Toxicity Ranking of European Industrial Facilities

Szilard Erhart (szilard.erhart@gmail.com)
Joint Research Centre
Kornél Erhart
McGill University

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Toxicity Ranking of European Industrial Facilities

Szilárd Erhart[1,*] **and Kormél Erhart**[2]

[1]Joint Research Centre, European Commission, Ispra, https://orcid.org/0000-0002-0550-895X
[2]McGill University
[*]szilard.erhart@ec.europa.eu

ABSTRACT

Here, we present a methodology to improve environmental assessment of Europe based facilities, industries and regions by linking the European Pollutant Release and Transfer Register and the USEtox, a scientific consensus model for characterizing human and ecotoxicological impacts of chemicals. Such environmental assessment is an increasingly important need in policy and finance. In this paper we measure human, cancer and non-cancer toxicity and ecotoxicity risks of more than 10,000 companies from point source pollutant releases in Europe from 2007 to 2017. We discuss water and air emissions of dozens of pollutants in urban, rural, coastal and inland areas. There are clusters of toxicity in the most industrialized regions of North-England, North-Italy, the German Ruhr-area, South-Poland, in the Benelux states, and in coastal areas of Spain, Portugal and Nordic countries. There is an overlap of areas of the largest emissions of human toxicity and ecotoxicity. We confirm toxicity potential of major pollutants in previous research papers (Hg accounting for 71% of the total human toxicity and Zn accounting for 55% of total ecotoxicity). Human toxicity is estimated to be mostly non-cancer type in Europe. Companies in the electricity production sector are estimated to have the largest human toxicity potential (52% of total) in the European Union 2017 and companies in the sewerage sector have the largest ecotoxicity impact potential (41%). Total human toxicity almost halved from 2001 to 2017, although the downward trend reversed in 2016. Ecotoxicity increased by 20% in the same period. A key advantage of our methodology and indicators is that they can be used to measure progress towards the United Nation's Sustainable Development Goals and the environmental objectives in the EU Taxonomy regulation on the company facility level and regionally.

Introduction

Earlier carbon and water footprint methodologies help assess resource consumption, carbon dioxide (CO2) emission and related climate change risks, but usually fails to measure other relevant impacts, like those related to the production and use of chemicals[1]. There are well-known benefits from chemical use, still the inadequate use or excess release of chemicals may cause harmful side effects on humans and the ecosystem. Hence, in this paper we present and discuss the relevance of developing a methodology for assessing the chemical footprint of industrial facilities in terms of point source emissions.

Our methodology also helps broaden the coverage of corporations' environmental assessment. Most common Environmental standards (ISO - International Organization for Standardization, GRI - Global Reporting Initiative, SASB - Sustainability Accounting Standards Board) fit and are available only for the largest companies. Furthermore, key Environmental Social and Governance (ESG) rating providers, Thomson Reuters, Sustainalytics, MSCI - Morgan Stanley Capital International, Bloomberg cover only few thousands of the largest corporations listed on international stock exchanges[2]. These rating institutions rely mostly on sustainability reports, annual reports, websites, and other public sources, as well as on company direct contact. Also, the content and quality of publicly disclosed environmental and sustainability reporting varies, and reports focus mainly on carbon-dioxide emission and are generally better for larger issuers.[3].

The key novelty of our research is that we constitute methods to broaden the scope of environmental assessment to non-listed companies in the European Union (EU). Investors, consumers, regulators, banks and other financial intermediaries increasingly need ESG information to make decisions. We present results on the company facility level, and further statistics on various pollutants and major industries across EU regions.

The Protocol on Pollutant Release and Transfer Registers (PRTRs) was agreed on by international parties to register environmental footprints across regions and times. PRTRs are increasingly used as a fundamental data source for chemical footprint research,[4],[5],[6]. However, the large and increasing number of pollutants makes it more difficult for non-expert public users to understand which substances are of greatest concern in their communities or globally. The impact of substances is best characterized when environmental release data of substances are combined with their toxicity properties. Earlier papers found that pollutant registers may not provide critical information on the real impact of pollutant releases by disclosing weight of pollutant releases, as severity of releases per emitted kilogram significantly differ by pollutants. Hence, there is a need to provide more context with quantitative data to increase usability of these registers.[7]

Using data from the Swedish Pollutant Release and Transfer Register on emissions to air and water from Swedish point sources, and characterization factors (CFs) from the USEtox model, earlier research papers suggested the aggregated impact potentials for human toxicity and ecotoxicity as key metrics to measure environmental footprints on the national level[8],[4],[9]. The first calculations showed that zinc contributed most to the impact potentials both for human toxicity (in the range of 30-60% of the total impact), and ecotoxicity (60%) in Sweden, in 2008.

Earlier macroscopic studies on Europe also found zinc compounds and and some other metals as the substances with largest contribution to toxicity in Europe in mid 2000s[10],[1].

The aim of this study is threefold. First, it re-assesses impact potentials for human toxicity and ecotoxicity associated with European point source emissions by pollutants, using the latest USEtox 2.12, a model based on scientific consensus providing midpoint and endpoint characterization factors for human toxicological and freshwater ecotoxicological impacts of chemical emissions in life cycle assessment, developed under the auspieces of the United Nations Environment Program (UNEP) and the Society for Environmental Toxicology and Chemistry, (SETAC) Life Cycle Initiative. Our study attempts to increase the precision of the calculations by using population grid and distance-to-sea-coast data to better connect pollution data with the USEtox model on the sub-compartment level, following the methodology presented for Sweden[9]. Third, it assesses chemical footprint at various levels from pollutants to industries and company facilities. Furthermore, trend and geographic spread of human toxicity and ecotoxicity are also discussed in this paper. Our research also enhances exchange-ability and acceptability of exposure knowledge within and across EU chemicals-related policies.[11]

Furthermore, our research aims at supporting the achievement of global environmental policy goals by presenting a new set of environmental indicators for monitoring industrial facilities across regions and times. In particular, our indicators can be used to measure progress on the company level and regionally towards the United Nation's Sustainable Development Goals (SDGs) and the environmental objectives in the EU Taxonomy regulation (2020/852 of the European Parliament and of the Council of 18 June 2020). Pollutant release data can help measure and monitor progress both towards specific of these goals multitudes of them[12],[13]. From the six environmental objectives in the EU Taxonomy regulation at least four can be directly related to chemical footprint assessment, and from the UN SDGs five goals can be identified (Table 1). In particular, SDG Target 12.4 on environmentally sound management of chemicals, and Pollution prevention and control (EU Objective 5) are likely the most closely aligned with pollutant data. The EU Taxonomy Objective 3 (Sustainable Use of Water and Marines) and SDG6 ('Ensure availability and sustainable management of water and sanitation for all') or Goal 3 ('Ensure healthy lives and promote well-being for all at all ages') are all influenced by pollutants released into water, air and soil, which are registered in the E-PRTR. Target 6.3 ("By 2030, improve water quality by reducing pollution, eliminating dumping, and minimizing release of hazardous chemicals and materials, halving the proportion of untreated waste water and substantially increasing recycling and safe reuse globally') is another specific example of relevant SDG targets. E-PRTR data can also support measure progress toward Target 3.9 ('By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination.'). Although the E-PRTR does not register mortality or health problems from hazardous chemicals, pollution or contamination, it can support constructing and monitoring of indicators to measure the related risk exposure by matching emission quantity and toxicity information on the substance level.

The European Commission's president declared in her political manifesto that 'Europe needs to move towards a zero-pollution ambition' and she 'will put forward a cross-cutting strategy to protect citizens' health from environmental degradation and pollution, addressing air and water quality, hazardous chemicals, industrial emissions, pesticides and endocrine disrupters.'

Table 1. SDGs and environmental objectives in the EU Taxonomy related to our research

SDGs	EU Taxonomy objectives
Good Health and Well-being (SDG 3)	Sustainable Use of Water and Marines (Objective 3)
Clean Water and Sanitation (SDG6)	Transition to a circular economy (Objective 4)
Sustainable Cities and Communities (SDG 11)	Pollution Prevention and Control (Objective 5)
Responsible Consumption and Production (SDG 12)	Protection of Healthy Ecosystems (Objective 6)
Life Below Water (SDG 14)	

The rest of the paper is structured as follows. Section 2 presents empirical results on pollutant, industry and facility level. Section 3 discusses the methodological framework and Section 4 details the limitations of our empirical set-up. Section 5 concludes.

Results

Pollutant releases by industrial facilities impact on humans and the environment. The seriousness of health and ecological consequences can be underestimated if only the quantity of pollutants is used[14]. The health consequences at the societal level depend also on the release media, length of exposure and population density[15]. Our results are presented here in terms of human toxicity and ecotoxicity impact potentials of point source emissions in Europe by major pollutants in the E-PRTR regulation, by industries and across regions. Impact potentials are measured in Comparative Toxic Units for human health (CTUh) and ecotoxicity (CTUe), respectively. It should be noted that CTUh and CTUe values can not be directly compared, as they are measured on different scales and in different units.

Toxicity impacts by pollutants and industries

The characterization factor for human toxicity impacts (human toxicity potential) is expressed in comparative toxic units (CTUh), which estimates the increase in morbidity in the total human population. Its unit [CTUh per kg emitted] is defined as the disease cases per kg emitted.

Human toxicity impacts are dominated mostly by mercury compounds in the EU as a whole, accounting for 71% of the total impact potential in 2017 (Table 2). An important risk of further mercury emissions has been already highlighted by earlier research due to mercury's bio-accumulation properties in organisms and humans during their lifetime. Hence, mercury concentrations usually increase when moving up the food web[16]. Our trend analysis in a later section of this study shows that mercury's annual emission was stable in the period from 2001 to 2017.

Table 2. EU Human toxicity and ecotoxicity impact potentials by major pollutants (in % of the total CTUh and CTUe , 2017).

	human toxicity impact in % of the total																												
Pollutant	AT	BE	BG	CY	CZ	DE	DK	EE	EL	ES	FI	FR	HR	HU	IE	IT	LT	LU	LV	MT	NL	PL	PT	RO	SE	SI	SK	UK	EU 28
Arsenic and compounds (as As) [a]	0%	1%	1%	1%	2%	0%	1%	7%	2%	1%	2%	1%	1%	8%	3%	7%	0%	0%	1%	0%	4%	1%	2%	1%	2%	0%	0%	2%	1%
Cadmium and compounds (as Cd) [b]	3%	2%	1%	2%	1%	0%	0%	3%	3%	3%	0%	4%	4%	0%	0%	3%	0%	0%	0%	0%	3%	1%	14%	2%	1%	1%	1%	1%	2%
Chromium and compounds (as Cr) [c]	0%	1%	3%	0%	0%	1%	0%	1%	1%	1%	3%	1%	4%	8%	0%	10%	18%	0%	3%	100%	1%	0%	4%	4%	2%	2%	0%	2%	8%
Lead and compounds (as Pb) [d]	5%	25%	2%	0%	5%	3%	0%	30%	3%	9%	2%	11%	0%	11%	0%	7%	0%	0%	0%	0%	15%	6%	7%	16%	0%	9%	83%	17%	8%
Mercury and compounds (as Hg) [e]	82%	58%	92%	83%	89%	92%	94%	43%	81%	67%	78%	57%	65%	51%	93%	59%	0%	10%	93%	0%	61%	84%	63%	54%	57%	87%	10%	63%	71%
Zinc and compounds (as Zn) [f]	10%	12%	1%	13%	2%	3%	2%	17%	10%	18%	13%	25%	26%	21%	3%	14%	72%	90%	3%	0%	15%	5%	10%	17%	34%	1%	4%	14%	8%
Largest contributions in % of total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**98%**	**100%**	**99%**	**99%**	**98%**	**99%**	**100%**	**99%**	**100%**	**99%**	**91%**	**100%**	**99%**	**100%**	**99%**	**96%**	**99%**	**95%**	**98%**	**100%**	**100%**	**99%**	**99%**
	ecotoxicity impact in % of the total																												
	AT	BE	BG	CY	CZ	DE	DK	EE	EL	ES	FI	FR	HR	HU	IE	IT	LT	LU	LV	MT	NL	PL	PT	RO	SE	SI	SK	UK	EU 28
Arsenic and compounds (as As) [a]	0%	0%	1%	0%	1%	0%	1%	3%	1%	0%	0%	0%	0%	1%	1%	1%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%
Cadmium and compounds (as Cd) [b]	1%	4%	26%	13%	4%	2%	0%	11%	4%	6%	4%	6%	7%	1%	1%	22%	0%	0%	4%	0%	1%	15%	10%	1%	5%	1%	36%	3%	8%
Chromium and compounds (as Cr) [c]	0%	4%	10%	3%	1%	3%	1%	6%	5%	4%	3%	2%	6%	7%	0%	9%	4%	0%	4%	100%	1%	2%	8%	4%	1%	5%	2%	2%	22%
Copper and compounds (as Cu) [g]	3%	2%	4%	1%	3%	3%	2%	1%	3%	4%	3%	4%	2%	2%	5%	1%	2%	0%	6%	0%	2%	1%	2%	12%	2%	3%	0%	7%	3%
Lead and compounds (as Pb) [d]	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	8%	0%	0%
Mercury and compounds (as Hg) [e]	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Nickel and compounds (as Ni) [h]	10%	7%	12%	51%	16%	11%	12%	9%	27%	26%	15%	12%	3%	12%	9%	18%	9%	0%	24%	0%	13%	6%	35%	7%	7%	14%	3%	14%	11%
Zinc and compounds (as Zn) [f]	85%	82%	47%	30%	74%	80%	84%	69%	60%	58%	70%	74%	81%	76%	85%	47%	86%	99%	62%	0%	81%	75%	42%	76%	83%	77%	50%	72%	55%
Largest contributions in % of total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**98%**	**95%**	**99%**	**100%**	**100%**	**100%**	**98%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**98%**	**100%**	**99%**	**100%**	**98%**	**99%**	**99%**

Notes: [a] As As(V). [b] As Cd(II). [c] As Cr(VI). [d] As Pb(II). [e] As Hg(II). [c] As Pb(II). [d] As Cr(VI). [e] As As(V). [f] As Zn(II). [g] As Cu(II). [h] As Ni(II).

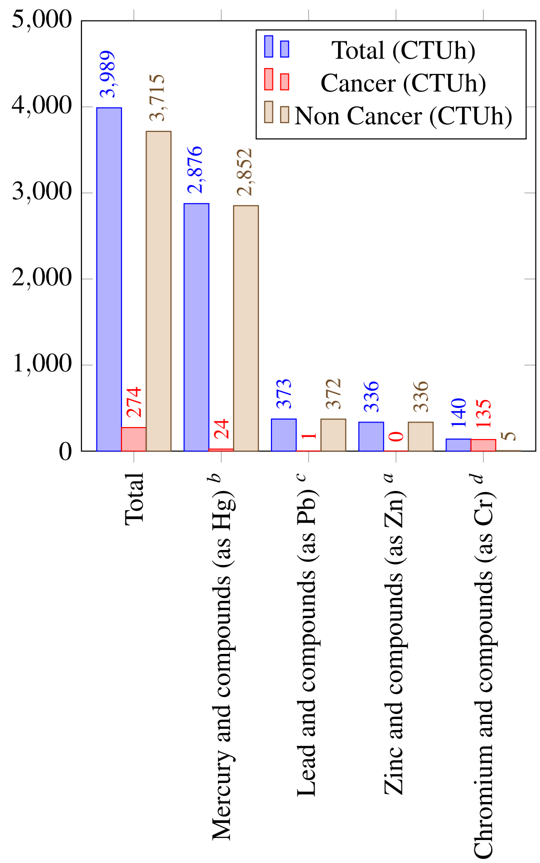
The World Health Organization (WHO) includes mercury in its list of chemicals of major public health concern[17]. There is some degree of variation across Member States, zinc and lead compounds are being the pollutants with considerable, 8% impact potential of the total on average.

For ecotoxicity, impact potentials are expressed in comparative toxic unit for freshwater ecosystem (CTUe) provides an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted. The pollutants with the largest contribution to ecotoxicity was zinc in 2017 (55% of the total) together with some other metals confirming earlier results[10],[1].

On the industrial level the largest estimated human toxicity footprint was estimated for the Production of electricity (52%) followed by Manufacturing of basic iron, steel, and ferro-alloys (16%) and Manufacturing of cement (9%) in 2017 (Table 4 in the Appendix. As for ecotoxicity, Sewerage (41%) is the industry with the largest estimated chemical footprint together with Production of electricity (22%) and Mining of other non-ferrous metal ores (7%). Our results together with the well-known large greenhouse gas emission of the energy sector further increases the importance of managing the sector's environmental footprint.

There is obvious variation of the results on the level of Member States in the European Union partly due to differences of national economic structures, in particular in case of ecotoxicity. The largest contribution to ecotoxicity is calculated for Manufacture of paper and paperboard (33%) and Manufacture of pulp (33%) in Sweden, while Mining of other non-ferrous

Figure 1. Contribution of substances to cancer, non-cancer and total human toxicity (CTUh), emitted from Swedish point sources to air and water (2008), characterized with USEtox 2.12. Only the total contribution and the four substances with largest contributions are shown.



Notes: [a] As Zn(II). [b] As Hg(II). [c] As Pb(II). [d] As Cr(VI).

metal ores for Poland (49%) and Romania (31%). The largest emitter facilities are further discussed in a later section of this study.

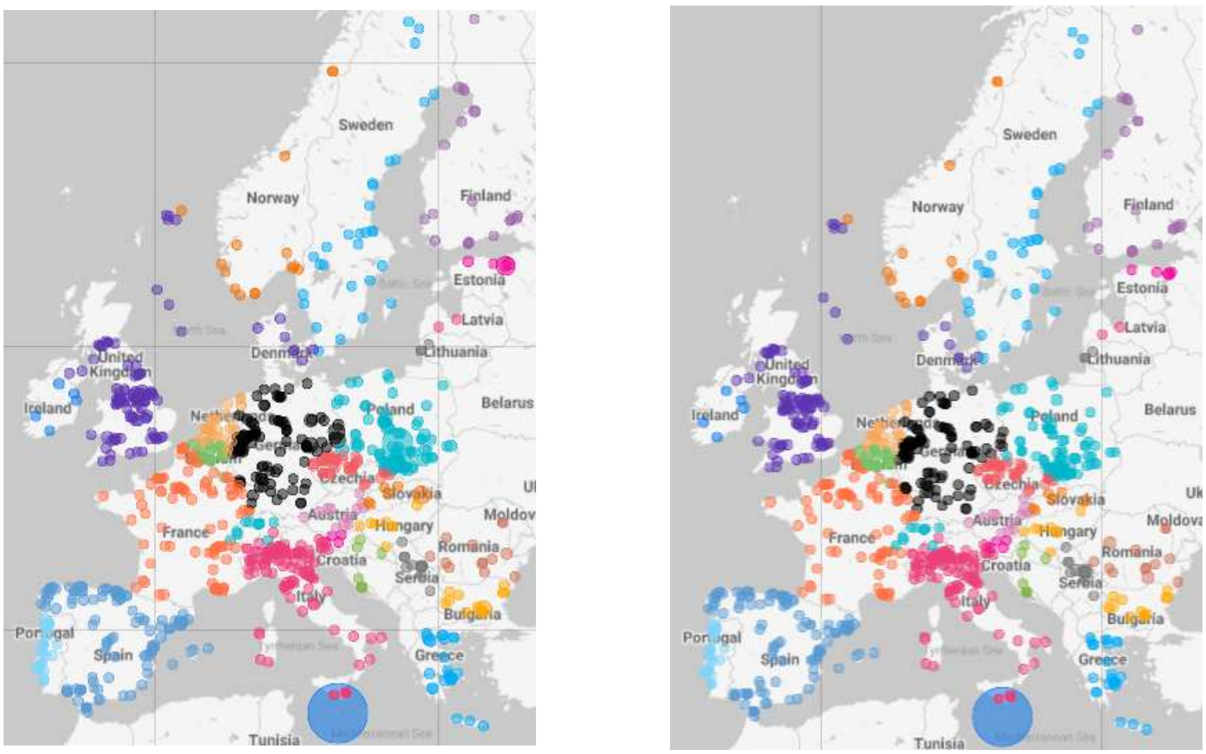
The USEtox model allows differentiation between cancer and non-cancer characterisation factors, assuming equal weighting between cancer and non-cancer due to a lack of more precise insights into this issue. We decomposed the results similarly to an earlier study on Sweden[9], and found that non-cancer human toxicity dominated the aggregated human toxicity impact potentials in Europe. Non-cancer human toxicity impact potential was 3715 CTUh of the total 3990 CTUh in 2017 calculated with USEtox 2.12, and cancer related CTUh was only a fraction of the total, 274 CTUh, (Fig. 1). When filtering our cancer toxicity results with he USEtox 2.12 model by pollutants and industries, we found that Chromium compounds and Polycyclic aromatic hydrocarbons (PAHs), Mercury compounds and PCDD + PCDF (dioxins + furans) have the largest cancer toxicity impact potential in Europe. The production of electricity, mining of hard coal, sewerage, manufacture of other inorganic basic chemicals are the industries with the largest cancer toxicity impact potential. Using a sample of 52 mobile phones manufactured between 2000 and 2013, it was demonstrated with the USEtox model that WMPs toxicity increased with technology innovation and copper posed the most significant ecotoxicity risk, and chromium showed the most significant risk for both cancerous and non-cancerous diseases.[18]

Regional mapping of European toxicity

The E-PRTR database contains important information for regional assessment, as companies shall report the geographic coordinates and addresses of facilities together with their country codes. By combining this information with the pollutant release data, we draw maps of facilities with the largest human toxicity and ecotoxcity impact potential (Fig 2). There are clusters of toxicity in the industrialized regions of North-England, North-Italy, the German Ruhr-area, South-Poland, in the Benelux states, and in coastal areas of Spain, Portugal and Nordic countries. There is an overlap of areas of the largest emissions of human toxicity and ecotoxicity.

Figure 2. The human toxicity (CTUh, left panel) and ecotoxicity (CTUe, right panel) of substances emitted from largest EU point sources to air and water in 2017 with USEtox 2.12. Observations are coloured according to country codes and sized as a function of the toxicity impact potential.

(a) Human toxicity in CTUh **(b)** Ecotoxicity in CTUe



Facility toxicity rankings

An important innovation of our research is that we drill down to the company facility level to investigate which facilities have the largest chemical toxicity footprint in Europe. This way we target stakeholders in sustainable finance and in sustainability in general. Investors, public policy experts and consumers, all need metrics and quantitative information so as to measure sustainability and make informed investment, regulatory and consumption decisions. Current environmental finance data providers (Refinitiv, MSCI, etc.) base their company level sustainability information on reports of listed companies which mainly focus on energy and green house emission data and lack the information on human and toxicity risks.

The facility with the largest contribution to human toxicity and also to ecotoxicity is Delimara Power station (Table 3). The Delimara Power Station complex at Marsaxlokk includes the four electricity generation plants which are dispatched on a daily basis to provide the electrical energy required by households and companies in Malta and Gozo. The second largest contributor to human toxicity is PGE Górnictwo Bełchatów which is part of the Poland's largest energy sector company with respect to sales and revenues. The Bełchatów Power Station is a coal-fired power station near Bełchatów, It is one of the largest coal-fired power plants in the world. Hence, it is also among the largest emitters of greenhouse gases. Eight of the top ten polluter facilities are in the energy sector. Most of the largest emitters release mercury compounds in the air, while Delimara Power Station also releases large quantities of chromium compounds to water.

Presumably it is not surprising that six of the top ten ranked facilities with the largest contribution to ecotoxicity is in the sewerage and water collection and treatment sector (Table 4). It should be remarked that the emmissions of waste water companies stem from other sectors as well. Furthermore, facilities in the sector of manufacturing other inorganic basic chemicals (Solvay Chimica IT S.P.A., Prayon S.A.) and in the metal mining sector (SC Cuprumin S.A., Zakłady Górniczo-Hutnicze) released pollutants with the biggest ecotoxicity footprint. Largest emitters in the sewerage sector release mainly zinc compounds, cadmium compounds and nickel compounds into water.

Toxicity trends

We conducted time-series analysis of the substances with the largest contribution to toxicity as suggested by earlier paper on Sweden[8]. In the sample period from 2001 to 2017 the first reporting year under the European Pollutant Release and Transfer

Table 3. The facilities with the largest contribution to human toxicity (CTUh) and ecotoxicity (CTUe), emitted from E-PRTR point sources to air and water in 2017, characterized with USEtox 2.12. Only the 10 facilities with the largest chemical footprint are shown. Assumptions made in characterisation are given in the Methods section, and follow Sörme et al. (2016). Calculations were based on the sub-compartment level.

No	Facility	NACE	Country	Human toxicity
1	Delimara Power St.	Production of electricity	MT	6.88E+03
2	PGE Górnictwo Bełchatów	Production of electricity	PL	2.91E+03
3	RWE Power AG	Production of electricity	DE	1.38E+03
4	Enefit Energiatootmine	Production of electricity	EE	1.24E+03
5	U.S.Steel s.r.o.	Manuf. iron, steel (...)	SK	1.12E+03
6	TAMEH Polska Sp	Steam, air cond. supply	PL	1.11E+03
7	TETs Maritsa	Production of electricity	BG	9.57E+02
8	LEAG, Kraftwerk	Production of electricity	DE	9.37E+02
9	Zespól Elektrowni	Production of electricity	PL	8.04E+02
10	LEAG Lausitz	Production of electricity	DE	7.78E+02
No	**Facility Name**	**NACE**	**Country**	**Ecotoxicity**
1	Delimara Power St.	Production of electricity	MT	7.24E+10
2	Central. postr. za pre. otp. voda u Cve.	Water coll., treat.&supp.	RS	2.63E+10
3	Zakłady Górniczo-Hutnicze	Mining, o. non-ferr. metal ores	PL	2.15E+10
4	Ogranak Termoelektrane A	Trade of electricity	RS	8.26E+09
5	Ebswien hauptkläranlage GmbH	Sewerage	AT	6.59E+09
6	SOLVAY CHIMICA ITALIA S.P.A.	Manuf., other inorg. bas. chem.	IT	4.91E+09
7	Sofiyska prech. stan. za otp.vodi Kubr.	Sewerage	BG	4.81E+09
8	ACQUE VERONESI S.C.AR.L.	Sewerage	IT	4.74E+09
9	EYDAP S.A.	Sewerage	EL	4.36E+09
10	Thames Water Utilities Ltd, Beckton Stw	Sewerage	UK	3.97E+09

Register (E-PRTR) was 2007. The E-PRTR followed the European Pollutant Emission Register (EPER) under which reporting was required every three year, first in 2001 and later in 2004. The EPER data is part of the E-PRTR dataset published by the European Environmental Agency, and hence covered in our trend analysis. The slope of the trend of total human toxicity is negative in the early 2000s (Figure 3a), although became again positive in the last years of the sample in 2016 and 2017. Total human toxicity in the sample decreased from 102K CTUh to 66K CTUh in 2017. Human toxicity of zinc was reduced monotonously, while human toxicity of mercury compounds was unchanged.

Although our study focuses on human and freshwater ecotoxicity, mercury can have a wide range of negative health effects on many types of terrestrial animals. Toxic effects include reduced fertility, impaired development of embryos, changes in behaviour and negative effects on blood chemistry[16].

Earlier research with USEtox 1.01 found that zinc and copper were the substances with the largest contribution to ecotoxicity impact potential in Europe in 2004 (70%, and 30% respectively)[10]. Our calculations confirm the importance of zinc and copper compounds, and shows the increasing ecotoxicity impact potential for copper. Contrary to the downward trend of human toxicity, ecotoxicity increased by 20% from 2001 to 2017 (Figure 3b). Another research on the Canadian National Pollutant Release Inventory (NPRI) calculated ecotoxicity potential with the USEtox model in Nova Scotia and showed that copper (51.06%) accounted for the largest share of ecotoxicity potential[7].

Time trends could be also used as a measure of data quality as substantial dispersion across years could indicate errors in data if assuming no significant change in production or technology[4]. The slope of the curves were more-or-less stable suggesting stability of data quality except for Chromium.

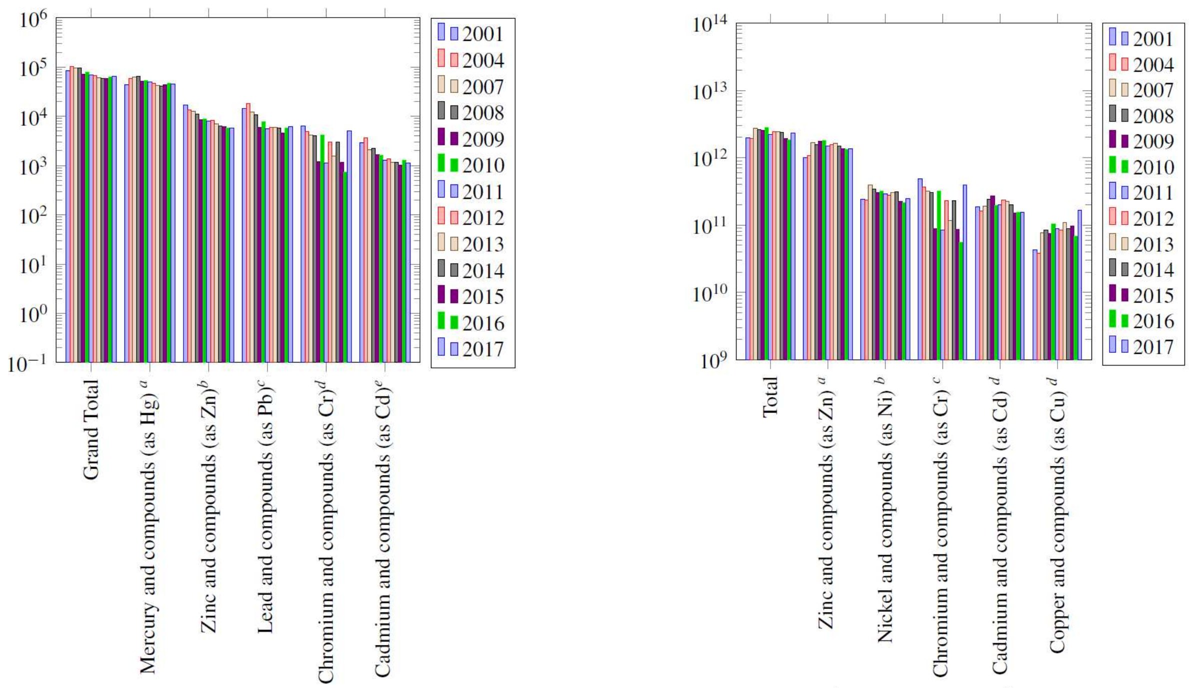
Discussion

The obstacles to the chemical footprint analysis based on the E-PRTR are numerous[8]. One obstacle of our approach is that the number of substances in the E-PRTR is limited, as less than 100 pollutants are on the E-PRTR reporting list, which is well below the 100,000 chemical products listed in the Swedish System of Environmental and Economic Accounting[19]. The E-PRTR list itself is also being revised currently[9]. Another obstacle to precise calculations is that the E-PRTR database does not register emissions below reporting thresholds. Reliability of data could be adversely affected by self-reporting and inappropriate estimations by facilities and there may be gaps and inconsistencies in reporting across countries[20]

Figure 3. Trend of contribution of substances to human toxicity (CTUh) and ecotoxicity (CTUe), emitted from EU point sources to air and water (2001–2017), characterized with USEtox 2.12. Only the total contribution and the five substances with largest contributions are shown. Assumptions made in characterization are given in the table footnotes. Under the European Pollutant Emission Register (EPER) data was reported every three year, first in 2001 and later in 2004. After 2007 data has been reported every year.

(a) Human toxicity in CTUh

(b) Ecotoxicity in CTUe



Notes: [a] As Hg(II). [b] As Zn(II). [c] As Pb(II). [d] As Cr(VI). [d] As Cd(II).

Notes: [a] As Zn(II). [b] As Ni(II). [c] As Cr(VI). [d] As Cd(II). [e] As Cu(II).

The E-PRTR data used in our research covers pollutants which enter the environment from point sources, for example from smokestacks or from discharge pipes of EU facilities. Nonpoint source pollution is more difficult to monitor and neither covered by the E-PRTR database nor by our study. Nonpoint source pollutants are emitted in broader areas usually in small concentration, but can later concentrate after transmitted by meteorological movements or rain, rivers and wind. Motor vehicles, smaller facilities and in general any kind of smaller scale human activities can have unreported emissions[9]. All these can further increase total pollution and toxicity impacts, and hence our calculations underestimate the real toxicity potential. Diffuse emissions of some pollutants have been shown to exceed point source emissions in Sweden[4]

Our methodology followed established research methodologies[4],[8] and calculated the chemical footprint of facilities by the additive aggregation formula. The additive formula is common in the international practice, however it has important consequences[9]. An undesirable feature of additive aggregations is the implied full compensation in a way that high emission in some pollutants can be compensated for by sufficiently low values in other pollutants. An alternative approach would be to use a non-compensatory formula (for example based on a geometric aggregation function) at the facility, industry or national level. Furthermore, the additive toxicity calculation formula in our analysis does not take into account the large number of possible interactions. Especially, the investigation of toxicity consequences from zinc's interaction with other pollutants could be a potential research direction[9].

A further limitation of the chemical footprint analysis is that the list of pollutants in the E-PRTR and the USEtox model can not be fully matched.

The recommended CFs for organic substances have an estimated uncertainty range of up to 2 and 3 orders of magnitude for ecotoxicity and human toxicity, respectively, primarily related to input data[8]. Previous authors have not considered these uncertainties in the calculations, and neither did we. Since metals were recognized as a priority group of pollutants for both human toxicity and ecotoxicity, we remark that all metal CFs are classified as "indicative" in the USETox model following earlier research[8]. The related uncertainties have not been quantified, but are larger than the uncertainties associated with organic

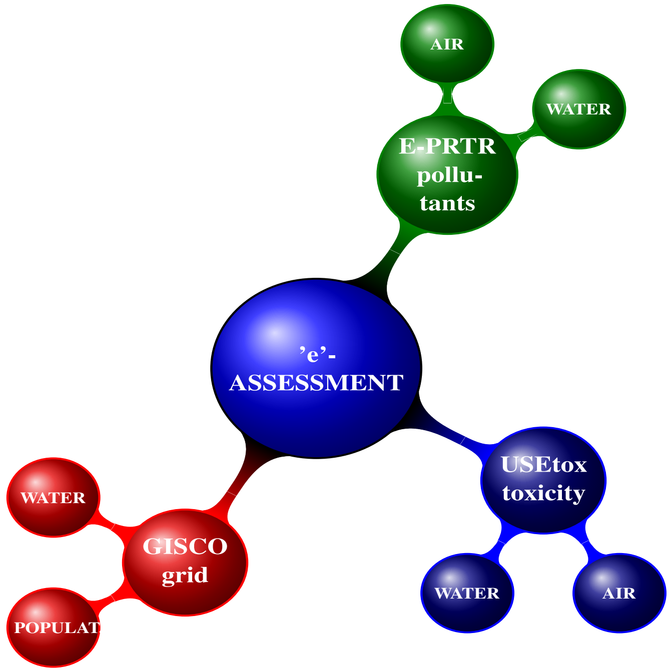


Figure 4. Structure of the environmental assessment

substances[21].

The usability of our methodology at the company level for environmental assessment or rating is hindered by the well-known problems of company registers. For example, reporting on company ownership or business activity is not mandatory in the E-PRTR regulation, hence aggregation of chemical footprint is not always possible at the final parent company level. Hence, requirement of reporting parent company, business activity information could help increase the usability of the E-PRTR for environmental rating.

Methods

We applied the same general method described in earlier research studies in the field[4],[8],[9] and calculated impact potentials for human toxicity and ecotoxicity associated with emissions from point sources in the European Union and in other countries which report to the European Pollutant Register (Figure 4). The emissions (E) of substances (i) in the EPRTR have been multiplied by their USEtox 2.12 characterisation factors (CFs) and aggregated across all substances and release media (j), Eq (1) as suggested in the USEtox Manual,[15].

$$Impact\,potential = \sum_{ijk} E_{ijk} \times CF_{ijk} \tag{1}$$

Impact potentials are measured in Comparative Toxic Units for human health (CTUh) and ecotoxicity (CTUe), respectively. It should be noted that CTUh and CTUe values can not be directly compared, as they are measured on different scales and in different units.

To further increase the precision of calculations, we draw distinction between different sub-types (k) of compartments (e.g. release media into which the pollutants are released) similarly to an earlier research[9]. Urban air and rural air were differentiated in accordance with the USEtox 2.12 grouping of sub-compartments. In the same vein, freshwater and seawater emissions were also differentiated. Other recent papers on Swedish national chemical footprint[4],[8] assumed that (i) water emissions were freshwater emissions and (ii) air emissions were rural air emissions.

To distinguish points sources emission in urban and in rural areas, we used the GISCO population database from[22]. Furthermore, the harmonised European definition of cities and rural areas by[23] was applied, and areas, where population density was below 150 inhabitants per km2 was classified as rural, and above 150 inhabitants per km2 as urban. To draw distinction between pollutant releases to seawater and freshwater we applied a technical rule. We classified seawater emissions as those pollutant releases into water in the EPRTR database, where the emission point sources' distance to the seacoast was less than 500 meters. The 'Distance to the Nearest Coast' dataset was also retrieved from the EUROSTATS GISCO database[22].

Carachterization Factors (CFs) were downloaded from the USEtox 2.12 model website (www.usetox.org). Here, both recommended and indicative CFs were used in the calculations, but similarly to[8],[9] we note that indicative CFs are associated with considerable uncertainties.

USEtox is a generalized model based on scientific consensus providing midpoint and endpoint characterization factors for human toxicological and freshwater ecotoxicological impacts of chemical emissions in life cycle assessment, developed under the auspieces of the United Nations Environment Program (UNEP) and the Society for Environmental Toxicology and Chemistry, (SETAC) Life Cycle Initiative. USEtox represents best application practice as an interface between ever advancing science and a need for stability, parsimony, transparency, and reliability[15]. Important new features of the latest USEtox model versions include human exposure to pesticide residues in crops; an indoor air compartment for human exposure through inhalation, and improved fate and effect modeling of metals.

Pollutants covered in our research are the same pollutants as in earlier works on Sweden[8],[9],[9]. The highest CFs, e.g. the CFs of the most toxic pollutant types were used when the E-PRTR does not provide information on the chemical types of a compound. This assumption is relevant for Cr and As. Also, AOX (Halogenated Organic Compounds) were assumed to be represented by 1,4 di-chlorobenzene, NMVOC by Benzene and PAH (Polyaromatic Hydrocarbons) by Benzo-(a)pyrene. These were chosen as a risk management conservative approach, because they have high CFs and are representative for the group.

Conclusions

Our study aims at broadening the coverage of company and facility level environmental assessment. Earlier carbon and water footprint methodologies helped assess resource consumption, CO2 emission and related climate change risk, but usually neglect relevant impacts, like those related to the production and use of chemicals[1].

The seriousness of health and ecological consequences can not be evaluated if only the quantity of pollutants are used[14]. To increase transparency and understanding we characterize the impact of substances by combining their environmental release data with their toxicity properties (by also controlling for the release media and population density). To implement our identification strategy, we link the European Pollutant Release and Transfer Register (E-PRTR) database to USEtox, a toxicity model based on scientific consensus. USEtox provides midpoint and endpoint characterization factors for human toxicological and freshwater ecotoxicological impacts of chemical emissions in life cycle assessment. It was developed under the auspieces of the United Nations Environment Program (UNEP) and the Society for Environmental Toxicology and Chemistry, (SETAC) Life Cycle Initiative.

We assesses chemical footprint at various levels from pollutants to industries and company facilities. Furthermore, trend and geographic spread of human toxicity and ecotoxicity are also discussed, which have been not investigated in earlier papers for Europe. Our research also aims at supporting the achievement of global environmental policy goals (Sustainable Development Goals, EU Sustainable Finance Taxonomy objectives) by presenting a new set of indicators, which could help operationalize the framework on the company level.

Human toxicity impacts are dominated mostly by mercury compounds in the EU as a whole, accounting for 71% of the total impact potential in 2017. An important risk of further mercury emissions has been already highlighted by earlier research due to mercury's bio-accumulation properties in organisms and humans during their lifetime. The World Health Organization (WHO) includes mercury in its list of chemicals of major public health concern[17]. There is some degree of variation across Member States, zinc compounds and lead compounds are being the pollutants, each with considerable, 8% impact potential of the total on average.

The pollutants with the largest contribution to ecotoxicity was zinc in 2017 (55% of the total) together with some other metals confirming earlier results[10],[1].

On the industrial level the largest estimated human toxicity footprint was estimated for Production of electricity (52%) followed by Manufacturing of basic iron, steel, and ferro-alloys (16%) and production of cement (9%) in 2017

As for ecotoxicity, sewerage (41%) is the industry with the largest estimated chemical footprint together with production of electricity (22%) and Mining of other non-ferrous metal ores (7%). Our results together with the large greenhouse gas emission of the energy sector further increases the importance of managing the sector's environmental footprint.

We decomposed the results similarly to an earlier study on Sweden[9], and found that non-cancer human toxicity dominated the aggregated human toxicity impact potentials in Europe. Chromium compounds and, Polycyclic aromatic hydrocarbons (PAHs), mercury compounds and PCDD + PCDF (dioxins + furans) have the largest cancer toxicity impact potential.

The E-PRTR database contains important information for regional assessment, as companies shall report their geographic coordinates. The geographic clusters of toxicity overlaps with the industrialized regions in Europe, in particular North-England, North-Italy, the German Ruhr-area, South-Poland, the Benelux states, and in coastal areas of Spain, Portugal and Nordic countries can be mentioned. There is an overlap of areas of the largest emissions of human toxicity and ecotoxicity.

The facility with the largest contribution to human toxicity and also to ecotoxicity in Europe is Maltese Delimara Power station. The second largest contributor to human toxicity is PGE Górnictwo Bełchatów, a coal-fired power station part of the

Poland's largest energy sector company. Eight of the top ten polluter facilities in terms of human toxicity are in the energy sector and release mainly mercury compounds in the air. Ecotoxicity impact potential is also concentrated, six of top ten most toxic facilities is in the sewerage and water collection and treatment sector, and release mainly zinc compounds, cadmium compounds and nickel compounds into water.

The slope of European total human toxicity trend was negative in the early 2000s, although became again positive in the last years of the sample in 2016 and 2017. Total human toxicity in the sample decreased substantially from 102K CTUh to 66K CTUh in 2017. Human toxicity of zinc was reduced monotonously, while human toxicity of mercury compounds was unchanged.

Although the obstacles to the chemical footprint analysis based on the E-PRTR are numerous[8], we believe that our analysis and methodology help make progress with environmental accounting and transparency.

We conclude that the 2.12 USEtox model version produces relatively consistent results with earlier research. Our results are significantly important due tore the fact that USEtox sub-compartment level toxicity characterisation factors are used for the for EU based facilities and matched with point source industrial pollutant releases on the basis of EUROSTAT GISCO population density and distance-to-coast grid data.

Understanding and measuring environmental impacts of individual companies and facilities is currently needed for environmental accounting, for informed consumer decisions and to scale up financing to clean production and to make progress with the European Green Deal and sustainable finance.

Data availability

The study is based on two publicly available data sources: i) the European Pollutant Release and Transfer Register [E-PRTR database v18] , ii) USEtox 2.12 model USEtox model download. Furthermore, the graphs and figures in the study will be publicly available in the Mendeley repository upon publication of the study.

Erhart, Szilárd (2022), "Industrial Pollutant Toxicity Map of Europe", Mendeley Data, V1, doi: 10.17632/5drfmgkrz2.1

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Author contributions statement

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, methodology, software, data curation, writing, original draft preparation, visualisation.

K.E. participated in the conceptualization, background database construction and curation. S.E. participated in the conceptualization and formulation of research, analyzed and visualized the results and wrote the main manuscript text. All authors discussed the results and contributed to reviewing the manuscript.

Additional information

The authors declare that they have no competing interests.

Appendix

Table 4. Human toxicity and ecotoxicity impact potential by NACE sectors (2017, in CTUh and CTUe)

															human toxicity impact in % of the total														
Industry	**AT**	**BE**	**BG**	**CY**	**CZ**	**DE**	**DK**	**EE**	**EL**	**ES**	**FI**	**FR**	**HR**	**HU**	**IE**	**IT**	**LT**	**LU**	**LV**	**MT**	**NL**	**PL**	**PT**	**RO**	**SE**	**SI**	**SK**	**UK**	**EU28**
Manufacture of cement	27%	15%	2%	87%	5%	9%	44%	0%	18%	14%	5%	8%	84%	50%	61%	3%	0%		93%		0%	10%	5%	1%	2%	69%	0%	6%	9%
Manufacture of basic iron and steel and of ferro-alloys	51%	30%			6%	12%			3%	22%	30%	38%		14%		46%		100%			40%	10%	5%	53%	28%	11%	92%	40%	16%
Production of electricity	0%	0%	91%	12%	69%	69%	33%	95%	53%	26%	1%	7%	0%	0%	21%	8%			0%	100%	19%	56%	32%	34%	1%	0%	0%	29%	52%
Sewerage	4%	1%	4%	1%	1%	1%	3%	0%	1%	2%	1%	1%	3%	8%	6%	11%					6%	0%	5%	6%	4%	2%	0%	4%	2%
Treatment and disposal of non-hazardous waste	0%	10%	0%	0%	0%	0%	17%	5%	0%	0%	0%	7%		7%	11%	2%	0%	0%		0%	11%	0%	0%	0%	0%	0%	0%	1%	1%
Treatment and coating of metals	0%	1%			0%	0%				2%		0%		11%		0%	28%					0%		0%				1%	0%
Mining of iron ores											0%														19%				0%
Manufacture of pulp		2%				0%		0%		1%	2%	3%	0%	0%									24%		7%		0%	0%	1%
Manufacture of other inorganic basic chemicals	2%	1%	0%			2%		0%	0%	11%	40%	7%		0%		3%					0%	0%	0%	0%	0%			8%	2%
Water collection, treatment and supply			0%							0%		0%	3%	0%		4%	43%		7%			0%	0%	0%		0%	0%	0%	0%
Largest contributions in % of total	**84%**	**59%**	**97%**	**100%**	**81%**	**93%**	**97%**	**100%**	**75%**	**78%**	**79%**	**72%**	**91%**	**91%**	**99%**	**79%**	**71%**	**100%**	**99%**	**100%**	**76%**	**77%**	**71%**	**94%**	**60%**	**82%**	**92%**	**90%**	**84%**
															eco toxicity impact in % of the total														
Industry	**AT**	**BE**	**BG**	**CY**	**CZ**	**DE**	**DK**	**EE**	**EL**	**ES**	**FI**	**FR**	**HR**	**HU**	**IE**	**IT**	**LT**	**LU**	**LV**	**MT**	**NL**	**PL**	**PT**	**RO**	**SE**	**SI**	**SK**	**UK**	**EU 28**
Manufacture of paper and paperboard	5%	3%			2%	0%				0%	51%	2%		0%		1%					0%	5%	4%		33%	6%	1%	0%	3%
Manufacture of basic iron and steel and of ferro-alloys	6%	16%			9%	5%			13%	10%	9%	15%		70%		6%		100%			4%	7%	0%	8%	6%	15%	63%	5%	6%
Production of electricity	1%	0%	1%	65%	13%	3%	0%	82%	11%	9%	0%	4%	0%	4%	0%	2%			0%	100%	0%	4%	3%	0%	4%	0%	0%	3%	22%
Sewerage	84%	29%	77%	27%	49%	58%	99%	11%	59%	53%	16%	33%	16%	21%	94%	59%					83%	23%	72%	54%	20%	60%	0%	59%	41%
Treatment and disposal of non-hazardous waste	0%	1%	0%	0%	0%	1%	0%	1%	0%	0%	0%	0%		1%	0%	3%	0%	0%		0%	1%	1%	0%	0%	0%	0%	0%	6%	1%
Water collection, treatment and supply			2%							10%		2%	72%	1%		15%	97%		100%			1%	5%	3%		16%	1%	1%	4%
Mining of other non-ferrous metal ores			7%						0%	0%	3%	0%			6%							49%	1%	31%	1%				7%
Manufacture of pulp		2%				0%		4%		2%	11%	3%	0%	0%									6%		33%		3%	0%	1%
Manufacture of other inorganic basic chemicals	1%	29%	0%			3%		0%	0%	1%	1%	3%		0%		9%					0%	0%	0%	0%	0%			1%	3%
Manufacture of refined petroleum products	1%	0%	0%		0%	1%	0%	1%	17%	3%	1%	5%	2%	0%	0%	1%	0%				1%	0%	4%	2%	0%		23%	1%	1%
Largest contributions in % of total	**97%**	**80%**	**86%**	**92%**	**73%**	**72%**	**99%**	**100%**	**100%**	**88%**	**91%**	**69%**	**89%**	**97%**	**100%**	**95%**	**97%**	**100%**	**100%**	**100%**	**90%**	**91%**	**94%**	**100%**	**98%**	**98%**	**92%**	**77%**	**89%**