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Part 3

Waste and by-products

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Preface

The purpose of this report is to provide general information and statistics on the treatment and processing of waste and by-products of the metal industry in Norway. There will be a focus on the waste hierarchy and how to process waste to achieve the least possible environmental impact and how the emissions of heavy metals have changed over time in Norway. In the end there is an overview of the waste and by-products of the different corporations and what challenges they face. This report will not focus on the emission of gasses, rather the emissions and accumulations of solid and liquid products.

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Introduction

The metallurgical industry in Norway has earlier in history been responsible for a lot of pollution. Then the demand for a more sustainable, less pollutive industry was sharpened and now many of the companies are in the world-elite in terms of sustainability. However, the amount of waste is steadily increasing, surpassing the growth in BNP. The increase in waste-volume creates the need for new, more efficient ways of reducing the amount of waste. By reuse and recycling one can make use of the waste, it is resource- and energy-efficient and it reduces the environmental impact. The potential for profit from efficient and sustainable waste-processing techniques is considerable. There is a double benefit, transforming waste into by-products which decreases the amount of waste and thus the cost of dealing with it, simultaneously it would create resources that can be sold or used as a part of the production process.

The European Commission defines a by-product as a substance or object, resulting from a production process, the primary aim of which is not the production of that item. By-products can come from a wide range of business sectors, and can have very different environmental impacts. Waste, however, is defined as any substance or object which the holder discards or intends or is required to discard.

The Waste Framework Directive sets out the following four conditions that a production residue must meet in order to be considered a by-product:

1. Further use of the substance or object is certain;
2. The substance or object can be used directly without any further processing other than normal industrial practice;
3. The substance or object is produced as an integral part of a production process;
4. Further use is lawful, i.e. the substance or object fulfils all relevant product, environmental and health-protection requirements for the specific use and will not lead to overall adverse environmental or human health impacts.

These tests are cumulative, meaning that all four conditions must be met[1].

One good example of a by-product is the utilization of silicon-dust. Previously, this dust was a waste-product from the silicon-production, but silicon-dust, or micro-silica as it is called has now, found its use. The ideal is to avoid deposition by finding new uses for the waste, either in its raw form or by

[1] Guidance on the interpretationof key provisions of Directive 2008/98/EC on waste

different cleansing and modification processes. In this way what used to be waste can become a resource, just like micro-silica is today. The challenge is to find uses for the waste, that is technically and economically feasible. This is not an easy task, it takes a lot of research and that research takes a lot of investments, but in the long run those investments will pay off. Taking climate-change seriously and acting upon it is not for free, but not acting in time is more expensive. The countries that are best at successfully creating opportunities, when transitioning towards a zero-emissions society will thrive in the coming decades.[2]

Waste and by-products

Traditionally waste has been substances, liquid or solid that in its current form holds minor usage and is considered a burden, not a resource. It is created during production of different products and is in most cases inevitable. A lot of metal-ores contain harmful and toxic substances or elements that must be removed in order to achieve the correct alloy-composition. Whereas today waste is to a large extent seen as a something with potential value. A lot of residue still contain lots of valuable materials that one wants to make use of. Alternatively, a company can sell its waste to another company that knows how to make better use of it. This is a win-win situation for the company and the environment. It is way better than depositing the trash underground or in landfills.

Unfortunately, this has not always been the case, during the 1950s there was a large growth to the scale of the metal-industry in Norway, but there was a lack of focus on environmental issues, which resulted in large emissions. These emissions are problematic to the wellbeing of the public health as well as the health of the fauna and ecosystems. In the 1960s environmental laws where drafted, but it took another decade for many of them to be implemented and environmental concerns were taken seriously. The government implemented strict yet realistic guidelines and demands for the pollution-levels that would be allowed. Despite protests from the industry, they managed to fulfill the demands. Thanks to this the metal-industry in Norway is as of today one of the cleanest, most sustainable and competitive in the world.[3] [4]

Technologically advanced production methods can reduce the emissions and waste significantly yet getting rid of all of it is very difficult. Therefore, it is important to continue treating waste and emissions seriously and seek to improve existing technologies, so that the environment and ecosystem isn't at stake. Unfortunately, the metal-industry has traditionally been one of the largest polluters and it has inflicted severe damage to the environment in its proximity, due to toxic

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[2]The Norwegian government's expert-council on green competitiveness, *Grønn konkurransekraft*, Oslo, 28.10.2016, page 3.
[3] https://slideplayer.no/slide/2978882/, Bjørnar Sæther, 2015.
[4] https://www.sintef.no/siste-nytt/forskningssenter-skal-styrke-metallindustrien/, 23.06.2015.

emissions. Waste was dumped into many Norwegian fjords, damaging the wildlife and polluting the environment. Even though the emissions have come close to a stop, the ecosystem still need time to recover. There will still be a while until all the toxins are gone from fish and other marine animals and food sources. In certain areas at certain times, eating seafood has posed a health-risk because the toxins accumulate in fish and shrimp etc.[5] In order to minimize pollution in the environment, there exists various laws and regulations, whose purpose is to protect the unique Norwegian nature. There are government institutions whose task is to make sure these laws and regulations are not violated. Since pollution follows the ocean- and air-currents, [6] it is important to cooperate with other countries. Therefore, the EU and EEA have the same environmental rules and guidelines.

Despite the implementation of a stricter waste-policy, the rate in which waste is produced has risen the last couple of years, as seen in Figure 1. The exceptions are 2008 and 2009, due to the financial crisis. In 2018 Norway generated 11,82 million tons of trash(including toxic waste), industry was responsible for 14 percent of the waste.[7] Compared to 1995, the total amount of waste has risen by 66,5% from 7,1 million tons in 1995.[8] The increase originates from both population growth and a significant growth in the consumer market, as the GDP has increased significantly in this time-period.

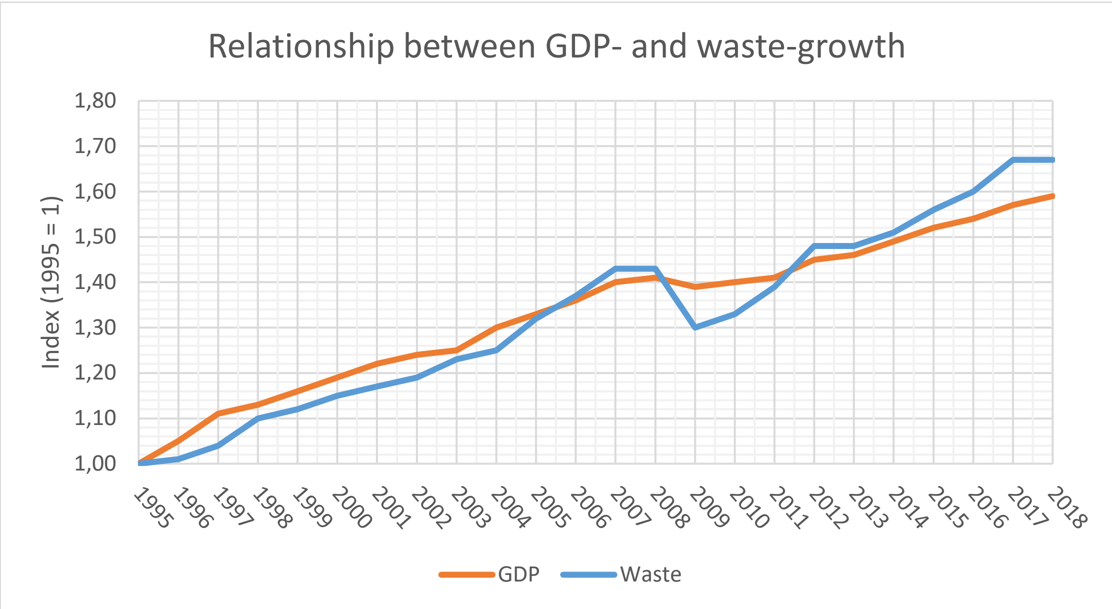

Figure 1: Relationship between growth of BNP and increase in waste (Norway)[9].

[5] http://www.miljostatus.no/tema/hav-og-kyst/miljogifter-langs-kysten/advarsler-mot-fisk-og-sjomat-fra-forurensede-omrader/, environmental and food-safety authorities, 22.06.2019.
[6] http://www.miljostatus.no/tema/kjemikalier/, environmental authorities, 29.05.2020.
[7] https://www.ssb.no/avfregno, 02.04.2020.
[8] http://www.miljostatus.no/tema/avfall/, environmental authorities, 03.06.2020.
[9] https://www.ssb.no/natur-og-miljo/artikler-og-publikasjoner/veksten-i-avfallsmengdene-flater-ut, 06.04.2020

Twenty years ago, waste was commonly put in landfills, but this is not the case anymore[10]. Some of the reason for this, is the ban on landfills containing biodegradable waste that was implemented the 1st of July 2009, to reduce emissions of the greenhouse-gas Methane.[11] In addition to the ban on landfills, we have become way better at utilizing waste-materials better and more efficiently. Most of the industrial waste is being recycled. In 2015, 58% of all ordinary (non-toxic) waste was recycled and 15% ended up in landfills. The total amount of waste(ordinary) was about 0,9 million tons.[12]

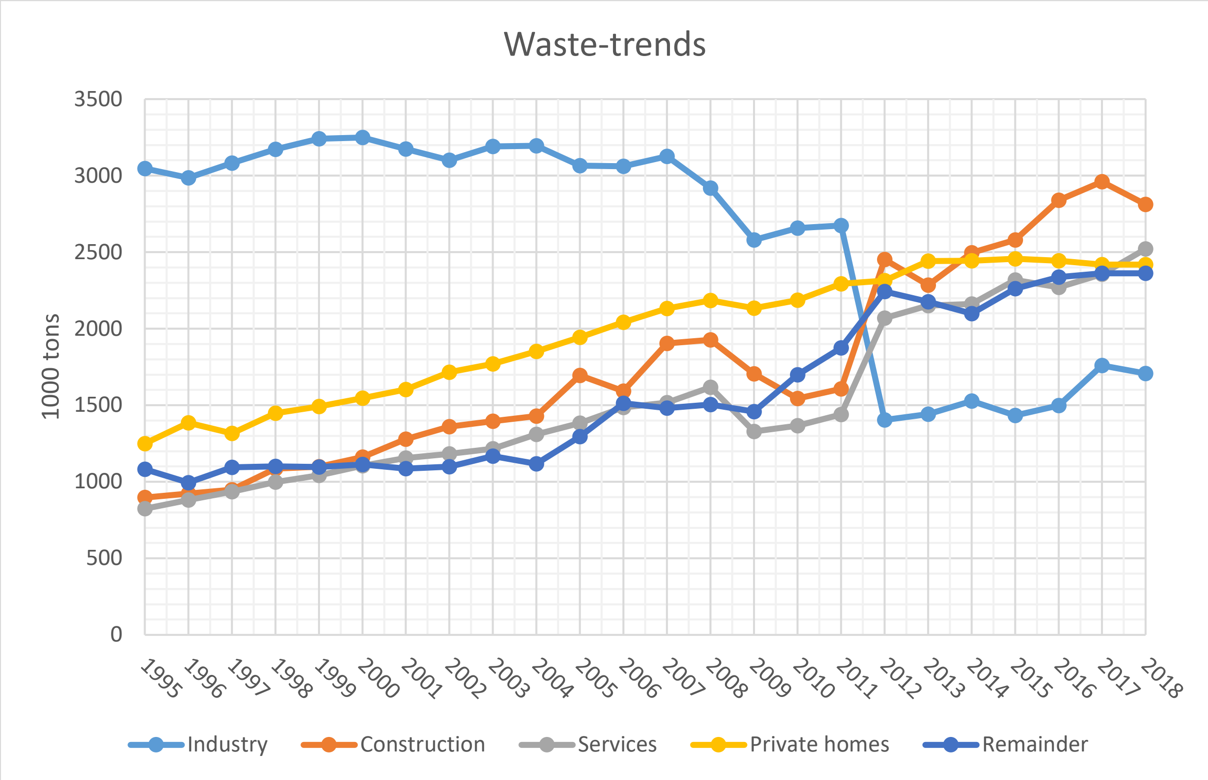

Figure 2: Waste-trends and their sources.

The metallurgical industry is of tremendous importance to Norway, as it provides jobs and tax-income. As shown in Figure 2, the industry (all of it, not only metallurgical) was the main source of pollution until 2011. After 2011 it plummeted despite the general trend of increasing waste-accumulation, as shown by Figure 2.[13] [14] The most important reason for that is a change of the definition of waste, after 2011 a lot of industrial waste was redefined as by-product, thus not being

[10] http://www.miljostatus.no/tema/avfall/, environmental authorities, 03.06.2020.
[11] http://www.miljostatus.no/Avfallsdeponering/, environmental authorities, 25.05.2020.
[12] https://www.ssb.no/natur-og-miljo/artikler-og-publikasjoner/industrien-leverer-over-halvparten-til-materialgjenvinning, 19.09.2017.

[13] https://www.ssb.no/natur-og-miljo/artikler-og-publikasjoner/laveste-gjenvinning-siden-2005, 24.05.2018.
[14] https://www.ssb.no/avfregno , 02.04.2020.

tracked in the statistics above.[15] The steady increase in waste-production after 2011, signals the need for better, more sustainable processes, in this way resources can be utilized more efficient and we avoid landfills and pollution.[16] The strategy for how to achieve this is provided to us in the form of the Waste-hierarchy (Figure 3), this is a systematic way of arranging different processing techniques from most sustainable/efficient (top) to least sustainable (bottom).

Waste-hierarchy

The waste-hierarchy as shown in Figure 3[17], illustrates what methods of handling waste that is the most efficient and thus the waste-policy of the Norwegian government and the EU. In Norway, we have set the goal of keeping the waste-growth lower than the economic growth.[18] From Figure 1 one can observe a trend of a higher waste-growth than economic-growth.[19] If we want to reach this goal we are dependent on the metal-industry along with other industries to decrease the waste generation.

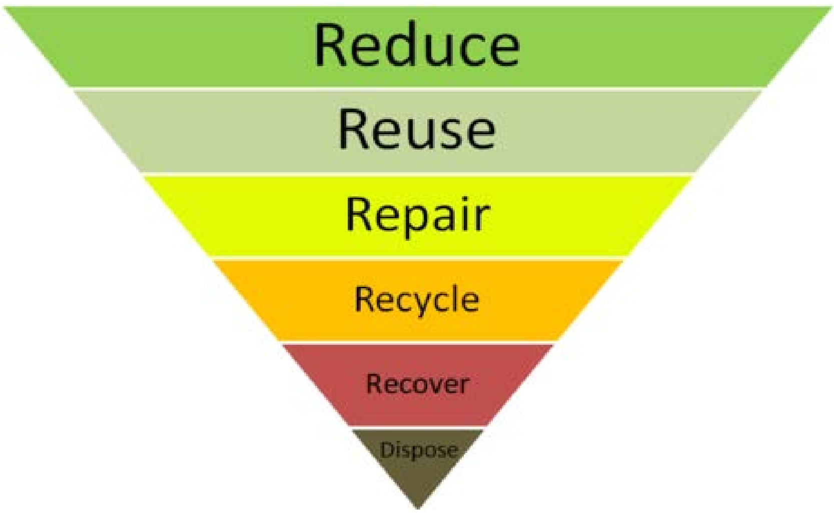

Figure 3: The waste-hierarchy

By letting the waste-hierarchy determine what we do with the waste, we are effectively reducing the amount of actual waste, by turning most of it into by-products or energy. This will further decrease the necessity for fossil-fuels and raw materials.[20]

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[15] https://www.ssb.no/natur-og-miljo/artikler-og-publikasjoner/industrien-leverer-over-halvparten-til-materialgjenvinning, 19.09.2017.
[16] http://www.miljostatus.no/tema/avfall/, Environmental authorities, 03.06.2020.
[17] https://whatplastic.co.uk/blogs/blog/the-waste-hierarchy, What Plastic, 09.06.2020
[18] https://snl.no/avfallshierarki, LOOP, 09.07.2018.
[19] https://www.ssb.no/natur-og-miljo/artikler-og-publikasjoner/laveste-gjenvinning-siden-2005, 24.05.2018.
[20] *Hillingdon's climate change strategy*, UK 2009, London Borough of Hillingdon. This source is also used in the next five sections.

Waste-reduction

Waste-reduction is the top step in the waste-hierarchy and is the most favorable, producing less waste is the most efficient way to save energy and resources. By for example reducing the amount of plastic packaging on goods that does not need it, we save energy and emissions from the production of the plastic and from the transport of it. Albeit we cannot remove all kinds of waste and products do not last forever. However, when waste inevitably is produced, we can put in the effort to salvage as much resources and energy as possible, this is especially important when dealing with rare raw materials like rare earth minerals and many metals.

Reuse

Reuse is the concept of utilizing an item or a material for as long as possible before we scrap it. If an item is worn out or decommissioned it or its components may still be used for other things. By reusing we limit the necessity for new products, thus reducing the need to produce more and that is really environmentally friendly. An added benefit is the lack of need to transport these new items and products to the costumer.

Recycling

Recycling is essentially all about bringing the raw materials once used back into the supply-chain. This is beneficial for several reasons. We make sure that rare raw materials are not lost, these materials are often valuable because of their scarcity. A lot of these rare raw materials are also critical to recycle due to geopolitical conditions, obtaining more of them may become troublesome in the future. Recycling of metals like aluminum is really beneficial because melting aluminum scrap consumes only a fraction of the energy it takes to produce aluminum from alumina. This applies to many other materials as well; recycling takes less energy and CO_2-emissions than primary production. However, recycling is not quite as efficient as reuse or waste-reduction.

Energy recovery

Waste that cannot be reused or recycled is often susceptible for energy recovery, the waste's chemically bound energy is freed with the use of combustion. This is a renewable process, because there is a steady supply of waste, it does however have a significant CO_2-footprint as the combustion of plastics etc. produces a lot of CO_2. Assuming the byproducts(gas) are cleansed properly, this process helps to remove certain toxic compounds.[21]

[21] https://snl.no/forbrenningsanlegg, 09.07.2018

Dispose

Disposing is at the bottom of the waste-hierarchy and it is the worst waste-management tactic. First and foremost, all materials and the energy it took to produce them are lost and the materials cannot be recycled. There is also the added risk of pollution, toxins and heavy metals can seep into the ground water thus ending up in the ecosystem. Many landfills must be monitored even after they are closed due to the leakage of toxins and if the landfill contains a lot of organic materials, additional methane is produced. Methane is a very potent greenhouse-gas. Disposed waste also must be put somewhere, eventually a landfill will be filled up and the waste must be put somewhere else, often increasing the price of waste-disposal. Albeit we must remember that in some cases deposits are unavoidable sine not all types of waste are recyclable, and in some cases, depositing waste is the best (and only) solution. Professional landfills with minimal leakage to the surrounding environment can sometimes be better than for example energy recovery through combustion. This especially applies to heavy metals.[22]

Hazardous waste

Hazardous waste contains substances that are dangerous for the environment or for public health. This type of waste cannot be treated equally to regular waste as it would result in severe pollution. There are strict guidelines as to how such waste has to be treated in order to minimize the hazardous effects on nature, wildlife and health. These guidelines are constantly changing as more knowledge is obtained about these hazardous substances and what products that contain or not contain these. More and more substances are considered hazardous, research has shown that a lot of previously "safe" substances can cause cancer. Due to the increase of substances that are being **defined** as hazardous, there has been an increase in the amount of hazardous waste produced each year, as shown in Figure 4.[23] Despite an increase in the amount of hazardous waste since 2013, the amount recycled has been stable and relatively low. Which means that a larger share of waste has been disposed. In 2018 1,54 million tons of hazardous waste was disposed, in which is about a 2,3% increase of the numbers from 2014.[24] Of all hazardous waste (in Norway) 20,2% was recycled, 16,2% was energy recovered, 61,6% was disposed or processed, the remaining 2% is due to change of storage capacity. In 2018 46,9% of all hazardous waste originated from industry.[25]

[22] https://www.avfallnorge.no/hva-jobber-vi-med/fagomr%C3%A5der/deponi, 10.06.2020.
[23] https://snl.no/farlig_avfall, 09.07.2018.
[24] https://www.ssb.no/natur-og-miljo/statistikker/spesavf, 05.12.2019.
[25] https://www.ssb.no/natur-og-miljo/statistikker/spesavf/aar, 05.12.2019.

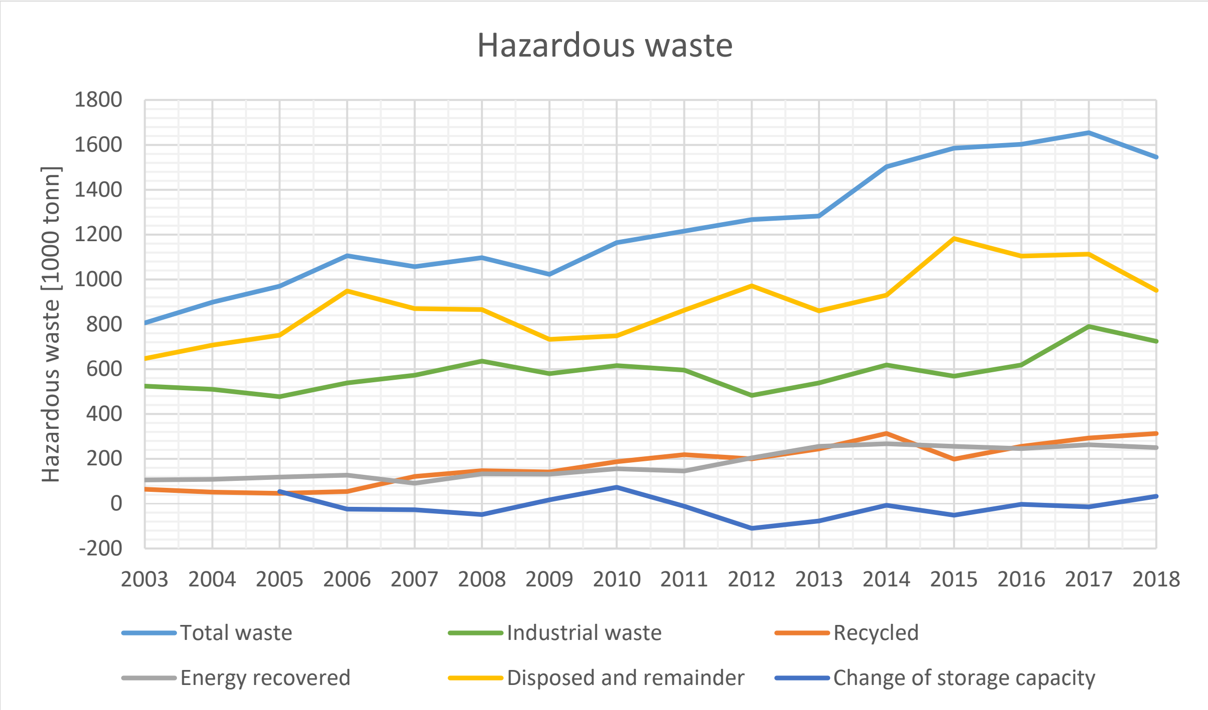

Figure 4: Overview over hazardous waste, the industrial share of the total and how hazardous waste is treated in Norway.

Heavy metals

Of all hazardous waste processed in 2018 the majority is hydrocarbon- or heavy metal -related at 577 000 tons and 519 000 tons, respectively.[26] The heavy metals compose mostly of metal hydroxides, slag, dust and different types of ash. Some of the heavy metals are harmful for the environment and affect health and eco-systems negatively, like mercury, lead and Cadmium. Heavy metals are a long-term problem because they accumulate within animals. Especially those at the top of the food chain, that includes humans. Not all heavy metal emissions originate from Norwegian industry, a large amount of heavy metals are transported here through air-currents and end up in Norwegian lakes through rain.[27] From the lakes the heavy metals can get into the eco-system and end up in our food. Fortunately, the emissions of mercury has significantly reduced the last couple of years because mercury is such a treat to the environment and people's health. Most factories have acquired mercury-cleaning facilities. Since 1990 the metal-industry have reduced their mercury emissions by over 90%. Due to this, mercury emissions in Norway was reduced by over 80% in this time-period.[28] Emissions of other heavy metals like Lead, Chromium and Cadmium has also been reduced, as seen in Figure 5 and 6.[29,30] The emissions vary from one year to the next, depending on the composition of the ores used by the metal-industry, but most of the reduction is due to better cleaning processes.

Compared to previously there has been an increase in the amount of hydrocarbon-related hazardous waste. This is because more hazardous waste has been brought back to shore from oilfields in the North Sea instead of being pumped back down into the reservoir.[31]

[26] https://miljostatus.miljodirektoratet.no/tema/avfall/avfallstyper/farlig-avfall/, 18.12.2019
[27] http://www.miljostatus.no/tema/ferskvann/miljogifter-i-ferskvann/tungmetaller-i-innsjoer/, 11.06.2020.
[28] https://www.ssb.no/statbank/table/09291, 11.06.2020.
[29] https://www.ssb.no/statbank/table/09291, 11.06.2020.
[30] https://www.ssb.no/statbank/table/07081/, 11.06.2020.
[31] https://miljostatus.miljodirektoratet.no/tema/avfall/avfallstyper/farlig-avfall/, 18.12.2019.

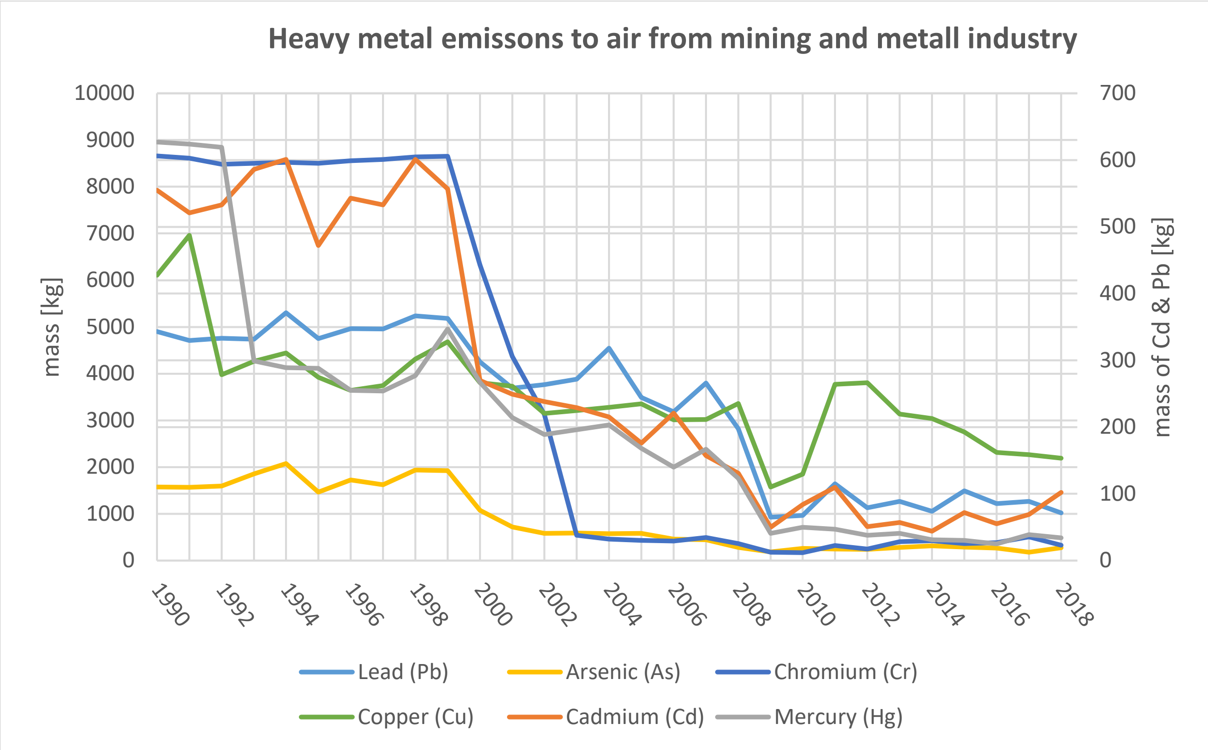

Figure 5: Heavy metal emissions to air from mining and metal industry.

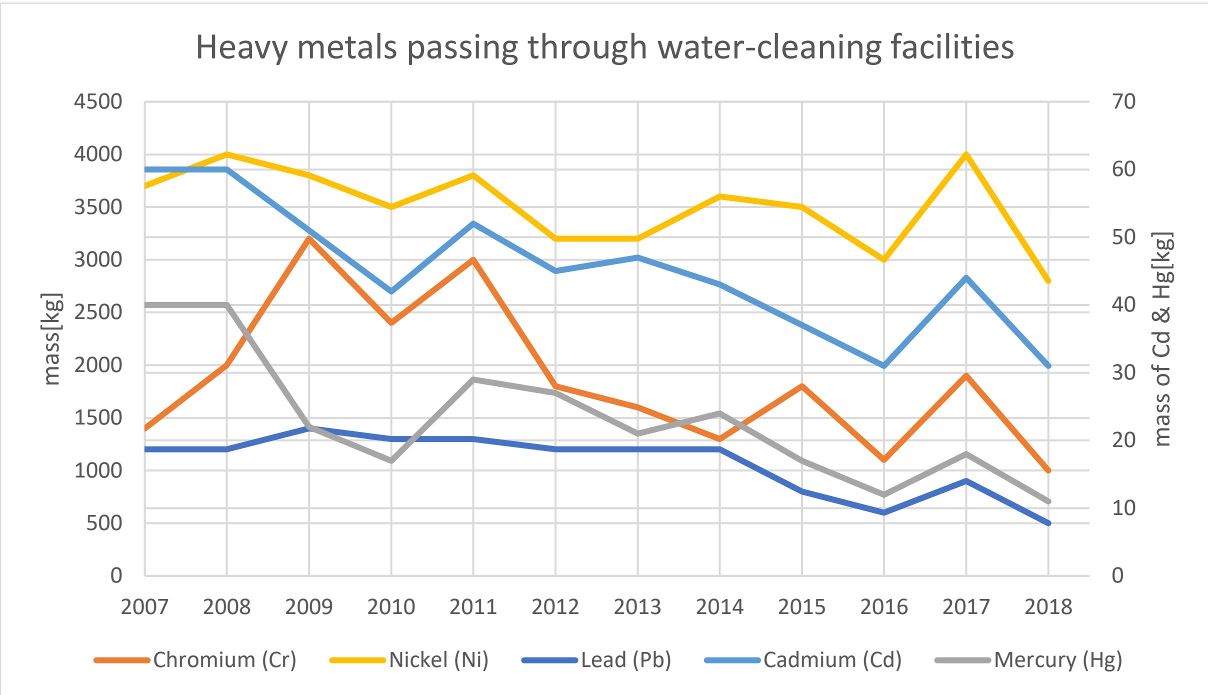

Figure 6: Mass-flowrate of some heavy metals through water-cleaning facilities. This is a good estimate of the distribution of the different metals emitted, but the actual amounts are probably larger.

Waste and by-products from Norwegian companies

Different production techniques generate different amounts of waste and by-products. The amount is usually linear proportional to the scale of the production, with some deviation due to construction work, refurbishments, etc…Different companies may have different priorities and tactics to optimize their production processes and limit their environmental footprint. This report will have a closer look into what amount of waste and by-products the different producers of metals generate and what their strategies for improvement is.

Aluminum

Aluminum is in Norway produced by Hydro and Alcoa.

By-products from the production are:

Anode butts: In the electrolytic production of aluminium from alumina, carbon anodes are needed. The large anodes cannot be fully consumed. The mechanical suspension of the anode and the current supply make it necessary to remove the butt. These anode butts are cleaned and are then recycled for the production of new anodes.

Surplus bath: small amounts of sodium in the alumina cause build-up of bath as AlF_3 is added to maintain wanted cryolite ratio (CR = mol NaF/mol AlF_3), usually around 2.2. Typical additions are in the range of 20-30 kg AlF_3 per tonne of Al produced. About 10 – 15 kg is needed to compensate for Na_2O in the alumina (0.3-0.45 wt% Na2O in Al2O3).

Typical wastes from Aluminum production are:

Waste from gas treatment like scaling, dust and limestone from the cast houses and sludge from wet scrubbing.

SPL: The used insulation of the electrolysis cells is called: Spent Pot Lining (SPL). This is composed mainly of carbon-materials and refractory materials. After service, also fluoride compounds, cyanide, polyaromatic hydrocarbons (PAH) and reactive metals are present in the SPL. SPL is therefore considered hazardous waste. The production of SPL varies with the relining of electrolysis cells, which is normally done every 4-7 years for established aluminium plants. This waste has traditionally been disposed in the landfill at Langøya in Holmestrand, Norway. However, there are now several initiatives ongoing to utilize the waste for something useful. For example, the carbon can be used for fuel and the refractory materials can be used in cement, concrete, or building insulation[32].

Fiber waste, like Rockwool insulation material.

Used refractories from the anode baking furnace.

Carbon waste, which is carbon dust from anode production, waste from anode butts cleaning, carbon lumps from rodding and from electrolysis.

Metal, that is steel, aluminium leftovers, bottom metal/electrolyte from electrolysis cell demolition, turnings

Prosess waste: Dust from anode butts cleaning, carbon soot, iron from anode service.

Dross is a waste made up of metallic aluminum and non-metallic compounds like oxides, nitrides and carbides that form at the surface of liquid aluminum. Dross may contain up to 90 % aluminum.[33] Dross does not contain toxic substances. This makes recycling a lot easier. Dross is recycled at a specialized recycling facility run by Real-Alloy, Norway. This facility recycles dross from aluminum plants all over Norway.

Sludge from the surface treatment of metal

Hydro[34] [35]

Hydro has five aluminum plants in Norway that produce primary aluminum through electrolysis. Hydro manages also several powerplants, research labs and special facilities for casting, recycling, rolling and refining of aluminum. In Brazil, Hydro has bauxite mines and an alumina refinery. Table 1 contains information about what amount of waste Hydro's aluminum plants produce in Norway. Hydro have agreements with Norcem regarding the anodic waste. Norcem has a cement plant in Brevik, Norway that can use the anodic waste for fuel. Spent potlining (SPL) from the electrolysis cells are defined as hazardous waste, Hydro has a goal of recycling 65% of all SPL within 2030. Hydro cooperates with Qatar steel and the cement industry in Brazil. SPL has a high energy content so it may substitute fuel.[36]

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[32] Merete Tangstad, *Metal production in Norway*, Akademika Publishing, 2013, page 51.
[33] https://www.sintef.no/publikasjoner/publikasjon/?pubid=CRIStin+1195319, 2014.
[34] Contact with Hydro, 2018 & 2020
[35] https://www.hydro.com/no-NO, 13.06.2020.
[36] https://www.hydro.com/globalassets/download-center/investor-downloads/ar19/annual-report-2019-web.pdf, Hydro annual report 2019, 18.06.2020.

Table 1: Overview of the by-products and waste from Hydro's plants in Norway.

Waste and byproducts from hydro, 2019 [tons]	**Husnes**	**Høyanger**	**Karmøy**	**Sunndal**	**Årdal**
By-products					
Anodebutts	7 749	4 646	28 629	37 460	25 223
Suplus bath	677	274		3 210	1 179
Waste:					
Waste from gas-treatment	41		1	22	1 472
Spent PotLiner (SPL)	9 294	1 174	4 009	7 821	3 789
Fiber-waste		3	26	36	52
Used refractories	28		265	1 592	2 019
Carbon-waste	899	959		5 981	7 412
Metal	650	270	1 229	4 749	2 427
Process-waste	913	1 248	1 645	6 141	978
Dross	1 295	1 281	3 535	5 074	2 566
Sludge from the surface treatment of metal			25		
Other	443	142	1 620	792	303
Grand Total	**25 193**	**9 997**	**40 985**	**72 876**	**48 676**

Alcoa[37]

Alcoa is a producer of primary aluminum and they have two plants in Norway, one in Lista and one in Mosjøen. Alcoa has a strong desire to recycle the waste from their aluminum plants all over the world. Alcoa is adapting their waste management techniques to the waste-hierarchy. In a long-term perspective their goal is to completely eliminate the need for disposal of waste. By 2025 Alcoa want to reduce the amount of landfilled waste by 15% and by 25% within 2030.[38] An overview of Alcoa's waste accumulation is provided in Table 2 and 3.

[37] Contact with Alcoa, 2018 & 2020.
[38] https://www.alcoa.com/sustainability/en/pdf/2019-Sustainability-Report.pdf, Sustainability report 2019, page 77, Alcoa.

Table 2. Overview of the by-products and waste from Alcoa Lista.

Waste from Alcoa Lista 2019		
Type of waste	Amount [tons]	Treatment
Cathodic waste	2314	Deposited
Oven-soot	2857	Deposited
Electrostatic-filter soot	1185	Deposited
Sweepings	910	Deposited
Slag	106	Combustion because of TOC
Sludge	557	Deposited
Dross (from foundry)	2010	Recycled
Fireproof materials	131	Deposited

Table 3 Overview of the by-products and waste from Alcoa Mosjøen.

Waste from Alcoa Mosjøen 2019			
Type of waste	Code	Current treatment	Amount [tons]
Slag from primary production	7096	Dross. Recycled, sent to Real Alloy Red	6898,68
Cathodic waste	7096	SPL. NOAH Langøya	2184,23
Coal emissions	7096	Disposed at private landfill until September 2019.	443,202
Coal emissions	7096	"Terrateam Miljøteknikk", Mo i Rana	276,07
Dust from filtering of smoke	7096	Disposed at private landfill until September 2019.	823,73
Dust from filtering of smoke	7096	"Terrateam Miljøteknikk", Mo i Rana	387,23
Sandblasting	7096	Sandblasting-sand. Disposed in private deposit.	117,6
Sandblasting	7096	Sandblasting-sand & coal-dust, NOAH Langøya.	128,95
Fireproof materials, including Metal-crucibles.	1614	Deposited in private deposit.	904,581
Asphalt/concrete	1619	SHMIL Retura	20,42
Fireproof materials from anode-oven.	1614	Recycled at Mineralen Kolle, Netherlands	952,5
Sweepings	1671	Private deposit and SHMIL Retura	153,478

Ferromanganese (FeMn) & silicomanganese (SiMn)

In Norway we have a total of four smelters for ferromanganese and silicomanganese owned by the companies Eramet and Ferroglobe. Typical wastes and byproducts are slag, sludge and different forms of dust. The slag-leftovers from FeMn-production contains such high amount of manganese that it is commonly added back into the oven together with raw materials to produce SiMn. The slag is considered a byproduct, not waste if it satisfies the criteria of the EU directives (EU DIRECTIVE 2008/98/EC).[39] It is used for road construction.

The sludge however is classified as hazardous waste, but it is still a good source of manganese, so recycling is beneficial. The sludge originates from the purification of gasses from the ovens, these gases contains dust and volatile compounds from the ore and raw materials. When the dust is removed by dry filters or wet scrubbers it gives either dust or a mixture of dust and water (sludge). One of the challenges regarding sludge, is its high content of alkalis. These alkalis come out of the oven together with the gas. If sludge is added back into the oven it will result in an accumulation of alkalis within the oven, this will in the long term be destructive for the process. In addition, it would require even stricter rules and control-procedures as it is counted as destruction of hazardous waste. As of today, sludge is usually deposited, but alternative solutions are being worked on.[40]

Ferroglobe[41]

Ferroglobe has a manganese smelter in Rana and produce ferromanganese and silicomanganese. In addition to ordinary waste, considerable amounts of dust and sludge is formed. The amounts are listed in Table 4.

Table 4 Overview of the by-products and waste from Ferroglobe, Rana.

Waste (2019)	Quantity [tons]	Current treatment
Dust from sintering (contains mercury from cleansing)	800	Treated by an approved third-party company
Dust from filters	1000	
Ferromanganese slag	5000	Recycled back to the oven
Silicomanganese slag	117000	Recycled. Sent to other companies, crushed and sent to various projects

The leftover silicomanganese slag is sent to other companies close by, that process it further. The slag can for example be crushed and used as filling for roads or constructions. Ferroglobe's smelter

[39] Contact with Ferroglobe Mangan Norge As, 2018 & 2020.
[40] Merete Tangstad, *Metal production in Norway*, Akademika Publishing, 2013, page 82.
[41] Contact with Ferroglobe Mangan Norge As, 2018 & 2020.

also produce hazardous waste, this includes sludge from their water-cleansing facility and filtered dust from their sintering facility. This waste contains heavy metals like for example mercury. The hazardous waste is deposited in compliance with rules and guidelines.

Eramet[42]

Eramet has three smelters in Norway, one in Porsgrunn that produce FeMn & SiMn, one in Kvinesdal (SiMn) and one in Sauda (FeMn). During the last couple decades, Eramet has seen significant improvements to their emissions. In 1994 their Manganese emissions from one day was equivalent to the emissions from 10 weeks in 2011.[43] In table 5, the amount of waste and by-products that was produced in 2019 is listed. SiMn-slag was previously considered a waste, but Eramet has managed to develop Silica Green Stone. Silica Green Stone has lower levels of heavy metals, than what one usually finds in natural bedrock. It is also free of organic toxins. Silica Green Stone can replace simple gravel as filling for construction projects like for example roads.[44]

Table 5. Overview of the by-products and waste from Eramet. [45]

Waste & byproducts from Eramet	Sauda	Kvinesdal	Porsgrunn
Sludge & Dust [ton]	9333	17894	4665
Metal waste [ton]	324	32	160
Hazardous waste [ton]	68	255,5	14
Silica Green Stone [ton]	N/A	204,8	91943

All of the slag from the smelter in Sauda is sent to Kvinesdal, thus Sauda do not produce any slag or Silica Green Stone. The slag from Sauda is used on the production process in Kvinesdal. Currently most of the waste disposed in landfills is sludge. Due to the high concentration of manganese, Eramet is interested in recycling the sludge and utilize it. Eramet has an initiative to make pellets from sludge, dust and some other components. These pellets can then be added back into the manganese smelter.[46]

[42] Contact with Eramet, 2018.
[43] Sustainability report 2013, Eramet Norway.
[44] Sustainability report 2019, page 57, Eramet Norway, https://issuu.com/erametnorway/docs/eramet_norsk_digital, 19.06.2020.
[45] Sustainability report 2019, page 67-68-69, Eramet Norway, https://issuu.com/erametnorway/docs/eramet_norsk_digital, 19.06.2020.
[46] Sustainability report 2019, page 61, Eramet Norway, https://issuu.com/erametnorway/docs/eramet_norsk_digital, 19.06.2020.

Silicon & Ferrosilicon

In Norway there are four companies that produce silicon and ferrosilicon. These companies are Finnfjord, Wacker, Elkem and REC solar. They are spread across the country, from Kristiansand in the south to Tromsø far North. Typical wastes and byproducts are slag, dust, silica and quartz.

Finnfjord[47]

Finnfjord's smelter is situated in Lenvik in Troms county, Norway, here they produce ferrosilicon. Most of the waste produced is inert materials that can be used for landfills, albeit there are some amounts of dust and hazardous waste from the isolation in the oven. Fireproof material waste is sold to a company in Mo I Rana, Norway. The isolation of the oven is replaced on a regular basis and what is not hazardous is used as filler in construction projects. The hazardous waste is treated by an approved third-party company. Of all the hazardous waste only around 1% is actually hazardous compounds, the rest is harmless, intertwined materials. This is not suitable as the waste takes up more space in the landfill and are not utilized properly.

Table 6. Overview of the by-products and waste from Finnfjord smelteverk.

Waste and byproducts from Finnfjord in 2019	Amount [tons]
Dust	73,52
Contaminated masses	23,70
Lightly contaminated masses	38,78
Non-flammable materials (disposed)	47,46

A challenge of Finnfjord is that in 2019 their Landfill from the silica production in the 1980s had to be moved. They were no longer allowed to have this landfill at their property and the deposit had to be moved to a mountain landfill. Leftover quartz is collected on-site and will be used to fill up the deposit when it's moved. Quartz is the largest waste-volume that Finnfjord has and in the future, it may be utilized. Previously microsilica was a useless byproduct from the FeSi-production, but due to improved cleansing techniques it is now useful. Microsilica is added to concrete to enhance its characteristics.[48]

Wacker Chemical Holla[49]

Wacker Chemicals Holla located in Hemne, Norway produce silicon. Table 7 provides an overview of by-products and wastes, as well as how this is treated.

[47] Finnfjord contacted, 2018 & 2020.
[48] http://www.finnfjord.no/no/produkter/25-silika, 23.06.2020.
[49] Wacker Chemical Holla contacted, 2018 & 2020.

Table 7. Overview of the by-products and waste from Wacker Holla.

Waste & byproducts(2019)	Treatment	Amount [ton]
Slag	Sold or recycled	
Fines from treatment of quartz	Filling in landfill	2000-2500
Burned carbon & silica	Sold & disposed	1500

There has been an increase in the amount of fines produced and thus landfilled, this is due to the startup of a new 45 MW oven. The disposed silica consists mainly of radiclone-dust with a higher concentration of impurities. Wacker has several ongoing research projects regarding recycling of silica and quartz. They also work with the top step of the waste-hierarchy, which is waste-reduction.

Elkem

Elkem has five smelters in Norway that produce Silicon and Ferrosilicon. These are located in Bjølvefossen, Bremanger, Rana, Salten and Thamshamn. Additionally, they have a plant in Fiskå that produce carbon-products. Typical wastes and byproducts are fireproof materials, silica (dust), slag and radiclone dust. The silica is known as micro-silica and is a valuable product used as additive in concrete and is sold off. Radiclone dust is a mixture of silica-dust, coal and charcoal and is disposed. The other byproducts are sold to other companies/re-used.[50]

Elkem is well known for their work here in Norway to utilize silica-dust, 50 years ago it was a huge environmental issue. The dust itself is not harmful, but the problem was that it was spread out in the surrounding area due to the lack of proper filters. In the 1970's, filters were installed to collect the fine dust. In the start the silica-dust was disposed, but after a bit of research Elkem figured it could be utilized. Elkem did not earn any money from the research when it was ongoing, but today Micro silica is almost as valuable as their main products. Elkem is the world's largest producer of micro silica so the research efforts definitively paid off.[51]

Elkem continues their research on how to minimize the amount of waste produced and to utilize the waste as new products. A major goal is to minimize the amount of disposed waste in the future to more efficiently use the resources in a circular economy model. During transport a lot of the raw materials get crushed or ground down into dust that cannot be utilized in the oven due to gas-flow considerations. This dust still contains a lot of valuable resources. By forming the dust into pellets, they can be utilized in the oven. This alone helps reduce the use of quartz by over 10 000 tons a year.

[50] Sarina Bao, Martin Syvertsen og Anne Kvithyld, *SFI-Metal Production, RD3/RD5*, Trondheim, unpublished report, 2018, page 14.
[51] https://www.tu.no/artikler/det-startet-som-opprydding-av-miljosynder-na-er-dette-stoffet-millionbutikk/407974?key=CKvs, Jørn-Arne Tomasgard, September 2017.

Another example is to utilize radiclone dust to form pellets that contain silicon, carbon and iron. Radiclone dust is otherwise considered a waste and is disposed. By recycling the radiclone dust, the amount of waste will decrease, and the yield will increase.[52]

REC solar

REC solar has sections both in Kristiansand and at Herøya, where they produce solar-grade Silicon. The wastes and byproducts are slag, sludge and silicon-fines. Solar grade silicon is a really pure form of silicon (99,9999% silicon), thus the byproducts are often pure as well. Today they make products of almost everything, but earlier several of the by-products were categorized as waste. Including "Solaritt" which is slag from the production. This product is now approved by the Norwegian food-safety authorities for use as liming agent in agriculture or to cleanse sulfurous masses from landfills. Water with different levels of pH is mixed and their pH levels is adjusted in such a way that impurities will deposit at the bottom of the tank. This forms a sludge that is filtered and sent for treatment. Resitec is a company that recycles the sludge into dry and clean silicon-powder. Resitec is also located in Kristiansand.[53] [54]

[52] https://www.elkem.com/globalassets/corporate/documents/elkem-sustainability-report-2016.pdfhttps://www.elkem.com/globalassets/corporate/documents/elkem-sustainability-report-2016.pdf, Sustainability report 2016, Elkem.
[53] https://www.eydecluster.com/no/aktuelt/2015/gjoer-andres-soeppel-til-stoev/, July 2015.
[54] https://renas.no/en-solskinnshistorie/, Lise H. Eide, May 2017.

Silicon-carbide

Silicon-carbide is produced by Washington Mills and Fiven.

Washington Mills[55]

Washington Mills is located in Orkanger, Norway. The plant does not produce the crude SiC. They produce fine Silicon-carbide for various applications. The company is certified according to ISO 14001, in practice this means that the company is subject to an ambitious environmental policy. Washington Mills is working to minimize the amount of waste and recycle as much as possible.[56] From the production processes there is formed different types of fines, sludge and remix.

Fiven[57]

Fiven is located in Lillesand and Arendal in Norway. Fiven produces and refines silicon-carbide. Waste-numbers from production is located in table 8. In 2017, 727,6 tons of ordinary and inertial waste was disposed, while 3 444 tons was used as cover-material (652 tons of dirt and 2792 tons of sand). Previously there was a deposit on site, but it is now closed and terminated. Currently the company Midtstøl is responsible for disposal and waste treatment.

Table 8. Overview of the by-products and waste from Fiven, Lillesand

Waste & byproducts 2017		Treatment	Amount [ton]
Fiven	Cleansed mass	Covermaterial	3444
	Concrete with rebars	Deposited	488
	Mixed inorganic materials	Deposited	239,6

[55] Washington Mills contacted, 2018.
[56] https://www.standard.no/fagomrader/miljo-og-barekraft/miljostyring----iso-14000/, June 2020.
[57] Fiven, contacted, 2018.

Fiven is motivated to streamline their production and minimalize losses. There is formed no significant amount of by-products, so most of the research revolves around maximizing the value of the products. There are also projects aimed at reducing the amount of waste disposed.

The overview of heavy-metal emissions shows that emissions to air varies from one year to the next. There are mainly two reasons for this, different types of coke and trouble with testing. Fiven has during the last couple of years had to use several different types of coke, due to increased pricing and lack of access to raw materials. The concentration of impurities in the different types of coke can vary significantly and this may be the reason for the huge changes in emissions, for Fiven and other companies. Additionally, the measured concentration of emissions/impurities in gas can be quite consistent, but when this concentration is multiplied with the total volume-flowrate during an entire year, the emissions can vary significantly.

Steel, nickel, zinc, titanium-slag & iron

The remaining metals yet to be covered is steel, nickel, titanium-slag and iron. As one can expect, these metals are produced quite differently. Some companies accumulate quite a significant amount of waste, while others generate less. An overview is provided in table 9.

Table 9. Overview of the by-products and waste from Celsa, Glencore Nikkel and Boliden.

Waste and byproducts 2017 (latest available info)	Treatment	Amount [tons]
Celsa	Slag from steel-smelter (svart slagg)	80 000
	Ladleslag (hvit slagg)	6 000
	EAF dust (rød støv)	8 000
	Crust (2016)	8 700
Glencore Nikkelverk	Sludge	22 120
Boliden	Total amount of waste	140 000
	Dross & dust	2 000

Celsa Armeringsstål[58]

Celsa Armeringsstål is located in Mo i Rana, Norway and manufacture rebar from recycled steel. Despite only utilizing recycled steel, thus being environmentally friendly there will be formed by-products and wastes. The waste must be treated properly, there is different types of slag, dust and mill scale. The quantities are shown in table 9.

Slag is approved by the environmental authorities for use in production of asphalt, as filling and in concrete. Mill scale is formed when steel is oxidized at high temperatures, especially during smithing

[58] Celsa Armeringsstål contacted, 2018.

or rolling. Mill scale is sold as additives for the alloying-industry. Dust is sold to Befesa Steel Services in Germany for extraction of zinc. Therefore, most wastes and byproducts are recycled by the company itself or by other processes. For the rest of the byproducts where they lack circular economy solutions, they are actively developing them.

Celsa thinks it is challenging to run a steel-plant and a roller, especially regarding the Norwegian emission-policy which is probably amongst the strictest in the entire industry. Their emissions are being carefully monitored by the government and Celsa is serious with their environmental policy.

Regarding hazardous waste, it is being recycled. In 2016 the amount of hazardous waste was 66 tons and other types of waste was 360 tons. Sewage-water released from smelter and roller consists of more than 23 300 000 m^3.[59]

Glencore Nikkelverk[60]

Glencore Nikkelverk is located in Kristiansand and produce Copper, Nickel, Kobalt & Sulfuric Acid. The production process generates a lot of sludge, sludge is the most common waste generated. The total amount of sludge generated in 2017 was 22 120 tons. Some of this is viewed as byproducts, such as Selenium, Copper and Bismut-sludge. The majority of the waste is disposed in a mountain landfill, whereas the rest of the waste is sent to external companies.

Glencore Nikkelverk cooperate with Eyde-klyngen with projects like “Waste to value”, where they investigate the opportunities for recycling of contaminated iron-hydroxide. An interesting project is about mixing iron-sludge from Glencore with Carbon-waste from aluminum producers and use the mixture as an alloying additive in cast iron production. Technologically they have found a solution, but its currently not profitable.[61] The continuously increasing demands for improvement in terms of emissions and circular economy is an effective motivator for increased environmental focus. The ISO-14001 environmental certification is efficiently taking environmental considerations when decisions are made.[62]

Boliden[63]

Boliden is a producer of Zink and sulfuric acid, they are located in Odda, Norway. Most of the waste is remaining chemicals from the leaching process as well as iron-sulfate and Sulphur. This is disposed in a deposit and is classified as hazardous waste, the total amount of deposited waste in 2017 was

[59] Miljørapport 2016 (environmental report 2016), Celsa Armeringsstål.
[60] Glencore Nikkelverk contacted, 2018.
[61] Eyde-klyngen contacted, 2018.
[62] https://www.nikkelverk.no/en/sustainable-development/Pages/environmental.aspx, June 2020.
[63] Boliden Odda contacted, 2018.

approximately 140 000 tons. Dross and dust add up to around 2 000 tons pr. year but is not a part of these statistics as it is recycled.

Boliden wants to become greener, but it is both technically and economically challenging. One way of becoming greener is to be able to extract as much of the metals from the raw materials as possible. However, this is challenging due to fluctuations in metal contents. Ores from different mines have various concentration of zinc and impurities like iron, silicates and calcium. Different compositions require different configuration in the facility. More metals can be recycled than what is currently done in Boliden, but this would require additional smelting process that would release lots of CO_2. Noise-pollution is also a topic as they are located close to the village of Odda. The main source of noise is loading and unloading of cargo to the ships.

TiZir titanium and iron[64]

In Tyssedal, TiZir titanium & iron is producing titanium-slag and iron. The by-products formed during production is stored in deposits before being sent back to production. This means that dust from filters and sludge from production is being recycled. Whereas other types of waste are sent for recycling. TiZir is working to minimize the amount of waste produced and to more efficiently utilize the raw materials.

[64] TiZir contacted, 2018.