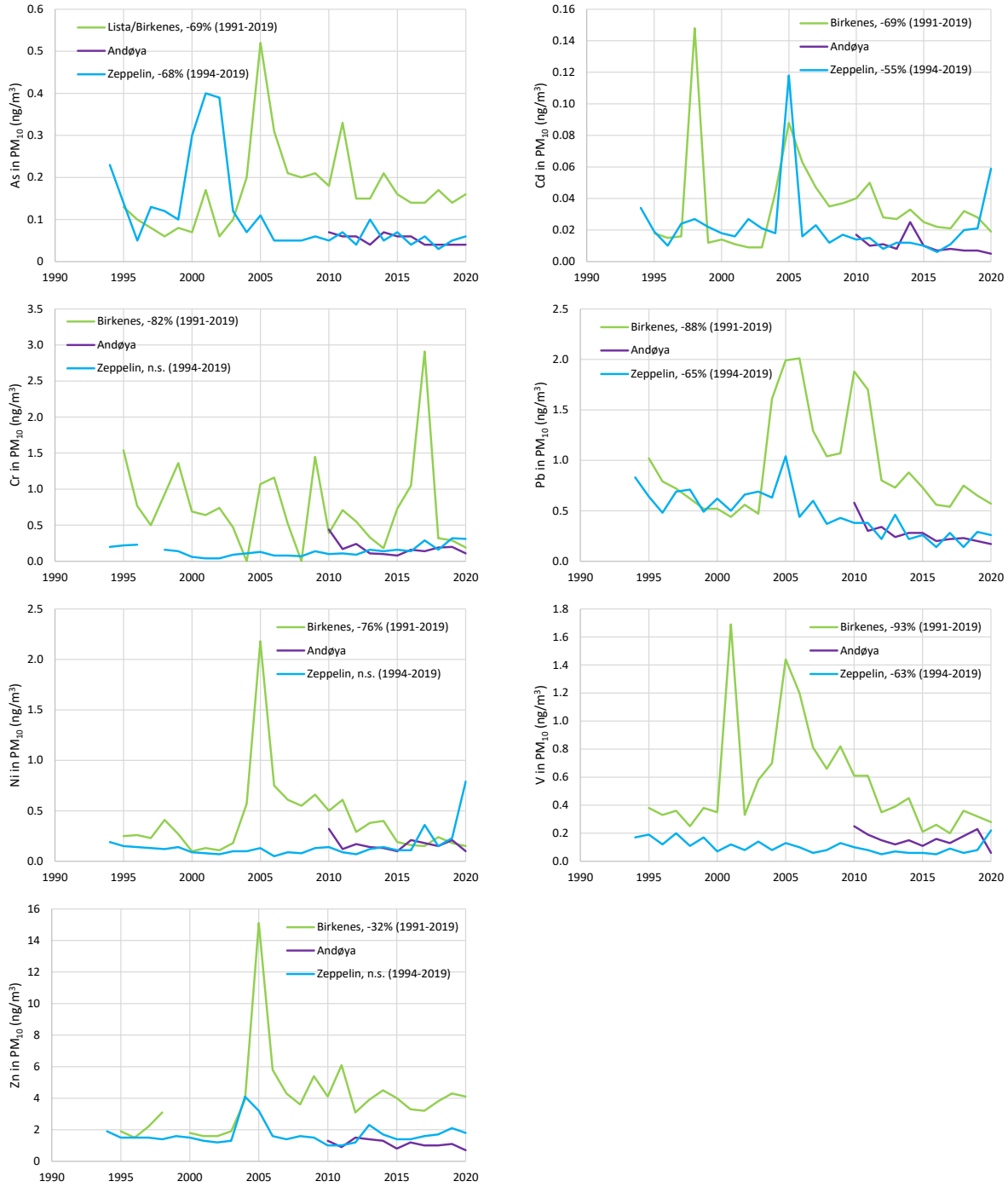


Figure 83: Variation of metal concentrations (ng/m³) at Norwegian background sites in the period 1995 – 2020. Annual averages of arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb),

[33] Aluminium is a light metal

nickel (Ni), vanadium (V), zinc (Zn) in PM_{10}. Trends over the last decades are indicated in the legend.

2.5.2 Emissions and ambient concentrations

Metal emissions are measured by the individual smelters and reported to the Norwegian Environment Agency (Miljødirektoratet). However, there are quite great uncertainties regarding the emission measurements of metals, and there have been some changes in methods, which makes historical trend comparisons difficult.

Fjarðaál

Emission data for heavy metals from Alcoa Fjarðaál were not reported.

No measurement data of heavy metals in air in the surroundings of Alcoa Fjarðaál are available.

Lista

Figure 84 illustrates the development in production and heavy metal emissions from 1992 (2000) to 2020, as reported by Alcoa Lista (www.norskeutslipp.no).

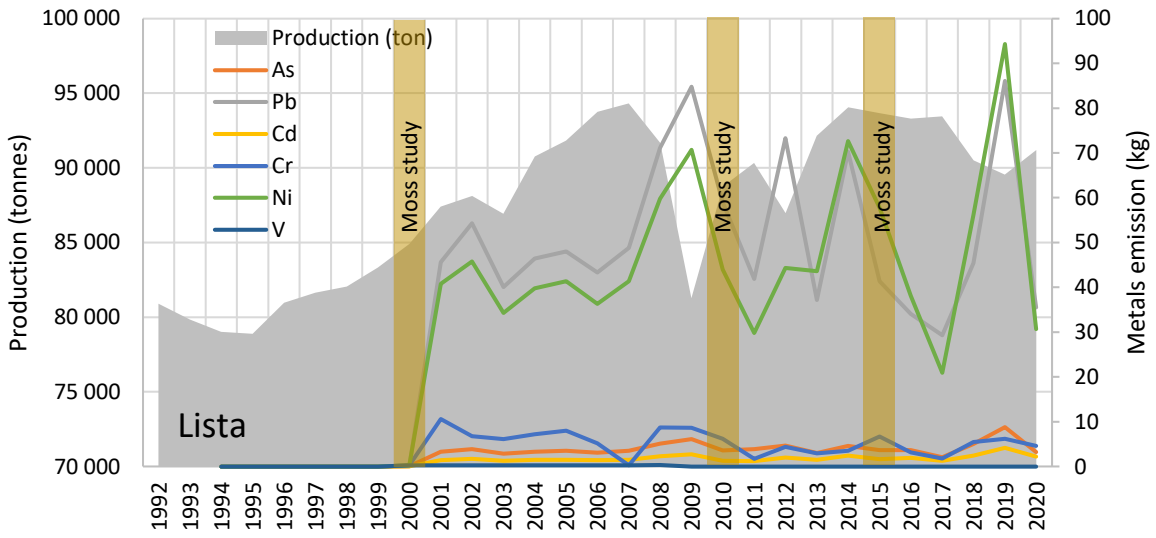


Figure 84: Emissions of heavy metals (unit: kg per year, right-hand y-axis) at Alcoa Lista from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). No measurement or modelling data are available for the period 1992 – 2020. The years moss studies were carried out, are highlighted.

No measurement data of heavy metals in ambient air around Lista are available

Alcoa Lista participated in the moss surveys in 2000, 2010 and 2015, where the deposition of heavy metals in moss around selected Norwegian industries was studied (see Section 3).

Mosjøen

Figure 85 illustrates the development in production and heavy metal emissions at Alcoa Mosjøen from 1992 to 2020. Pb emissions decreased from 2000 to 2001, at the same time Ni emissions increased.

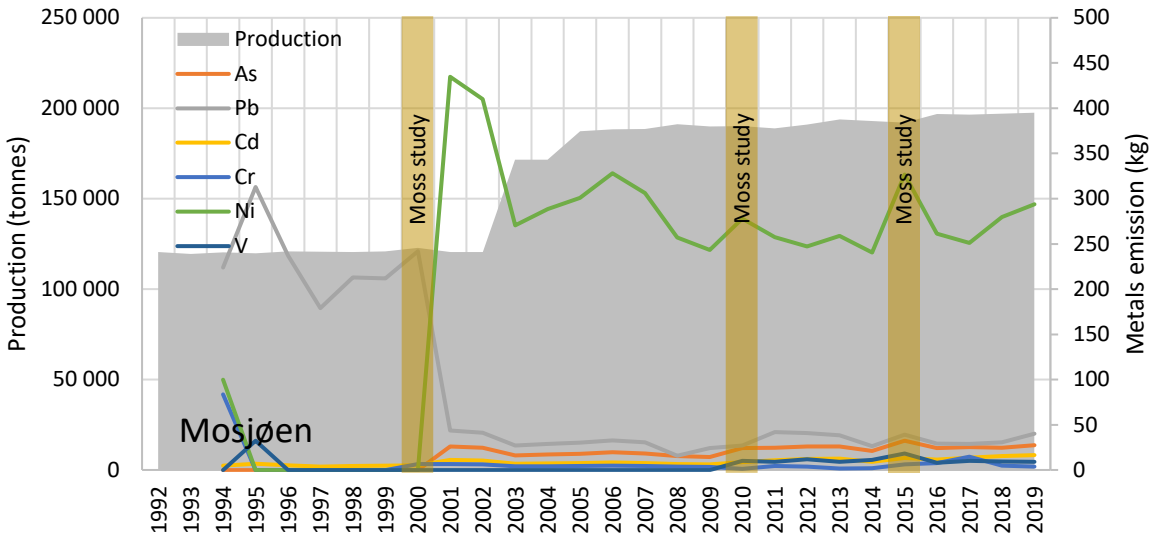


Figure 85: Emissions of heavy metals (unit: kg per year, right-hand y-axis) at Alcoa Mosjøen from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). No measurement or modelling data are available for the period 1992 – 2020. The years moss studies were carried out, are highlighted.

No measurement data of heavy metals in ambient air around Mosjøen are available.

Alcoa Mosjøen participated in the moss surveys in 2000, 2010 and 2015, where the deposition of heavy metals in moss around selected Norwegian industries was studied (see Section 3).

Husnes

Figure 86 illustrates the development in production and heavy metal emissions at Hydro Husnes from 1992 to 2020. The production in 1998 was not reported[34].

34

https://www.norskeutslipp.no/Templates/NorskeUtslipp/Pages/company.aspx?id=61&CompanyID=6256&epslanguage=no&SectorID=600

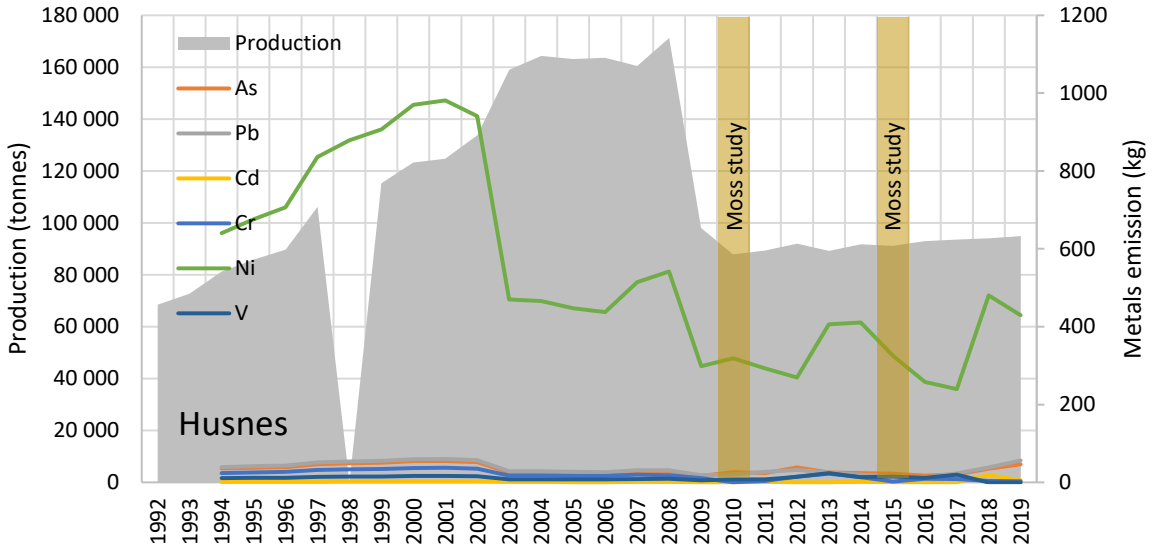


Figure 86: Emissions of heavy metals (unit: kg per year, right-hand y-axis) at Hydro Husnes from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). No measurement or modelling data are available for the period 1992 – 2020. The years moss studies were carried out, are highlighted.

No measurement data on heavy metals in air was available for Husnes.

Hydro Husnes participated in the moss surveys in 2010 and 2015, where the deposition of heavy metals in moss around selected Norwegian industries was studied (see Section 3).

Høyanger

Figure 87 illustrates the development in production and heavy metal emissions at Hydro Høyanger from 1992 to 2020. Both production and heavy metal emission decreased when the Söderberg lines were closed in 2006.

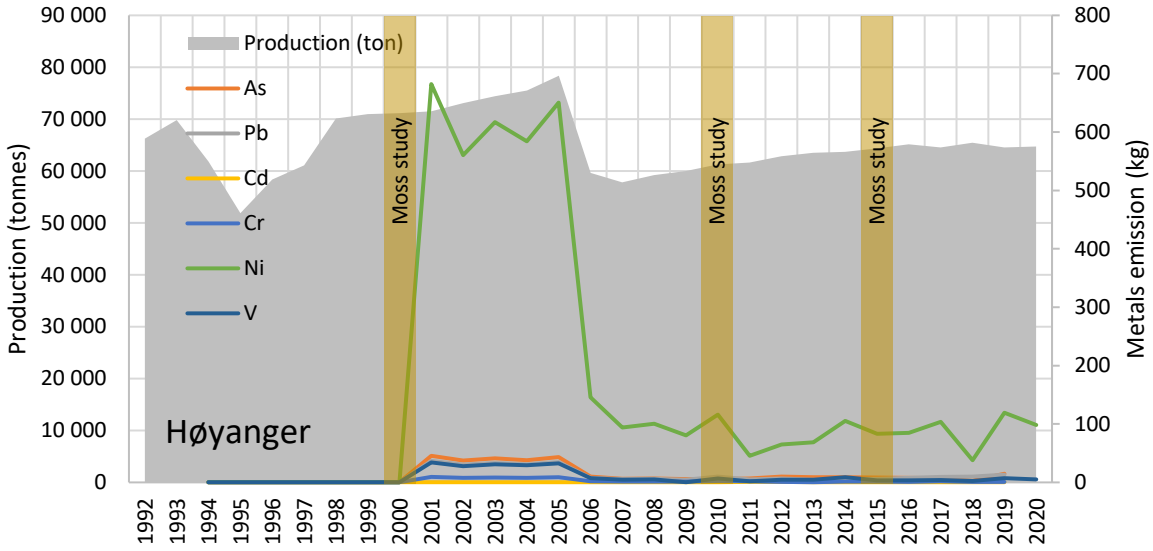


Figure 87: Emissions of heavy metals (unit: kg per year, right-hand y-axis) at Hydro Høyanger from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-

hand y-axis). No measurement or modelling data are available for the period 1992 – 2020. The years moss studies were carried out, are highlighted.

No measurement data of heavy metals in ambient air around Høyanger are available.

Hydro Høyanger participated in the moss surveys in 2000, 2010 and 2015, where the deposition of heavy metals in moss around selected Norwegian industries was studied (see Section 3).

Karmøy

Figure 88 illustrates the development in production and heavy metal emissions at Hydro Karmøy from 1992 to 2020. Both production and heavy metal emission decreased when the Söderberg lines were shut down in 2009.

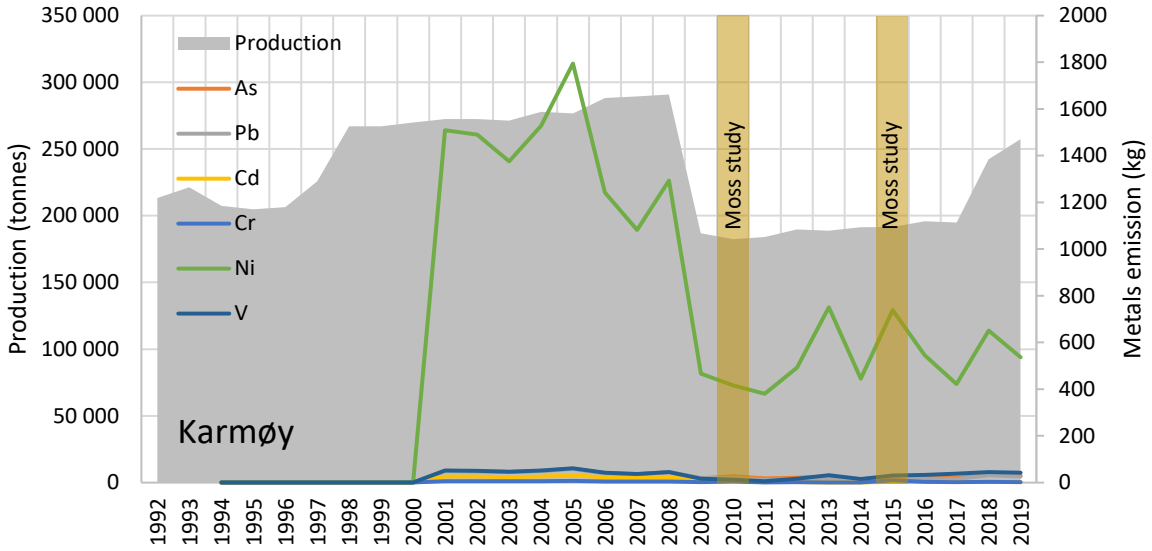


Figure 88: Emissions of heavy metals (unit: kg per year, right-hand y-axis) at Hydro Karmøy from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). No measurement or modelling data are available for the period 1992 – 2020. The years moss studies were carried out, are highlighted.

No measurement data of heavy metals in ambient air around Karmøy are available.

Hydro Karmøy participated in the moss surveys in 2010 and 2015, where the deposition of heavy metals in moss around selected Norwegian industries was studied (see Section 3).

Sunndal

Figure 89 illustrates the development in production and heavy metal emissions at Hydro Sunndal from 1992 to 2020. The emissions of metals were not reported in the beginning of the 1990s. Nickel emissions were almost halved between 1999 and 2019. No reduction of arsenic, lead, cadmium, chromium and vanadium emissions has been reported over the last 20 years.

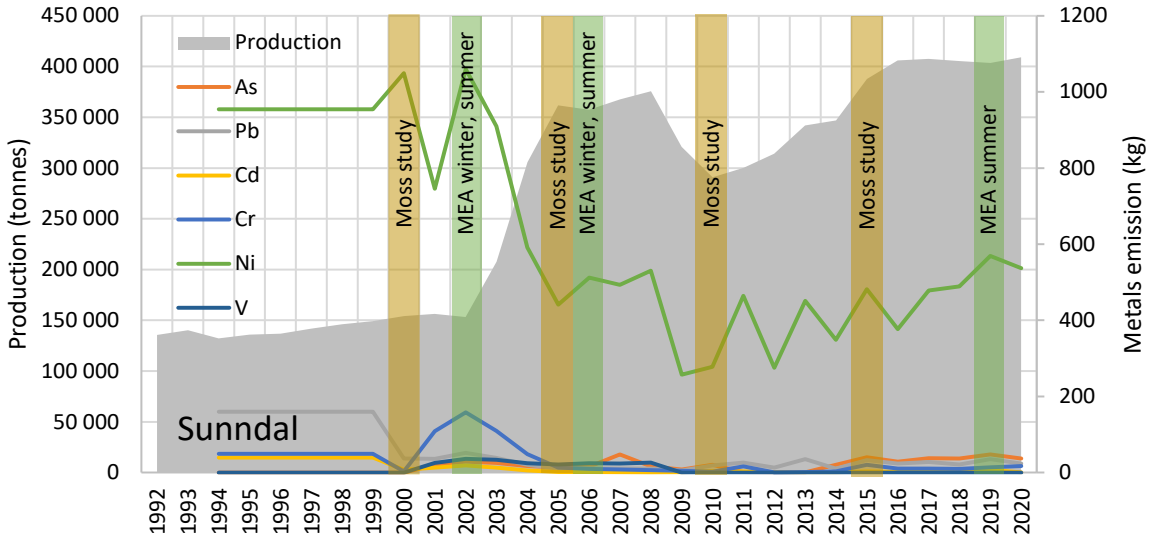
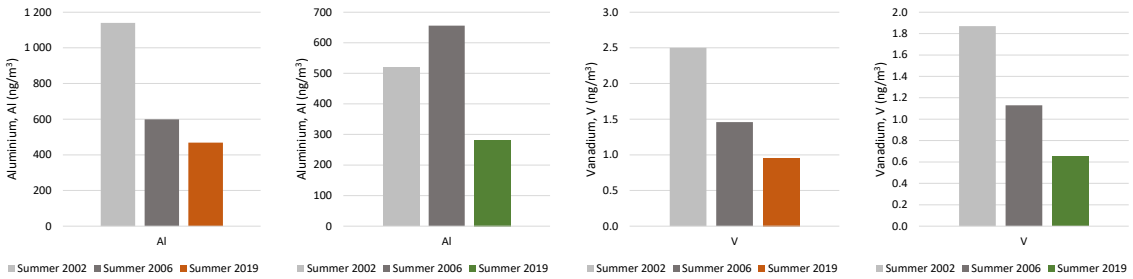


Figure 89: Emissions of heavy metals (unit: kg per year, right-hand y-axis) at Hydro Sunndal from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). The years measurement (MEA) studies were carried out, are highlighted in green. The years moss studies were carried out, are highlighted in yellow.

Hydro Sunndal participated in the moss surveys in 2000, 2005, 2010 and 2015, where the deposition of heavy metals in moss around selected Norwegian industries was studied (see Section 3).

The most recent measurements of heavy metals in ambient air were carried out in summer 2019 (Hak, 2021a) at two stations, Pensjonistsenteret (in the centre of Sunndalsøra) and Vennevold (6 km up the valley). Heavy metals in air/particles have also been included in measurement studies in 2002 and 2006 (see Hagen, 2003; Hagen, 2006). In Figure 90, levels of metals measured in 2019 are compared to results from summer 2002 and summer 2006. Gallium (Ga), antimony (Sb) and bismuth (Bi) were not analysed in previous campaigns. Chromium and nickel were not analysed in 2002. For most compounds (Al, V, probably Cr, Pb), the levels went down from 2002 and onwards. For nickel, the level is unchanged since 2006, at both sites. Arsenic levels were lower in 2006, compared to 2002, but are slightly higher in 2019 than in 2002 even though the PM_{10}-levels are reduced compared to earlier measurements.



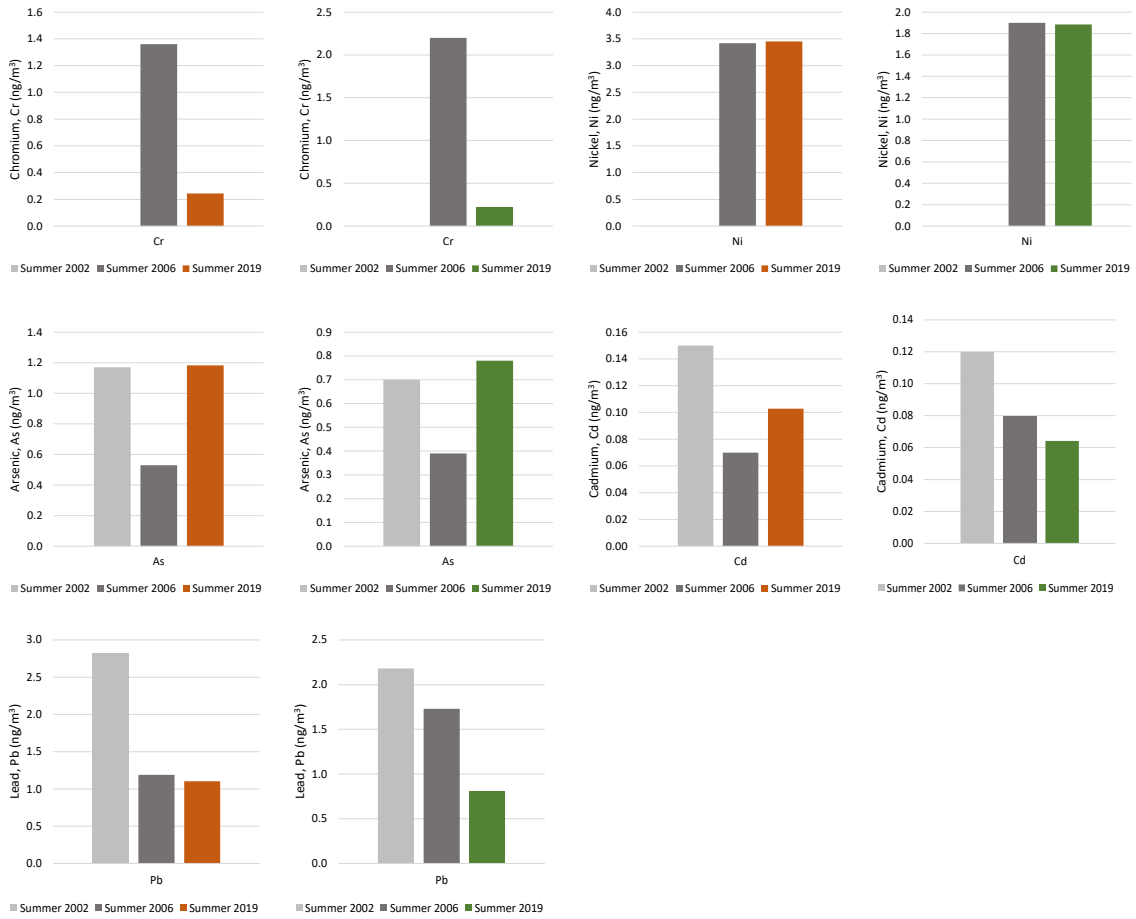


Figure 90: Average concentration of heavy metals in summer 2002 (10 weeks), summer 2006 (9 weeks) and summer 2019 (12 weeks) at Pensjonistsenteret (red) and at Vennevold (green). Note different scales.

In 2002 and 2006, measurements were carried out on 20 days distributed over 3 months. These results are more sensitive to time variations and not directly comparable to long-term mean values over 3 months.

Emissions of several metals are reported to the responsible authorities (see Figure 89). For nickel, the highest emissions were reported before the conversion of the smelter in 2003/2004. In 2002, when high emission was reported, nickel was not analysed. Today's (2019) nickel emission is at the same level as in 2006. Nickel concentrations were the same in 2019 as in 2006 at both sites. For chromium, high emission was reported for 2002. Emission in 2006 was strongly reduced and remained around the same level until 2019. However, chromium concentrations in 2019 were significantly lower than in 2006. For lead, higher emissions were reported 2002 than 2006, but also higher emissions were reported in 2019 compared to 2006. The lowest measured concentrations were observed in 2019. For vanadium, reported emission in 2002 was slightly higher than in 2006. Since 2009, no vanadium emissions are reported. Measured concentrations have decreased in the period 2002 – 2019. Arsenic emissions reported have been varying between 2000 and now and have increased recently. No decrease has been observed in measured concentrations. For cadmium, emissions reported in 2002 were higher than in 2006 and 2019. In 2019, higher Cd emission than in recent years were reported. The highest ambient cadmium concentrations were observed in 2002. At Pensjonistsenteret, the Cd level in 2019 was higher than in 2006.

Øvre Årdal and Årdalstangen

Figure 91 illustrates the development in production and heavy metal emissions at Hydro Årdal and Årdalstangen from 1992 to 2020. According to data received from Årdal Metallverk, approximately 80% of the heavy metal emissions come from the halls.

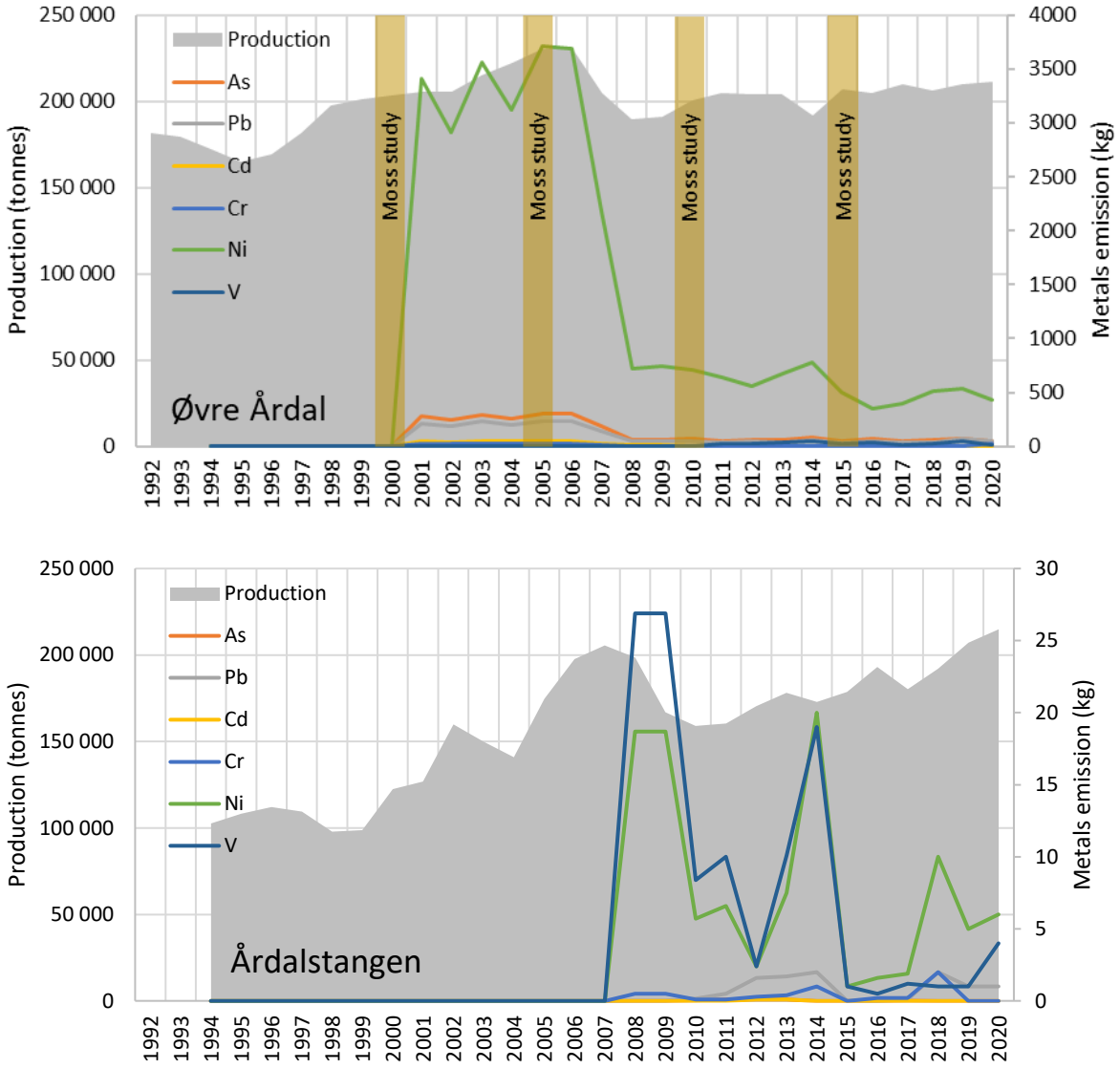


Figure 91: Emissions of heavy metals (unit: kg per year, right-hand y-axis) at Hydro Årdal and Årdalstangen from 1992 to 2020. Development of production (grey background, unit: tonnes per year, left-hand y-axis). No measurement or modelling data are available for the period 1992 – 2020. The years moss studies were carried out, are highlighted.

No measurement data of heavy metals in ambient air around Øvre Årdal and Årdalstangen are available.

Hydro Årdal participated in the moss surveys in 2000, 2005, 2010 and 2015, where the deposition of heavy metals in moss around selected Norwegian industries was studied (see Section 3).

Dispersion calculations for SO_2, fluorides, particulate matter and heavy metals at Øvre Årdal were carried out in 2012 (Hak and Castell, 2012b) to map the effect on air quality in Øvre Årdal of emissions to air under normal operating conditions, using meteorology from 2010. Dispersion calculations of SO_2 were used as a basis for calculating the dispersion of fluoride, particulate matter

and heavy metals. Annual average concentrations of most heavy metals were found to be well below recommended guidelines and target values. Simulated As level was ca 2 ng/m^3, while the target value was 6 ng/m^3 and the simulated annual average for Ni was 17 ng/m^3, only slightly lower than the target value (20 ng/m^3). Based on the model results, it was recommended to follow up the Ni and As levels in the surroundings of the smelter (As 1.9 ng/m^3, Pb 1 ng/m^3, Cd 0.12 ng/m^3, Cu 2.7 ng/m^3, Co 0.13 ng/m^3, Cr 0.05 ng/m^3, Hg 0.0007 ng/m^3, Mo 0.05 ng/m^3, Ni 17 ng/m^3, Zn 1.4 ng/m^3, V 0.8 ng/m^3).

Kubal

Emission data for heavy metals from Kubal were not reported.

The Environmental Office has measured the metals nickel, cadmium, arsenic and lead in air at the main road E4 in central Sundsvall during the period November 2011 to April 2012. The measured compounds have different toxic effects but are all toxic. Several metals are also carcinogenic. Average concentrations in the measurement period were:

- Nickel 1.16 ng/m^3
- Arsenic 0.19 ng/m^3
- Cadmium 0.04 ng/m^3
- Lead 1.31 ng/m^3

The results of the analyses show values far below the environmental quality standards (Sundsvall municipality, 2013).

ISAL

Emission data for heavy metals from ISAL were not reported.

No measurement data of heavy metals in ambient air around ISAL are available.

3 Moss surveys

Moss surveys, studying the deposition of heavy metals around selected Norwegian industries, have been carried out by NILU/NTNU every fifth year in the period 2000 – 2015 (Steinnes et al., 2001; Steinnes et al., 2007; Steinnes et al., 2011; Steinnes and Uggerud, 2017)[35]. This industrial moss survey comes in addition to the national moss survey program conducted approx. every 5th year from 1977 until 2015 (2020 for the county of Finnmark). In the moss surveys, the contents of heavy metals in moss samples collected around metallurgic industries in Norway were evaluated relative to corresponding background levels in moss in parts of Norway with low impact of air pollution. The reports show how the deposition of 32-59 elements[36] varied geographically at each location, with emphasis on the contributions that can be attributed to the main industrial source. Monitoring of atmospheric deposition of heavy metals by analysing moss samples is a well-established technique[37]. The method is described by Steinnes and Uggerud (2017).

[35] The moss surveys have not been continued, so there was no national survey in 2020 and further development of metal levels in moss is not mapped.

[36] In 2000, samples from 11 industries were analysed for 32 elements, in 2005, 44 elements were analysed from 7 industries. In 2010, samples were collected from 14 industries and 59 elements were analysed and in 2015, there were 17 industries and 57 elements were analysed.

[37] The moss biomonitoring technique is particularly well suited in territories where mosses are frequent and grow on a humic soil substrate.

Samples of moss (*Hylocomium splendens*) were collected around metallurgic industries in Norway and analysed for, e.g. lead, cadmium, chromium, copper, mercury, arsenic, which occur in raw materials and reduction materials of the individual smelting plants. All Norwegian aluminium plants participated in at least two surveys in the period 2000 – 2015; two smelters participated in all four surveys. Samples were collected in the period May – August (growing season). Sampling points were located 1 – 10 km from the individual plants and according to the local topographic conditions and assumed prevailing wind directions. The results are strongly influenced by the processes used in the different industries as well as by local topographic and meteorological conditions. For industries located in a narrow valley or a fjord (e.g. Årdal, Sunndal, Høyanger, Mosjøen), a larger part of the emissions will deposit locally compared to locations with larger dispersion of emissions (e.g. Lista, Karmøy, Husnes). Concentrations are given in ppm (mg/kg dry moss).

Some limitation should be taken into account when interpreting the data presented in the moss surveys. The moss method does not distinguish between contributions from wet deposition and dry deposition, nor can the data give information about which size fractions of particles the different metals mainly are associated to. The data also does not provide information of the physical or chemical form of the metals deposited. Hence, conclusions regarding health risks and environmental consequences should not be drawn solely based on the results presented in the moss surveys.

Of the large number of metals analysed, some were found to be elevated in the surroundings of aluminium smelters:

Beryllium (Be): Obvious contamination with Be was registered from the Al industries in **Høyanger** (2000 and 2010 survey), **Karmøy** (2010 survey), **Årdal** (2000, 2005 and 2010 survey) and **Sunndalsøra** (2000, 2005 and 2010 survey). Even though the background levels in moss were significantly exceeded, the values were still low. The beryllium problem in the aluminium industry is well known, and is due to the content of Be in the raw material. The Be pollution previously observed from the **Karmøy**, **Høyanger**, **Årdal** and **Sunndal** aluminium smelters had been substantially reduced in 2015.

Aluminium (Al): The presence of Al in moss is usually a measure that the sample contains particle contribution from wind erosion of soil or other materials of geological origin. However, in the moss surveys, samples from areas surrounding Al plants show the greatest values, which indicates a certain emission to air from these companies (2000, 2010 survey). The deposition of Al among the sites was similar in 2015 as in 2010.The Al deposition varied by a factor of 10 among the sites in the following approximate order: **Sunndal** > **Årdal** > Mo i Rana > **Lista** > **Husnes** > remaining sites (2015 survey).

Vanadium (V): Like Al, the presence of V in moss can be due to particles from the local natural environment. However, there are many indications that V is characteristic of emissions from Al plants and some other smelters (2000 survey).

Cobalt (Co): Deposition of cobalt was registered in a number of places, mostly in **Årdal** and Mo, but the levels are in no case of significant importance (2000 survey).

Nickel (Ni): A noticeably deposition of Ni was registered in a number of places. The largest deposition is at Mo, followed by **Årdal** and **Høyanger** (2000 survey). In 2005, the largest deposition was in Kristiansand (nickel refinery), followed by **Årdal**, **Sunndal** (2005 survey). In 2010, the largest deposition was in Kristiansand and **Årdal**. In 2015, obvious Ni pollution was evident at Årdal and Kristiansand, at the same general levels as in 2010. Appreciable Ni deposition was also observed at **Høyanger**, **Sunndal** and Mo i Rana (2015 survey).

Gallium (Ga): Ga is a metal that is rarely mentioned in connection with air pollution. However, the moss surveys show that Ga is a typical emission compound from Al plants. Ga is closely chemically

related to Al and occurs in the deposition around all Al plants (2000, 2005, 2010, 2015 survey), as demonstrated in the results from **Lista**, **Årdal**, **Høyanger** and **Sunndal** (2010 survey).

Antimony (Sb): Antimony is an element that is typical of air pollution, but usually the levels are relatively modest. Local emissions were registered especially in **Årdal** (2000 survey). Local emissions are registered in **Årdal**, Mo i Rana, Odda, Kristiansand and **Sunndal** (2005 survey). The highest values are found in **Årdal** and **Høyanger** (2010 survey).

Tungsten/Wolfram (W): The presence of W in moss near companies may primarily indicate that this element occurs in raw materials for the process. (2000 survey)

Bismuth (Bi): Bismuth is a rare metal, and little is known about any effects. Emissions of Bi were registered especially in **Årdal**, but the levels were low (2005 survey). Results from the moss survey 2010 suggest that Bi is a general pollution compound from several types of industries, based on the results from Kristiansand, Odda, **Husnes**, **Årdal**, **Mosjøen** and Mo i Rana. Obvious pollution was observed in 2015 at Kristiansand, Odda and **Årdal**, followed by somewhat lower levels at **Mosjøen** and **Husnes**. In most cases, the 2015 values do not differ much from those observed in 2010.

Tellurium (Te): Tellurium is a rare but very toxic element. The moss survey 2010 showed that it acts as air pollution from a number of industries, albeit in small quantities. The emission was particularly marked in Kristiansand, **Årdal**, **Høyanger** and Mo i Rana, but occurred also at most other metal plants. The levels were probably too small to have any significance in nature, but any exposure of employees in the companies should possibly be investigated (2010 survey).

Lista

The aluminium smelter at Lista is situated in a flat terrain with a generally high wind exposure. Emissions from the aluminium plant are dispersed over larger areas than at the other aluminium plants. This may partly explain the low deposition of most metals in its surroundings. **Gallium (Ga)** is a very likely contribution from the aluminium smelter and was found with distinctly higher levels near the smelter than in the Norwegian background in all moss surveys (2000, 2010, 2015). High levels of **thallium (Tl)** in the 2010 survey were concluded to possibly be attributed to other sources, as the levels were much lower in the sampling locations closest to the plant – or they may be a result of emissions over a short period under special wind conditions.

Mosjøen

The topographical conditions in Mosjøen are similar to those at Høyanger, Årdal and Sunndal, but the landscape is somewhat more open. This probably contributes to the relatively low metal levels in moss around Mosjøen compared to what is registered at most other Al plants (2000 survey). Mosjøen appeared to be one of the least polluted locations in the 2010 survey. Relatively high values for **tellurium (Te)** and **bismuth (Bi)** were observed at Mosjøen in 2010 as at most other aluminium plants. Except for moderate levels of **Bi**, the levels of all metals were low around Mosjøen in 2015.

Husnes

The aluminium smelter at Husnes has not been included in the first two surveys in 2000 and 2005. Generally, the level of metal deposition was reported to be low (2010, 2015), but there is reason to assume that the relatively high levels for **nickel (Ni)**, **Te** and **Bi** may be due to emissions from the aluminium plant. In 2015, moderate levels of **Ni**, **antimony (Sb)** and **Te** were observed near the smelter.

Høyanger

The topographical conditions in Høyanger correspond to those for other smelters located between high mountains in the innermost part of a fjord. The deposition from the aluminium plant found in the 2000 survey obviously included a number of metals, but most of them in relatively modest amounts. Most marked was the deposition for **Ga**, as for most other aluminium plants. **Ni** and **Bi** also appeared to be characteristic metals associated with the deposition from Al plants (2000).

2010: There have been changes in the smelter since the first survey in 2000 (last Söderberg line closed in 2006), which is clearly shown in the results of the 2010 survey. While the deposition from **Al** and **Ga** has fallen sharply, **Ni** was at the same level in 2010, and **Sb** and **lead (Pb)** have risen markedly. The values for **Te**, which were not determined in 2000, were on the same level with Årdal and among the highest in the 2010 survey. Another element that showed high levels was **mercury (Hg)**, possibly related to an emission in 2007 from a small company that recycles metals from industrial waste.

2015: Metal deposition at Høyanger found in the 2015 was generally low to moderate. There were still distinctly elevated high levels of **Hg**, probably related to a previous local accidental release, but decreased to about 40% of the 2010 level. Moderately elevated levels of **Ni**, **Sb** and **Bi** were noted in the 2015 survey.

Karmøy

The aluminium plant at Karmøy has not been included in the first two surveys in 2000 and 2005. The smelter is located in a flat and wind exposed terrain, indicating a good dispersion of emissions from the plant. In accordance with this, the deposition levels were found to be generally low, but there were clearly elevated values of **Be** and **Te** at the sampling locations closest to the plant (2010). In the 2015 survey, the results showed that deposition of metals in its neighbourhood was generally limited.

Sunndal

The smelter at Sunndalsøra was included in all four moss surveys. The plant is located between high mountains in the innermost part of a fjord. The pollutants from the plant are transported mainly along the north side of the fjord and into the valley. In the 2000 survey, deposition of the same elements as in Høyanger and Årdal (**Ni, Bi**) was mostly registered.

The deposition situation around the plant in the 2005 survey was characterised by a clear decline since 2000 for many of the metals. An exception was **Ni**, where there has been an increase.

Emissions of metals related to the aluminium plant such as **Al** and **Ga** were at the same level in the 2010 survey as in 2005, while the deposition of **Ni** has been reduced to one third.

In addition to the major metal **Al**, moderately elevated levels were observed for **Ti**, **V**, **Ni**, **Ga** and **Bi** in the 2015 survey. These levels have stayed relatively constant since 2000.

Øvre Årdal and Årdalstangen

The smelter at Øvre Årdal was included in all four moss surveys. Øvre Årdal appeared as one of the most polluted places in all moss surveys, which is partly related to the fact that the smelter is located in a narrow valley, surrounded by high mountains.

Among the many metals that were identified as probable emissions from the Al plant were **Be**, **Al**, **V**, **Ni, Ga** and **Bi**, where the values in the moss samples in the 2000 survey were higher than at the other

Al plants. The same was observed in the 2005 survey, where the levels in the moss samples showed small changes since 2000. The dispersion pattern was not exactly the same for all the elements, which may indicate that they originate from different sub-processes in the company or that they are bound to particles of different sizes (2000, 2005, 2010).

2010: Clear pollution from industry is registered for **Be**, **Al**, **Ni**, **Ga**, **Sb**, **Te** and **Bi**. However, the development over time is different for the different metals. The deposition of **Al** and **Ga** was lower than in the 2005 survey, possibly due to a restructuring in aluminium production. For **Bi**, there was no difference from before, while the deposition of **Ni** has increased somewhat. A particularly large increase compared to the 2005 survey is shown for **Sb** (approximately doubling) and **Te** (approximately fivefold).

2015: The small town of Øvre Årdal is considerably exposed to deposition of several metals presumably related to activities at the nearby smelter, e.g. **V**, **Ni**, **Ga**, **Sb** and **Bi**. The levels of these elements were similar to corresponding data from 2010. Looking at time trends for 2000 – 2015, a slightly increasing trend for **Ni** and a small decreasing trend for **Bi** were observed.

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Appendix A

Measurement methods applied

NILU's EK sampler[38]

The EK sampler collects aerosols and gas in a filter package which in this case contained a pre-filter for aerosols (fluoride) and a filter with added KOH (potassium hydroxide) for gases (SO_2 and HF). A water extract is used to release fluoride (F) from the pre-filter. In the analysis of fluoride, ion chromatography is used. The gases SO_2 and HF (hydrogen fluoride) are absorbed on the KOH-impregnated filter. A water extract added to H_2O_2 is used to release what has been absorbed. The water extract then contains sulphate and fluoride ions. Sulphate is determined by ion chromatography. The amount of fluoride is determined with an ion-selective electrode. As HF is very reactive, some of this gas can be absorbed by particles already deposited on the aerosol filter. It is therefore possible that some of what has been reported as particulate fluoride was originally HF in gaseous form.

NILU's PUR sampler

NILU's "PUR sampler" is used for sampling PAHs in air. When using this sampler, with polyurethane foam plugs after the particle filter, the most important PAH compounds are quantitatively collected. Gas and particle phases were determined together. Benzo(a)pyrene is in the particle phase. Mainly particles with a diameter of less than 10 µm are collected on the particle filter. Larger particles can occur, but hardly in significant amounts. During the analysis, PAHs are extracted from filters and plugs, and the extracts are analysed by gas chromatography with flame ionisation detection. The detection limit for PAH is 0.01 – 0.02 ng/m^3. NILU's method for sampling and analysis is accredited. A working group has been set up within CEN (European committee for standardization) to present a measurement and analysis method that will become the reference method in the EU directive for PAH / BaP.

In summer (relatively high air temperatures) there is a significant breakthrough of especially the bicyclic compounds in the PUR sampler. Higher temperature causes the collection efficiency (retention volume) of PUR to decrease. The breakthrough gradually decreases for the compounds from No 5 to No 9, so that the gas phase of phenanthrene, fluoranthene and pyrene is collected quantitatively.

PAH sampling and analysis, KUBAL, Sundsvall, Sweden

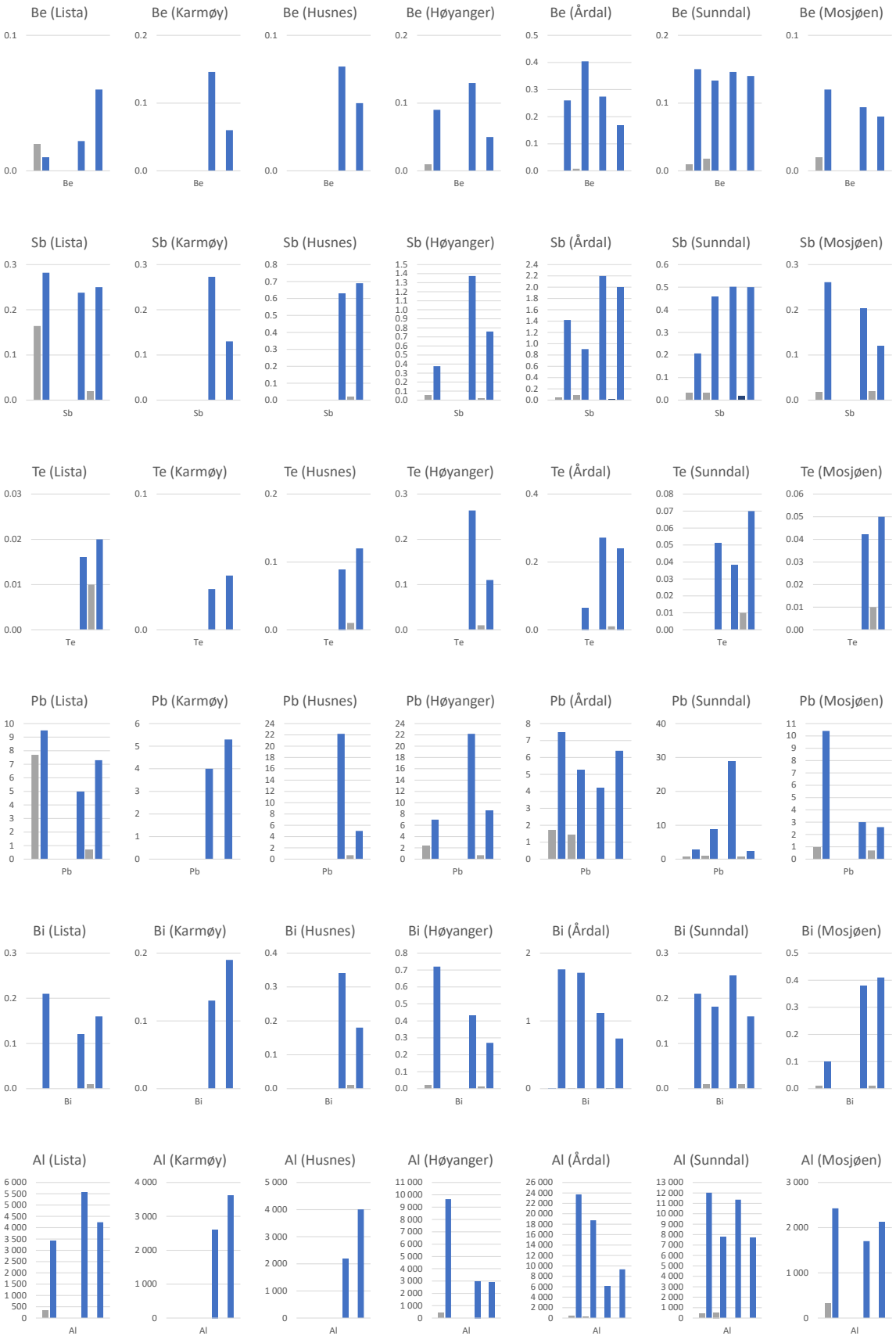
Glass fibre filters (Gelman type A/E, 142 mm) are used for sampling particle-bound PAHs. The analysis method used for the determination of particle-bound PAHs in urban air, i.e. in air samples with low levels of PAH is described in "Analysmetod för PAH immission, KUBAL 87-10-19". The method is intended to determine PAH levels in the order of ng/m^3. The samples are Soxhlet-extracted and evaporated/diluted to the appropriate sample volume/concentration (concentration range of calibration solution) and analysed on HPLC.

Fluoride sampling and analysis, KUBAL, Sundsvall, Sweden

Gaseous and particle-bound fluorides are sampled in a filter package consisting of a pre-filter for aerosols (37 mm Millipore filter, 0.8 µm) and a filter impregnated with sodium formate for gases (sodium fluoride is thereby formed). Fluoride sampling is carried out continuously on a weekly basis at two sites, Villa Marieberg in the north and Kubikenborgskolan in the south. Ion-selective titration is used to determine fluorides in urban air, i.e. air samples with relatively low levels of fluoride. For analysing the filter, a special buffer is added to the filter, which will extract the fluorides from the filter. Interferences of hydroxide ions and complex-forming cations such as Si4+, Fe3+ and Al3+ up to 20 ppm in the sample solution are eliminated by the addition of the buffer. The method is not reliable if air pollutants are more acidic than formic acid, e.g. SO_2 is present in such concentrations that more than 3000 µg of SO_2 or the equivalent amount has been adsorbed by the formate filter during the sampling period. The methods used refer to "Analysmetod för fluoridimmission, GA Metall

[38] https://innovation.nilu.no/wp-content/uploads/sites/14/2022/06/EK-air-sampler_brosjyre_v3-6.pdf [URL]

83 11 98" and ISO DP 10529; Ambient air, Determination of the mass concentration of gaseous and soluble particulate fluorine containing compounds.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Sb (Husnes)
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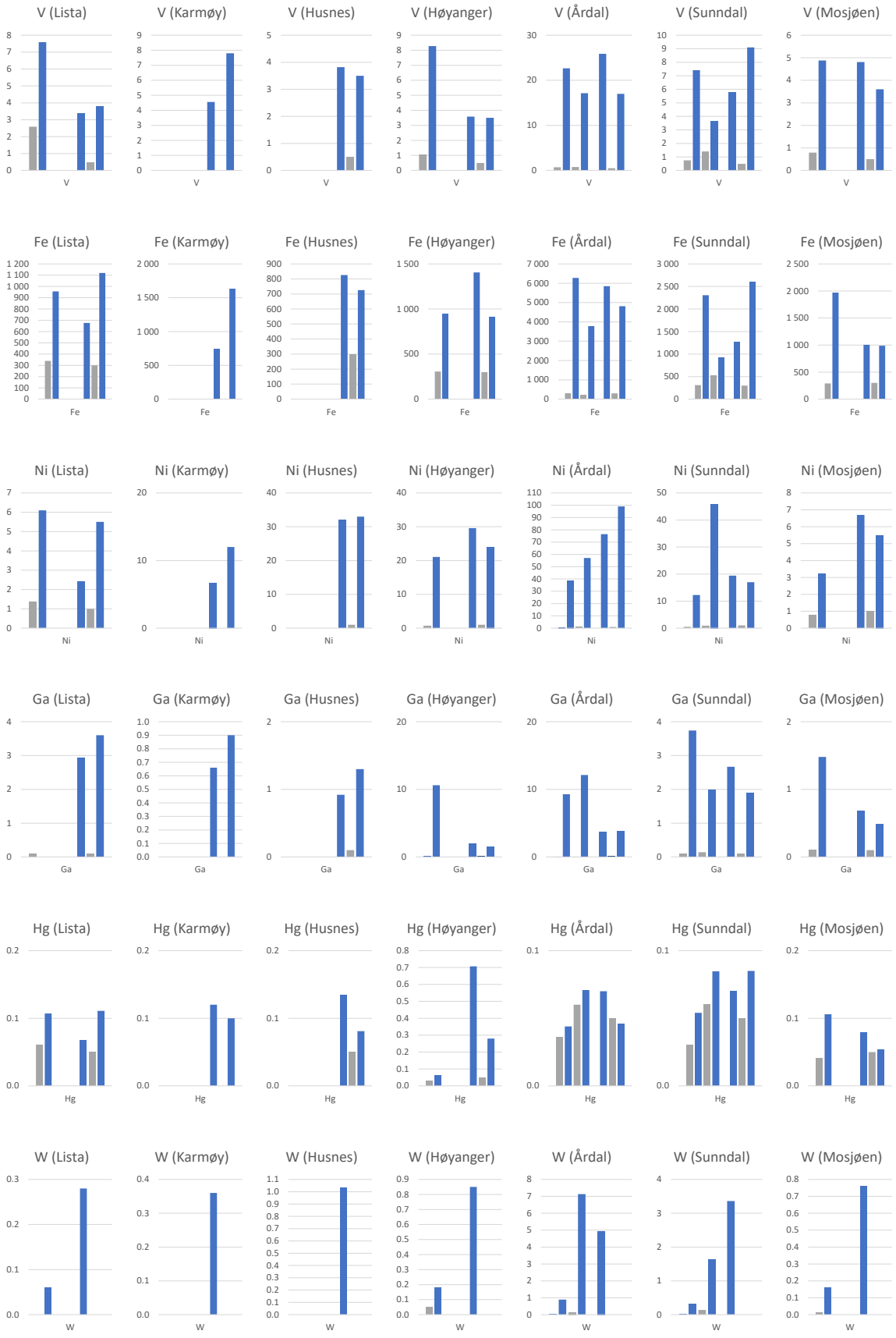

Metal concentrations in the surroundings of aluminium smelters from the moss surveys in 2000, 2005, 2010 and 2015 (blue bars from left to right). Metals concentrations from close-by background

sites are shown by grey bars (also for years 2000, 2005, 2010 and 2015, from left to right). Note different y-axis.

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