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ERICA
Environmental monitoRIng
through Civic engAgement

Empowering Communities with Citizen Science

Tools to monitor the impacts of fossil fuel industries and drive *change*

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ERICA – Environmental monitoRIng through Civic engAgement

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Coordinated and edited by Rachele Ossola (Source International)

Formatted by Eleonora Tassan, Michele Maistrelli, and Rosalia Giuga (Social IT)

Contributing authors: Rachele Ossola, Diana Alonso, Flaviano Bianchini, Karolina Dziubata-Smykowska, Laura Grassi, Marek Jaskólski, Aleksandra Lis-Plesińska, Clara Masetti, Gorka Muñoa, Martí Orta-Martínez, Lina Pita, Lorenzo Pellegrini, Neus Roig, Giorgio Santoriello, and Francesca Savoldi.

Reviewed by Alice Lazzarin, Alessia Marzotto, and all contributing authors.

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ERICA

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1. Introduction

The fossil fuel industry has become increasingly central to the geopolitical balance and modern lifestyle – we need natural gas to keep our homes warm, gasoline to drive our cars, and plastics for almost everything. Despite the significant improvements in environmental legislation and industrial techniques over the last decades, extracting and processing oil, gas, and coal remains a "dirty" business even in developed countries. Communities living near fossil fuel facilities withstand annoying odors, environmental degradation, health problems, and the subsequent impacts on the local society, in remote areas of the Ecuadorian Amazon and busy European harbors alike.

In the last two decades, citizen science has emerged as a powerful tool to collect scientific data while educating and empowering citizens. Citizen science involves non-scientists in defining the project's scope and in data collection, analysis, and results sharing – different levels of engagement exist fitting citizens' time, interests, and needs. This participatory approach to science has already been exploited by thousands of communities to gather independent evidence of environmental degradation, support grassroots campaigns, engage with politicians and institutions, trigger academic investigations, and raise awareness in the local society.

In this context, ERICA – **E**nvironmental monito**RI**ng through **C**ivic eng**A**gement – aims to educate citizens living near fossil fuel industries to perform independent environmental monitoring and use this information to create a positive change. This ERASMUS+ project involves academic institutions (the Erasmus University Rotterdam, the University of Barcelona, and the Adam Mickiewicz University), non-governmental and civil society organizations (Cova Contro, Source International, and the European Association for Local Democracy), technical partners (Social IT), and focus groups from the pilot sites in Tarragona (Spain), Val d'Agri (Italy), the Konin mine region (Poland).

The project will run from November 2023 to 2026, will produce free educational material on participatory monitoring, and will deploy these tools in citizen science initiatives at the three pilot sites.

This e-booklet – the first deliverable of the project – summarizes tools and best practices to run citizen science initiatives that maximize societal change, with a focus on the extraction and processing of natural gas, oil, and coal in Europe. This publication is the result of the comprehensive literature reviews performed by the partners during the first project year and represents the starting point for the development of the ERICA training methodology and e-learning platform.

The booklet is structured into seven parts. Following this introduction, Section 2 provides background information on fossil fuels – what they are and how they are processed. Section 3 analyzes the main pollutants emitted during fossil fuel extraction and processing, their impacts on human and environmental health, and existing legislation and guidelines to protect us. Section 4 overviews affordable tools and technologies suitable for citizen science initiatives on the environmental impacts of fossil fuel industries. Section 5 describes best practices to maximize the amount of *actionable knowledge* produced in citizen science projects. Finally, Section 6 presents virtuous examples of projects led by communities impacted by fossil fuel exploitation, in Europe and abroad. The most relevant publications, books, websites, and tools we dragged information from are embedded as hyperlinks in the text or listed in Section 7.

Illustrations by Storyset

2. What are fossil fuels and how are they extracted?

This section overviews basic concepts about oil, gas, and coal: what they are, how they form, and how they are processed industrially. Beyond basic knowledge, this information clarifies the environmental impacts one can expect at each processing stage – and helps explain, for example, why residents around Tarragona's petrochemical complex are worried about 1,3-butadiene (Section 6.1) but not about river water conductivity, which is the primary concern of citizens in the Upper Silesian coal mining area (Section 6.3). Bibliographic references for this chapter are in Section 7.

2.1. What are fossil fuels?

Fossil fuels refer to carbon-rich materials that accumulate underground during the geological processing of dead organisms. Depending on the organisms and processing conditions, fossil fuels can be gaseous, liquid, and solid – referred to, respectively, as natural gas, oil, and coal. Although their chemical composition varies, they all contain carbon (along with hydrogen, sulfur, oxygen, and nitrogen) and release heat when burned.

Natural gas and oil are generally formed and found together, though one of the two can be prevalent. They originate from the plankton that lived in shallow, warm oceans millions of years ago. After dying, the plankton sank onto the ocean floor and was covered by sediments. Over time, underground heat and pressure transformed it into kerosene and then petroleum. Being viscous, petroleum spread into porous rocks until it was trapped by impermeable layers, creating an oil (or gas) field (Figure 1, top). These reservoirs have always a heterogeneous composition, including gases (e.g., methane) and liquids, both hydrocarbons and water – this water represents an important waste of the oil extraction process (see Section 2.2.1).

Coal formed in swampy forests during the Carboniferous period, 300 to 350 million years ago. Dead trees fell into swamps, where the lack of oxygen prevented their decomposition. As time passed, these trees turned into peat and eventually into various types of coal: lignite, sub-bituminous coal, bituminous coal, and anthracite (Figure 1, bottom). Among other elements, coal contains carbon and sulfur. Sulfur content is crucial when it comes to coal processing and environmental impacts. Coal also contains small quantities of methane and other volatile organic chemicals, which are entrapped in its solid structure and get released during extraction.

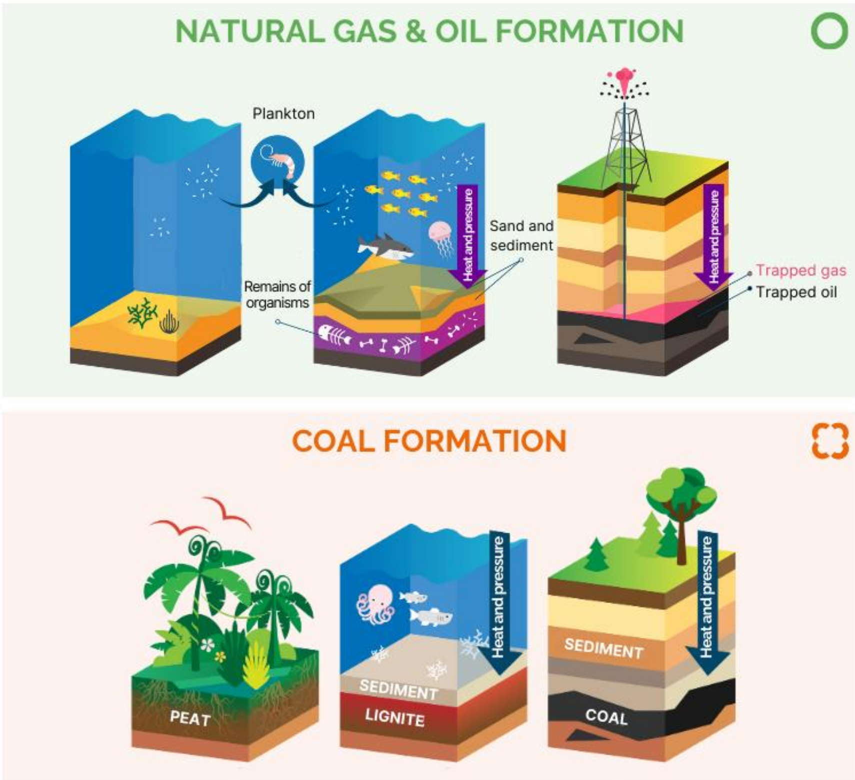

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Figure 1 *Schematic overview of how natural gas, oil, and coal form.*

2.2 Oil and gas – Extraction and processing

2.2.1 Extraction

After an oil field is discovered, engineers drill a first well to assess the quality and quantity of hydrocarbons. If the results are good, they build an extraction plant – a series of wells designed to efficiently extract the oil or gas. How the facility operates depends on the mixture of hydrocarbons and the extraction stage. In the early phase, gas and oil are passively pushed up by underground pressure. Up to 90% of the natural gas and 30% of the oil are extracted in this way. In the second stage, gas and water are injected into the wells to recover an additional 10 to 15% of the oil. The last step uses emulsions and chemical solvents, which are pumped underground to extract another 10 to 15% of the remaining oil.

Once extracted, the crude material is stabilized and sent to a refinery via pipelines. The stabilization process involves the separation of liquids from gas followed by the removal of water (dehydration), hydrogen sulfide (desulfurization), and salts (desalination). The gas contains methane and light hydrocarbons and is either processed for sale or disposed of through **gas flaring** (Box 1). Dehydration produces **wastewater** rich in salts, hydrocarbons, heavy metals, radionuclides, and – if from the third extraction stage – organic solvents and emulsifiers. This wastewater is treated and usually re-injected underground.

Box 1. Gas flaring and its environmental impacts

Gas flaring is a controversial practice that involves burning the gas that gets out during oil extraction – indeed, not all companies have the infrastructure to collect, process, and transport the gases that oil fields contain (Figure 1, top). Gas flaring and venting are also adopted as a safety precaution to avoid dangerous pressure buildups. Flaring converts the waste gas into CO_2, contributing to about 1% of global warming – however, venting the waste without burning it is even worse: methane, the gas' primary constituent, is a more potent greenhouse gas than CO_2. Flaring also emits pollutants like black carbon (a component of particulate matter) and sulfur dioxide, degrading local air quality and contributing to water and soil acidification. Last, gas flaring is a waste of natural resources: if collected, the 150 billion m^3 of gas flared annually could meet the energy needs of the whole African continent. In 2015, the World Bank launched a pledge to end all flaring by 2030, but efforts to meet this goal are running short.

2.2.2 Oil processing – Refinery

After extraction and pre-treatment, crude oil is sent to refineries, where it is transformed into a variety of products. The process begins by heating the crude to 400˚C at the base of a refining tower (Figure 2). As the oil heats up, its components evaporate and rise. When they reach the height at the right temperature, they condense and get collected. This process – called hydrocarbon fractionation – separates groups of hydrocarbons based on their boiling points, which are linked to the number of carbon atoms. Light hydrocarbons like propene and butene are collected as gases at the top of the tower, while heavier ones stay at the bottom and are further separated into fuels, lubricants, and other products. After fractionation, all products go through additional processes like cracking, alkylation, and reforming, which alter their chemistry and convert them into usable products.

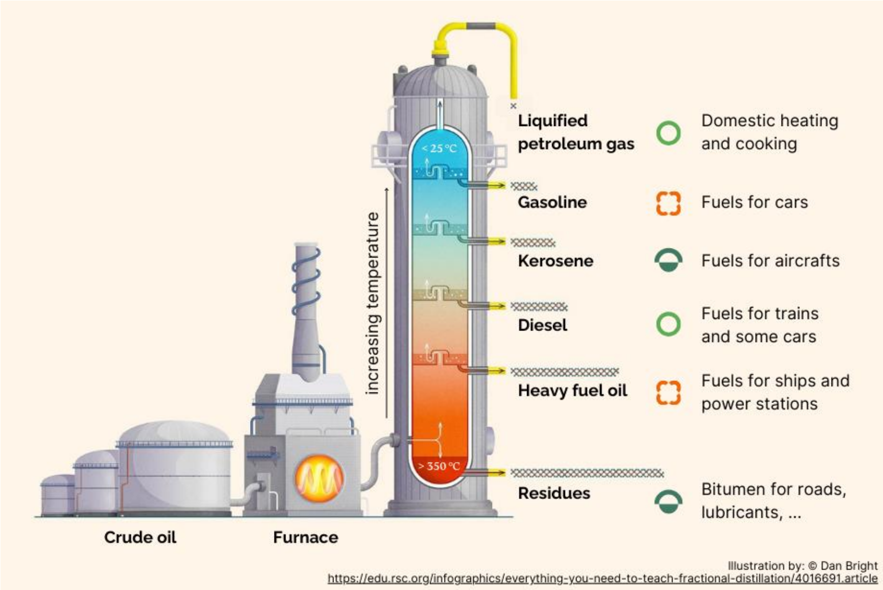

Figure 2 *Fractionation of crude oil in a refining tower. The various fractions are collected and further processed to obtain fuels, feedstock, and other everyday items.*

As processing crude oil requires a lot of energy, refineries typically have their own **power plant**, which runs on liquid and gaseous fuels and byproducts from the refining process. As for extraction, **gas flaring** units may be present for safety reasons.

2.2.3 Oil processing – Petrochemical plants

After refining, oil-based products may be sent to a petrochemical plant for further processing. These plants use any fossil fuel-derived feedstock to produce a wide range of products: plastics, rubbers, textiles, medicines, and pesticides. Because there are so many possible options, it is difficult to provide a *general* description of the process and the expected environmental impacts.

As they exploit the refinery's end products, large petrochemical plants are often located next to refineries – such as in Tarragona (Section 6.1) and Marseille.

2.3 Coal – Extraction and processing

Coal can be found near the earth's surface or deep underground. Surface fields are mined using methods like strip mining, contour mining, or mountaintop removal mining. In contrast, underground, coal is extracted via longwall or room-and-pillar mining. In general, underground mining requires more personnel and has a higher occupational hazard than surface mining: in the US, is among the most dangerous jobs that one can take.

After extraction, coal is crushed and resized for burning. Most coal, especially if rich in sulfur, needs to be washed with water or chemical solvents before processing. This washing can remove up to 40% of inorganic sulfur, therefore reducing the amount of sulfur dioxide released during burning but generating **wastewater**. If not managed correctly, this wastewater can damage the ecosystem due to its acidity, high content of heavy metals, and, often, high conductivity. Wastewater is also generated when groundwater invades the mine during regular operations (e.g., Section 6.3). Alongside water, coal processing produces large amounts of **solid waste** that must be disposed of properly – coal refuse can auto-combust and produce acid drainage (e.g., Section 6.4.2). Some of these impacts continue beyond the mine's lifetime, requiring thorough decommissioning and remediation.

In the final stage, coal is burned to generate electricity, often in a nearby **power plant** to cut transportation costs. Compared to other fossil fuels, coal is more likely to produce particulate matter and release heavy metals, especially mercury, in the environment. The leftover material from burning, named **fly ash**, is also rich in heavy metals and requires careful disposal.

Illustrations by Storyset

3. How is the fossil fuels industry impacting the environment?

3.1 Which pollutants do fossil fuel industries emit?

Although we are all aware of the *global* impacts of fossil fuels in terms of CO_2 emissions, communities living close to extraction and processing plants face an additional set of environmental and health concerns. This section summarizes the main pollutants to be expected around these facilities. This overview is based on the 2023 edition of the EMEP/EEA Air Pollutant Emission Inventory Guidebook and focus groups discussions, and refers primarily to *process emissions* – in other words, pollutants emitted during regular operations, not accidents. Accidents release all pollutants listed below but in significantly higher concentrations, with dramatic and lasting effects on nearby communities. Besides specific chemicals, extraction and processing activities have also broader environmental impacts including changes in microclimate, reduced levels of ground and surface waters, soil deformation, and landslides.

3.1.1 Overview by environmental matrix

Regular fossil fuel extraction and processing **primarily impact air** – though they can also damage water bodies and terrestrial ecosystems.

The main air pollutants *specific* to fossil fuel industries are **volatile organic compounds** (VOCs). VOCs are carbon-containing chemicals largely present as gases at common pressures and temperatures – although some compounds can be detected also in water and soil. Methane, benzene, toluene, and polycyclic aromatic hydrocarbons (PAHs) all belong to this category (Box 2). Specific stages of oil refining and coal burning also release sulfur-containing gases like **sulfur dioxide** (SO_2) and **hydrogen sulfide** (H_2S). Specific VOCs and S-containing chemicals are the main responsible for the **bad smells** often reported in industrial areas.

Fossil fuel industries also release pollutants associated with general combustion processes like **particulate matter** (PM), oxides of nitrogen (NO and NO_2, collectively indicated as $\mathbf{NO_x}$), $\mathbf{SO_2}$, carbon monoxide, and CO_2. These industries also emit **heavy metals**, either as gases (as, for instance, mercury) or attached to particles. The exact mix of pollutants depends on factors like the type of fuel, its specific composition, and the technicalities of the industrial process (see Section 3.1.2).

Box 2. What are volatile organic compounds (VOCs)?

Organic compounds – chemicals containing only carbon (C), hydrogen (H), and, sometimes, oxygen, nitrogen, and sulfur – encompass thousands of species with a range of properties. Because of this variety, classifying these molecules is challenging.

Here, we define volatile organic compounds (VOCs) as those molecules present *primarily* in air at standard temperatures and pressures – though some can also be found in water and soil (Box 3). VOCs include methane (CH_4) and other compounds collectively known as non-methane volatile organic compounds (NMVOCs). NMVOCs encompass aliphatic compounds like 1,3-butadiene, ethylene oxide, ethylene, and formaldehyde, and aromatic chemicals such as benzene (B), toluene (T), ethylbenzene (E), xylenes (X), and polycyclic aromatic hydrocarbons (PAHs) like benzo[*a*]pyrene. NMHCs – non-methane hydrocarbons – is another acronym common in the oil pollution literature. NMHCs are a subset of NMVOCs that include molecules made *only* of carbon and hydrogen. For example, they include 1,3-butadiene (C_4H_6) and ethylene (C_2H_2) but not ethylene oxide ($C_2H_4\mathbf{O}$) and formaldehyde ($CH_2\mathbf{O}$), which also contain oxygen (O). To avoid confusion, this publication adopts the classification shown in Figure 3.

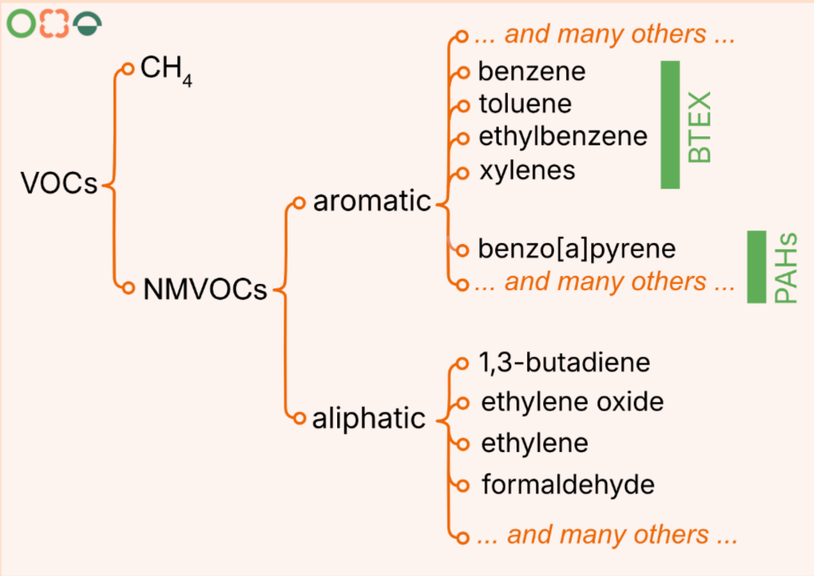

Figure 3 *Simplified classification of volatile organic chemicals adopted in this booklet. The acronyms are explained in the text.*

Fossil fuel industries can also pollute **aquatic ecosystems** – though, under regular operations, this primarily concerns the wastewater generated during extraction and pre-processing. Depending on the local geology, type of fuel, and process stage, these wastewaters can contain high levels of **salts** (often sodium chloride), **acids** (mainly sulfuric acid), **heavy metals**, **organic chemicals**, and **radioactive elements** (mainly radium). The organic compounds can derive from the fuel (called total petroleum hydrocarbons or TPHs; see Box 3) or from additives used during oil extraction. If not properly managed, this wastewater can seep into nearby water bodies, groundwaters, and terrestrial ecosystems and cause significant harm.

Box 3. What are total petroleum hydrocarbons (TPHs)?

TPHs is another acronym referring to an ill-defined collection of chemicals including aliphatic and aromatic compounds. Like oil refining products (Section 2.2.2 and Figure 2), THPs are classified by their number of carbon atoms. For example, "gasoline range organics" have 6 to 10 carbons, while "diesel range organics" have

10 to 22. These two sub-groups include BTEX (in gasoline) and PAHs (in diesel), chemicals that are detected *primarily* in air (as part of NMVOCs; see Box 2) but can also be found in water and soil.

3.1.2 Overview by fossil fuel type and process stage

Although fossil fuel exploitation releases a relatively consistent and characteristic mix of pollutants, each fuel type and process stage has a unique "emission fingerprint". Understanding the origin of these signatures can help citizens identify which chemicals to prioritize in their community monitoring initiatives.

Figure 4 (top) highlights the key air pollutants released during **oil and gas extraction and processing**. During extraction, the main emissions are **VOCs** from gas leaks, venting, wastewater treatment, and stabilization of crude oil. In facilities adopting gas flaring practices, one can expect additional **combustion-related emissions** – PM, NO_x, SO_2, carbon monoxide, CO_2, and unburned or partially burned fuel (thus, VOCs). *Specific* heavy metals are also released: for oil, primarily vanadium and nickel; for natural gas, mainly mercury and arsenic. Likewise, refineries emit VOCs and pollutants associated with gas flaring, plus sulfur-containing chemicals (from desulfurization) and combustion-related species (from the refinery's power plant). Sulfur-containing compounds include **SO_2**, **H_2S**, and organics like mercaptans. Emissions from **petrochemical plants** are unique to the specific process and are thus hard to generalize. One can look for **VOCs** as a group; however, each process has a unique fingerprint that can help track down the emitting unit – for example, the production of polyethylene plastic may release ethylene, the starting material. During regular operations, wastewater mismanagement is mainly a concern during extraction and pre-treatment.

While oil and gas exploitation mostly affect local air quality, coal extraction and processing have a more nuanced effect on the environment (Figure 4, bottom). Most emissions to air come from **coal burning** in power plants, which are often located near the mining site. Compared to oil and gas, burning coal releases more **particles** and **heavy metals** – in addition to all other combustion-related pollutants. The extraction process *per se* releases only methane and a few other VOCs entrapped in the rocks. If coal waste is not properly managed, it can self-ignite and release further combustion-related pollutants (see Section 6.4.2).

Coal mining has also a significant impact on nearby **aquatic and terrestrial ecosystems**. When coal and its waste encounter water, they release **salts**, **acids**, and **heavy metals** – the predominant effect depends on the chemical makeup of the ore. For instance, coal containing pyrite (a mineral made of iron and sulfur) releases sulfuric acid when it gets wet, while coalfields rich in halides (as in Poland; see Section 6.3) form solutions saltier than seawater when moistened. Coal can get wet during the extraction process (for example, when the ore is washed) but also when open pits are exposed to rain. If not properly managed, the resulting drainage can harm the ecosystem due to an excessive increase in salinity, acidity, and toxic metals.

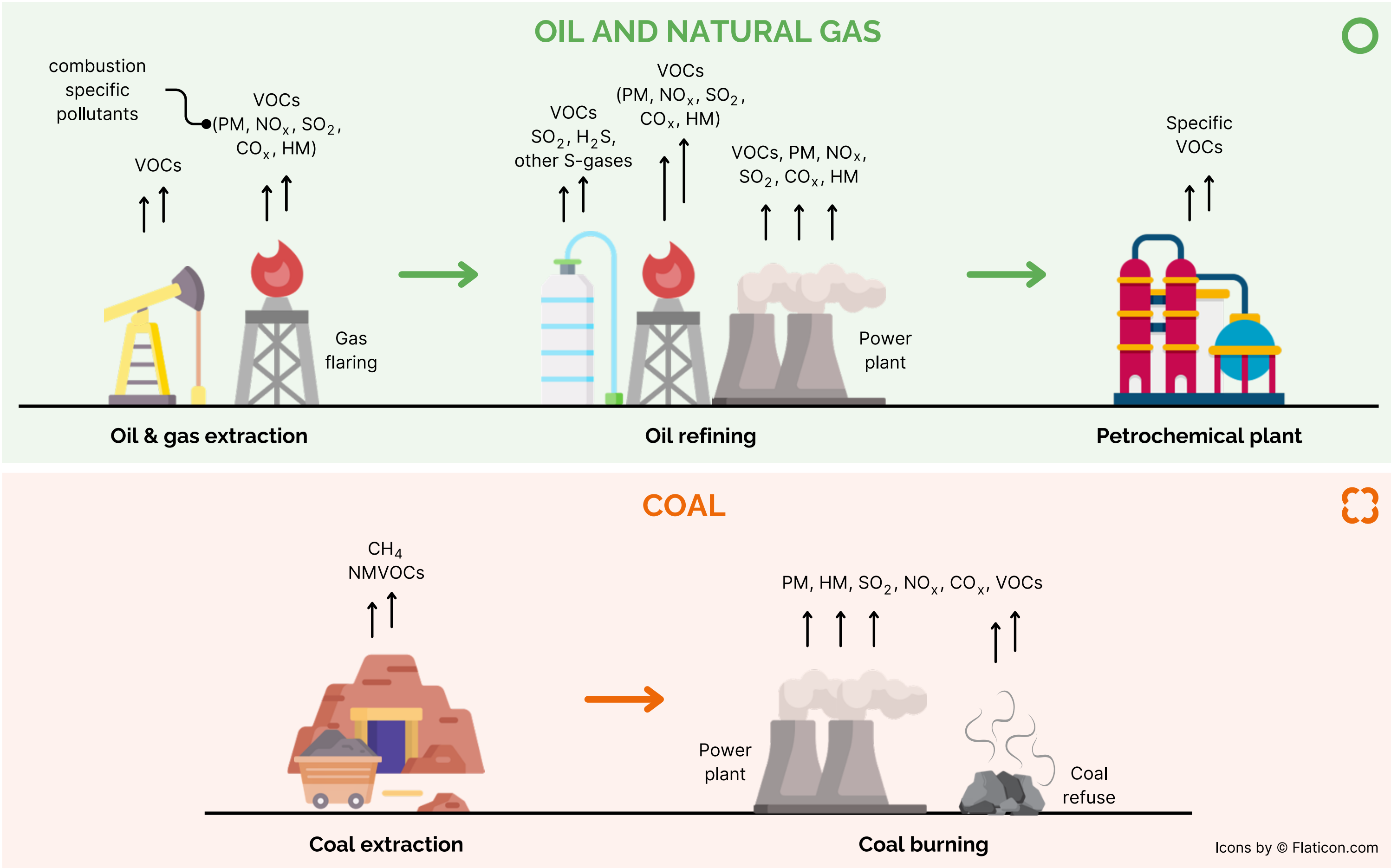

Figure 4 *Schematic representation of the environmental impacts of fossil fuel extraction and processing. Unintentional spills and other accidents are not included. Legend: HM = heavy metals; CO_x = oxides of carbon (carbon monoxide and CO_2); VOCs = volatile organic compounds; NMVOCs = non-methane volatile organic compounds (see Figure 3).*

3.2 How dangerous are these chemicals?

According to a famous say in chemical toxicology, it is “the dose [that] makes the poison” – that is, any chemical can be harmful in large amounts, while substances considered dangerous can be harmless if they are present only in traces. This idea applies also to pollutants from the fossil fuel industry. In the next sections, we explain how fossil fuel-related pollutants affect human health (Section 3.2.1) and review environmental quality standards and guidelines (Section 3.2.2), which define the pollutant levels considered safe for health. For simplicity, we focus on the most relevant compounds based on previous sections, focus group discussions, and data availability.

3.2.1 Human health effects – which pollutants should we watch for?

Pollutants from fossil fuel exploitation harm human health in many ways – they can affect the lungs, the brain, and even cause cancer. Here, we provide a simplified overview of these effects dragging from two sources. The first is the International Agency for Research on Cancer (IARC), which rates substances based on their risk of causing cancer. Group 1 substances are carcinogenic to humans, Group 2A are *probably* carcinogenic, Group 2B are *possibly* carcinogenic, and Group 3 cannot be classified (full list here). Second, we summarize the toxicological effects of each pollutant based on profiles from the United States Agency for Toxic Substances and Disease Registry (ATSDR). Full toxicological profiles can be accessed through hyperlinks in the following tables.

Table 1 highlights the health risks of key organic chemicals associated with fossil fuel extraction and exploitation. Benzene, 1,3-butadiene, and ethylene oxide stand out as the most carcinogenic ones, followed by benzo[*a*]pyrene, a representative polycyclic aromatic hydrocarbon.

While not necessarily causing cancer, all other non-methane compounds have hepatic, neurological, and developmental effects. Methane is a concern primarily due to its climate-warming potential: its impact on human health is negligible at typical outdoor concentrations.

Pollutant	IACR classification	Other health effects (ATSDR)
Benzene	Group 1	Gastrointestinal, hematological, immunological, neurological [ref]
Benzo[*a*]pyrene	Group 2A	Developmental, hepatic, reproductive [all PAHs; ref]
1,3-Butadiene	Group 1	Developmental, gastrointestinal, hematological, neurological, reproductive [ref]
CH_4	Group 3	n.a.
Ethylbenzene	Group 2B	Developmental, hepatic, neurological, renal [ref]
Ethylene oxide	Group 1	Developmental, endocrine, hematological, neurological, reproductive, respiratory [ref]
Toluene	Group 3	Cardiovascular, developmental, immunological, neurological, respiratory [ref]
Xylenes	Group 3	Dermal, hepatic, neurological, renal, respiratory [ref]

Table 1 *IARC classification and other health effects for specific fossil fuel-related organics in air and water (n.a. = not available).*

Particulate matter is the most harmful pollutant released from the combustion of fossil fuels – it is linked to cancer, higher death rates, heart diseases, respiratory illnesses, and neurological problems (Table 2). High levels of sulfur dioxide can also have respiratory effects, especially in children and sensitive groups. As we will see in Section 6.2, evidence of respiratory issues in kids was pivotal in triggering a legislation update on SO_2 emission around the Saras oil refinery in Sarroch.

Pollutant	IACR classification	Other health effects (ATSDR)
NO_x	Group 3	None [ref]
$PM_{2.5}$	Group 1	Mortality, cardiovascular, respiratory, neurological [ref]
PM_{10}	Group 1	
SO_2	Group 3	Respiratory [ref]

Table 2 *IARC classification and other health effects for combustion-specific air pollutants. $PM_{2.5}$ and PM_{10} are particles ranging 1 – 2.5 µm and 2.5 – 10 µm, respectively, in size.*

Certain heavy metals can also harm human health (Table 3). Vanadium and nickel are the most relevant in crude oil and can be released during its combustion. While vanadium is not of concern, nickel compounds are Group 1 carcinogens.

Pollutant	IACR classification	Other health effects (ATSDR)
Arsenic	Group 1 (I, M); Group 3 (O)	Cardiovascular, dermal, endocrine, gastrointestinal, hematological, neurological, renal, respiratory [ref]
Cadmium	Group 1 (M, I, O)	Gastrointestinal, musculoskeletal, renal, respiratory [ref]
Chromium (VI)	Group 1 (I, O) Group 3 (M)	Dermal, gastrointestinal, hematological, reproductive, respiratory [ref]
Lead	Group 2A (I) Group 2B (M) Group 3 (O)	Developmental, hematological, neurological, renal, reproductive [ref]
Mercury	Group 2B (O) Group 3 (I, M)	Cardiovascular, developmental, immunological, neurological, renal, reproductive [ref]
Manganese	n.a.	Developmental, neurological, reproductive, respiratory [ref]
Nickel	Group 1 (I, O) Group 2B (M)	Dermal, developmental, immunological, respiratory [ref]
Vanadium[a]	Group 2B	Developmental, gastrointestinal, hematological, neurological, respiratory [ref]

Table 3 *IARC classification and other health effects for relevant heavy metals (n.a. = not available). Cancer groups are given for three categories: inorganic compounds (I), organic compounds (O), and metallic element (M). For chromium, we only refer to chromates (also known as chromium (VI) or hexavalent chromium). The classification for vanadium refers only to vanadium pentoxide ([a]).*

Arsenic and mercury, which can be emitted during the combustion of natural gas, can also have a range of health effects – for instance, arsenic and its inorganic compounds cause cancer. Other heavy metals like cadmium and chromates (compounds with chromium in its higher oxidation state) are also carcinogenic.

3.2.2 Environmental quality standards and guidelines – at which concentrations should we get worried?

Although most pollutants associated with fossil fuel exploitation – and human activities in general – impact human health, aiming for a *fully pristine* environment is unrealistic. Still, everyone has the right to live in a safe, clean, and healthy place, which makes it essential to define what levels of pollutants one can consider "acceptable".

Depending on the environmental matrix and assessment criteria, different references can be used to define what "acceptable" means. The first are the guidelines from the World Health Organization (WHO). These are flexible, science-based recommendations that one can use for a general assessment of pollution. In this booklet, we refer to the WHO's guidelines on air pollutants and recreational water quality. Environmental quality standards are a second set of reference values. Unlike the WHO guidelines, they set legally binding limits on maximum pollutant levels, balancing health protection with economic factors. Here, we focus on the most recent European Union (EU) Air Quality Directive and the Environmental Quality Standards Directive, which apply to Member States. The full references to these and other relevant documents are in Section 7.

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Air

Table 4 summarizes air quality standards and guidelines for pollutants emitted during fossil fuel exploitation. Concentrations are yearly averages in µg/m^3 (unless otherwise noted).

Pollutant	Yearly concentration in air (µg/m^3)		Does it cause cancer?
	WHO	EU	
Main fossil fuel-related VOCs			
Benzene	1.7[a]	5	*
Benzo[*a*]pyrene	0.012[a]	0.001	
1,3-Butadiene	n.a.	n.a.	*
CH_4	n.a.	n.a.	
Ethylbenzene	n.a.	n.a.	
Ethylene oxide	n.a.	n.a.	*
Toluene	260[b]	n.a.	
Xylenes	n.a.	n.a.	
Combustion-related pollutants			
NO_2	n.a.[e] 25[c] 10	200[e] [18][d] n.a.[c] 40	
$PM_{2.5}$	15[c] 5	n.a.[c] 25	*
PM_{10}	45[c] 15	50[c] 40 [35][c]	*
SO_2	n.a.[e] 40[c]	350[e] [24][d] 125[c] [3][d]	
Heavy metals			
Arsenic	0.0066[a]	0.006[f]	*
Cadmium	0.005	0.005[f]	*
Chromium (IV)	0.00025[a]	n.a.	*
Lead	0.5	0.5[f]	
Mercury	1	n.a.	
Manganese	0.15	n.a.	
Nickel	0.025[a]	0.02[f]	*
Vanadium	1	n.a.	

Table 4 *WHO guidelines for air quality and EU Air Quality Directive (2008/50/EC) for selected pollutants associated with fossil fuel exploitation (n.a. = not available). The last column marks Class 1 carcinogens according to the IARC classification (Tables 1–3). [a] Reference level estimated assuming an acceptable risk of additional lifetime cancer risk of 1 in 100 000. [b] Weekly average. [c] Daily average. [d] Permitted exceedances each year or day. [e] Hourly average. [f] Measured as metal content in PM_{10}.*

For *individual* VOCs, the European Union sets air quality standards only for benzene and benzo[*a*]pyrene. Class 1 carcinogens like 1,3-butadiene and ethylene oxide are regulated in some countries but not in Europe (see Section 6.1) – for example, Ontario (Canada) sets a maximum annual mean of 2 μg/m^3 and 0.04 μg/m^3 for 1,3-butadiene and ethylene oxide, respectively. VOCs *as a class* are difficult to regulate due to their heterogeneity. The EU has not yet imposed legal limits for total VOCs in air, although since 2016 it requires Member States to reduce emissions of non-methane VOCs. Some European countries have also national thresholds for indoor VOCs. As an order-of-magnitude reference, total VOCs should be ≤ 300 μg/m^3 indoor and ≤ 2’000 μg/m^3 around industrial facilities.

For pollutants released during fossil fuel combustion, different limits exist based on the averaging period. The European law also allows certain daily values to be exceeded a fixed number of times during the year. For example, for SO_2, the Air Quality Directive sets maximum hourly and daily averages of 350 and 125 μg/m^3, respectively, allowing up to 24 hourly exceedances and 3 daily exceedances per year. Both the WHO and the EU set annual limits for ozone and carbon monoxide. Although not *directly* related to fossil fuel exploitation, ozone forms in the presence of high VOCs, NO_x, and sunlight – conditions often found around refineries during the day (Figure 4). Carbon monoxide is a side product of combustion and may be found when oil, gas, or coal burn – e.g., in power plants.

For heavy metals, the EU regulates arsenic, cadmium, nickel, and lead (all quantified as metal content in PM_{10}). The WHO recommends reference levels also for chromium (VI), mercury, manganese, and vanadium.

Although hydrogen sulfide (H_2S) is not toxic at typical outdoor concentrations (eye irritation, the first health symptom, occurs at

15’000 – 30’000 μg/m^3), this compound has a strong smell. To avoid annoyance, the WHO advises a maximum daily average of 150 μg/m^3 and a 30-minute average of 7 μg/m^3.

Water

Table 5 summarizes yearly average concentrations (in μg/L) for selected pollutants relevant to fossil fuel exploitation. The list excludes methane and other species present only in air like particulate matter.

Pollutant	Yearly concentration in surface water (μg/L)		Does it cause cancer?
	WHO	EU	
Main fossil fuel-related VOCs			
Benzene	200	10 [50][a]	*
Benzo[*a*]pyrene	n.a.	0.00017 [0.27][a]	
1,3-Butadiene	n.a.	n.a.	*
Ethylbenzene	10’000	n.a.	
Ethylene oxide	n.a.	n.a.	*
Toluene	14’000	n.a.	
Xylenes	6’000	n.a.	
Heavy metals			
Arsenic	200	n.a.	*
Cadmium	60	0.08 – 0.25[b] [0.45 – 1.5][a,b]	*
Chromium	1’000	n.a.	*
Lead	200	1.2 [14][a]	
Mercury	n.a.	n.a. [0.07][a]	
Manganese	8’000	n.a.	
Nickel	1’400	4 [34][a]	*
Vanadium	n.a.	n.a.	

Table 5 *Reference values for surface water taken from the WHO Guidelines on Recreational Water Quality and the EU Environmental Quality Standards Directive (inland surface waters; n.a. = not available). The third column marks chemicals known to be Class 1 carcinogens according to the IARC classification (Tables 1–3). [a] Maximum allowable concentration in short-term pollution events. [b] Values depend on water harness.*

Guidelines for recreational water quality are available for BTEX and several heavy metals and are typically in the mg/L range. For toluene, ethylbenzene, and xylenes the recommended concentrations are bigger than their odor threshold – thus, water may still be safe even if it smells. The WHO has also guidelines for drinking water quality, which are more stringent (20-fold lower) and cover more substances than those for recreational waters.

The EU Environmental Quality Standards Directive gives yearly averages and maximum allowable limits (for short-term pollution) for some chemicals specific to fossil fuel industries. This Directive regulates also naphthalene and anthracene, two PAHs not included in Table 5, alongside chlorinated solvents and other priority pollutants.

Conductivity and pH are not covered by the EU legislation nor the WHO guidelines but are valuable proxies of pollution: their measurement is quick and inexpensive, and out-of-range values are clear signs of contamination (for example, see Section 6.3 and 6.4.2). Typical values vary depending on geology; in general, unpolluted freshwater has pH of 6.5 – 8.5 and conductivity of 50 – 1'500 µS/cm. In contrast, waters impacted by mine drainage may have a pH as low as 2 – 3, while industrial wastewater and seawater have conductivities above 10'000 and 55'000 µS/cm, respectively.

Illustrations by Storyset

4. Which tools can citizens use to monitor the health of their environment?

A key goal of ERICA is to help people near fossil fuel industries gather reliable information about their local environmental quality. This section introduces affordable tools anyone can use to monitor air and water, with a focus on the pollutants outlined in Section 3.1: VOCs, H_2S, SO_2, and other combustion-related substances in the air; acids, salts, heavy metals, and organic chemicals like TPHs in water.

We categorize these tools by (1) origin and cost, and (2) approach. According to the first criterion, technologies are commercial or do-it-yourself (DIY). Commercial tools are low- (≤ 2’000 €) or mid-cost (2’000 – 30’000 €), while DIY technologies are generally below 2’000 € – though some may not be much cheaper than low-cost commercial devices. While mid-cost technologies may be too expensive for private citizens, they may be accessible to NGOs or other organizations with funding. Concerning data collection, approaches involve (1) measuring pollutant concentrations, (2) collecting samples, or (3) recording other data (like georeferenced photos showing pollution).

Table 7 gives an overview of these technologies with links to relevant websites; a selection of these tools is further described below. Most low-cost and DIY tools for air detect particulate matter of various sizes and sometimes total VOCs. For water, colorimetric kits are the most accessible option for acids, heavy metals, and other pollutants. Data quality is a general drawback of low-cost approaches – while low-cost and DIY technologies are excellent for education and raising awareness, projects requiring high-quality data should consider collaborating with universities or accredited laboratories.

	Citizens measure concentrations			Citizens collect samples		Citizens collect other data
	Commercial		DIY	Commercial	DIY	
	Low-cost	Medium-cost		Low-cost		
AIR	• Smart citizen kit • PurpleAir • Airnote	• Aeroqual S500	• DustBox • Frackbox • airRohr • CanAirIO • Simple Air Sensor • GLOBE sun photometer	• Radiello	• Bucket Monitor • Copper strips	• Smell (e.g., OdourCollect) • Photos / visual inspection • Bioindicators
WATER	• Colorimetric kits – ChemMetrics – SenSafe – Modern Water RaPID assay – Hanby TPH test kit[a] • Horiba LAQUAtwin compact meters • eXact iDip Photometer	• Hanna multiparametric field probe • UVF-500D Handheld Analyzer • UVF-TRILOGY Benchtop Analyzer • enviroFlu-HC 500	• Publiclab's water sensors	• passive sampler (e.g., here)	• a simple container	• Photos / visual inspection • Bioindicators • Satellite images

Table 7 *Overview of accessible technologies available to detect pollution related to fossil fuel exploitation in air and water. Highlighted entries are described more in detail below.* [a] *A similar system is available for TPHs detection in soil.*

Citizens can still play an active role by collecting samples or/and gathering ground-based data. In environmental justice, “simple” observations are often more impactful than data collected with expensive instruments (for example, see Section 6.4.1) and represent powerful tools to get the process started.

4.1 Tools for air monitoring

4.1.1 Commercial low- and medium-cost sensors

There is a wealth of affordable sensors to monitor air pollutants, including some that are specific to the fossil fuel industry. Their working principle depends on the pollutant – for instance, particles are detected with optical particle counters, VOCs with photo ionization detectors, and NO_x, ozone, and carbon monoxide with metal oxide or electrochemical sensors.

Data quality can be a limitation for low-cost air sensors. The Air Quality Sensor Performance Evaluation Center (AQ-SPEC), a program that evaluates the performance of sensors below 2’000 USD, is an excellent resource to identify the devices suitable for each need. The AQ-SPEC website provides a comprehensive list of products classified by supplier and pollutant, along with cost, technical specs, and performance reports comparing the sensors to reference methods.

Among the variety, we recommend **PurpleAir** and **Aeroqual S500**. Available for less than 300 €, PurpleAir is widely used for real-time detection of $PM_{2.5}$ and is popular in citizen-led air monitoring programs. The newest models (PurpleAir Zen, Touch, and Flex) detect also total VOCs using a metal oxide sensor. Although more expensive (2’100 – 2’800 €), the Aeroqual S500 is an excellent alternative for a wider range of pollutants, some of which are specific to fossil fuel exploitation. By changing the sensor head, this handhold instrument can detect total VOCs, CH_4, H_2S, SO_2, NO_2, and PM, with detection limits generally in the tens of parts per billion (ppb) – below the legal values set by the European Union (Figure 5). According to AQ-SPEC, the Aeroqual S500 is one of the best low-cost options available for total VOCs.

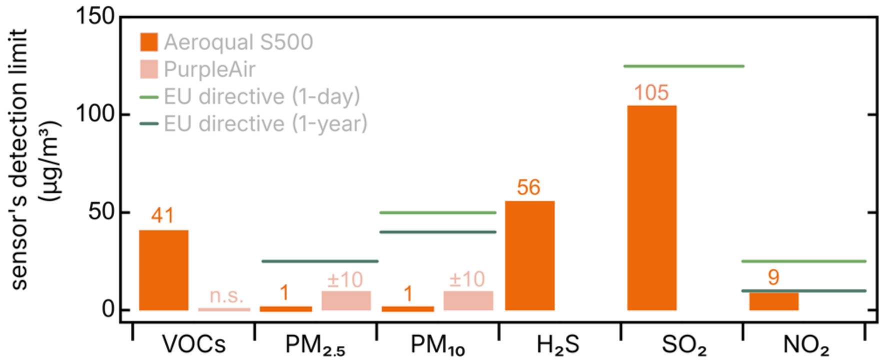


Figure 5 *Detection limits for the two recommended air quality sensors vs. the values set by the EU Air Quality Directive 2008/50/EC (Table 4). The PurpleAir website does not specify detection limits for total VOCs (n.s.). The EU Directive 2008/50/EC does not cover total VOCs and H_2S; for guidelines on acceptable levels for these chemicals, see Section 3.2.2. Detection limits in ppm were converted to µg/m^3 as detailed in Section 7.*

4.1.2 DIY sensors

Most DIY air sensors are low-cost optical particle counters enclosed in a shield and connected to a data logger. A good example of this setup is the **DustBox**, developed by the Citizen Sense initiative. This device uses a low-cost PM sensor housed in a 3D-printed case and connects to WiFi through a microcontroller (Figure 6). While the construction manual is detailed and thorough, building the DustBox requires confidence in electronics, soldering, and coding. The total cost is not provided but is estimated at a few hundred euros. More specific for oil and gas is the **Frackbox**, always from the Citizen Sense initiative. The Frackbox detects total VOCs using a low-cost photoionization detector, alongside NO_2, ozone, and meteorological data. Detection limits are 9 µg/m^3 for NO_2 and 20 µg/m^3 for total VOCs, quite like the Aeroqual

S500 (Figure 5). At the time of writing, this device is still a prototype, and detailed building instructions are not available.

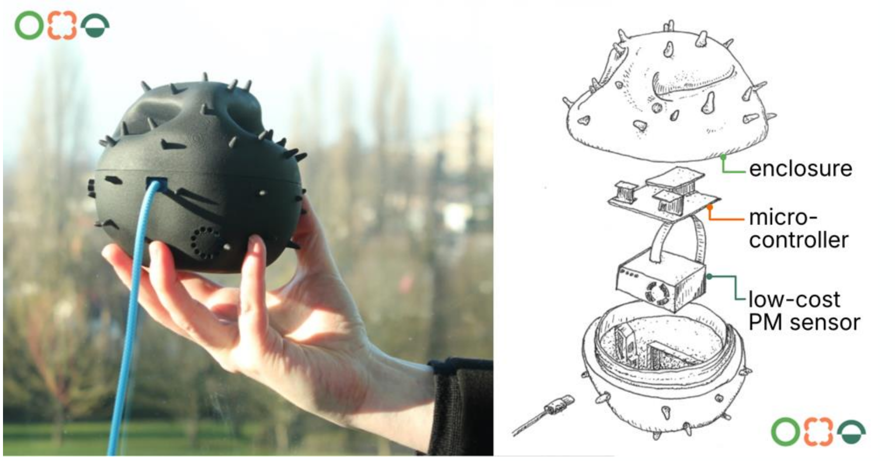


Figure 6 *Image and schematic of a DustBox 2.0. Readapted from Citizen Sense's online material.*

4.1.3 Commercial and DIY samplers

An excellent alternative to low-cost sensors is to ask citizens to collect samples. **Passive samplers** are particularly suitable for air monitoring, as they only need to be deployed for a fixed time (generally a few weeks), are lightweight, and don't need power. On the other hand, **active samplers** force air through a collection bag for a shorter period, normally an hour, but require electricity. After collection, both sampler types are mailed to academic or certified labs for analysis via standard methods. For example, *individual* VOCs can be detected using the standard EPA method TO-15, which is designed to measure 97 air pollutants above 0.5 ppb (around 2 μg/m^3). Costs and detection limits vary on the lab, pollutants, and method used.

Both commercial and DIY samplers are suitable for citizen science projects. **Radiello** is a convenient option if funding is available, costing 400 – 600 € for 20 units (including chemical analysis). This firm offers various models tailored to different pollutants and sampling needs. For example, Source International deployed Radiello samplers to monitor H_2S around the COVA oil plant in Val d'Agri, while researchers from Universitat Politècnica de Catalunya used analogous devices to measure baseline levels of 1,3-butadiene around the petrochemical complex in Tarragona (Section 6.1). Compared to air sensors like the Aeroqual S500 (Section 4.1.1), Radiello samplers have much lower detection limits (Figure 7) but require longer deployment times (from tens of hours to days) and only provide average concentration levels over that period.

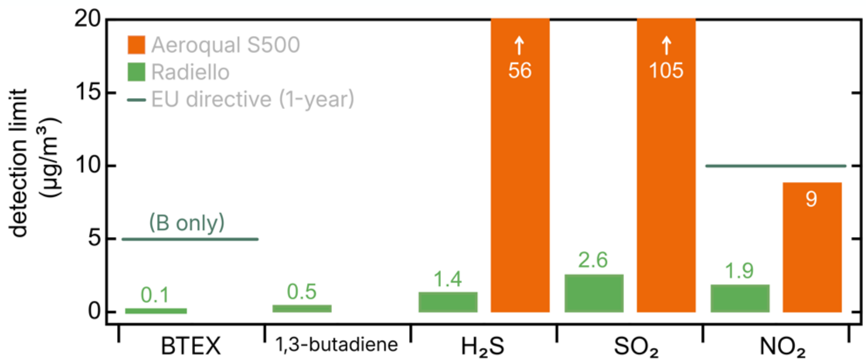


Figure 7 *Radiello and Aeroqual S500 detection limits vs. the EU Air Quality Directive 2008/50/EC (Table 4). Of the four BTEX, the EU Directive regulates only benzene (B). References for these numbers are in Section 7.*

The **Bucket Monitor** is an example of a DIY active sampler for VOCs and sulfur-containing chemicals. Developed in the 1990s by California residents concerned about pollution from petrochemical plants, it has been tested and approved by the US Environmental Protection Agency for participatory air quality monitoring (for example, see Section 6.4). The Bucket Monitor consists of a closed 20 L food storage bucket containing a 5 L Tedlar bag. Air is collected using a battery-powered camping vacuum or bike pump, and the sample is sent for analysis within 24 – 72 hours. Each bucket costs about 75 € (excluding analysis) but requires shorter collection times than passive samplers, making it more effective for detecting spikes of pollution.

4.1.4 Other approaches

Communities can use additional low-cost methods to gather evidence of poor air quality. Bad smell is a common trigger of local actions – as seen in Tarragona (Section 6.1) and Sarroch (Section 6.2). Since odors come from various human activities – not just oil refineries and petrochemical plants – there are already platforms dedicated to participatory mapping of bad smells. **OdourCollect** and Smell My City (available in the US) are two examples of these tools. Developed through the European project D-NOSES, the OdourCollect allows users to log the location, type, intensity, and duration of odors anywhere in the world. D-NOSES has also launched the International Odor Observatory to share knowledge, stories, and best practices on odor pollution.

Beyond reporting smells, citizens can take georeferenced photos of pollution events or share their insights on local industrial activities. When this data is collected onto a map, the process is called **"participatory mapping"**. The participatory mapping of gas flaring activities in the Ecuadorian Amazon is an outstanding case of the power of this cheap approach (Section 6.4.1).

Biomonitoring offers another engaging way to assess air quality while learning about local biodiversity. Biomonitoring requires tracking the occurrence and health of certain organisms that respond to pollution. Certain plant species and lichens are the most often employed to detect bad air. The Citizen Sense initiative developed a "Phyto-sensor toolkit" with resources and guidelines to detect air pollution using plants – for example, numerous species are sensitive to ozone: in the US, there is a whole network of "Ozone Gardens". Likewise, the citizen science project VOCE in Marseille involved citizens in air quality assessments by observing the biodiversity of lichens and the growth and flowering of *Petunia* plants (Section 6).

4.2 Tools for water monitoring

4.2.1 Commercial low-cost kits

Colorimetric kits are the top choice for semi-quantitative and qualitative water testing and are widely used in participatory water monitoring programs (like the Freshwater Watch). They typically cost between 50 – 200 € for 30 to 100 tests and can be purchased from general (like Sigma Aldrich) or specialized suppliers (such as ChemMetrics and SenSafe); they are intuitive and quick to use. The kits work by adding a reagent to the sample (or dipping a test strip embedded with the reagent into the sample). After a short wait, the sample (or strip) color is compared to a chart that shows intervals of concentrations (Figure 8). For some chemicals, kits are available in different concentration ranges, with detection limits that vary but are generally in the part per million (ppm).

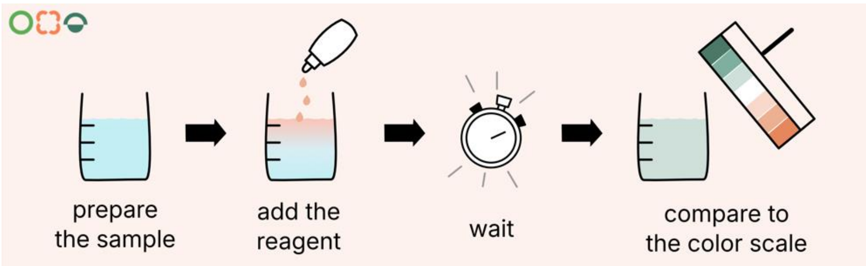


Figure 8 *Working principle of a colorimetric kit that uses liquid reagents.*

Most kits focus on general water quality indicators like pH and soluble metals, including arsenic, chromate, manganese, and lead. A few products are designed for industrial pollutants like H_2S and organics – for example, some ChemMetrics kits detect sulfide and phenols in water. There are also more expensive options specific to petroleum hydrocarbons: the **Modern Water RaPID Assay** and the **Hanby TPH Test Kit**. The former quantifies total BTEX/TPH in water using a magnetic particle immunoassay, providing a result in under 60 min. The second is a more qualitative option that involves extracting the sample with an organic solvent and comparing the extract's color to a color scale. Both kits are also available for soil.

4.2.2 Commercial low-cost sensors

Commercial low-cost sensors measure primarily simple water quality parameters. Among the many, we recommend the **Horiba LAQUAtwin Compact Meters** and the **eXact iDip Photometer**. For only a few hundred euros, Horiba offers pocket-size meters for pH, conductivity, oxidation-reduction potential, and selected ions. Similarly priced, the eXact iDip Photometer quantifies metals and other pollutants – including sulfides and hydrogen cyanide – in addition to general water quality parameters. This device works as a colorimetric kit (Figure 8) but utilizes a photometer to accurately quantify color change – thus concentrations.

4.2.3 Other approaches

Similarly to air, georeferenced **visual inspection** and **photos** are valid low-cost alternatives for participatory water quality monitoring. For example, the Public Lab describes a method to distinguish between natural bacterial films and oil pollution, an approach that can help locate contaminated water. The Good Karma Project (Section 6.1) has also engaged residents to report plastic pellet pollution on an online map. **Biomonitoring** is also viable for aquatic ecosystems – for instance, the French association VOCE organized monitoring activities with the local diving club to assess the impact of Marseille's petrochemical complex on marine biodiversity.

Illustrations by Storyset

5. How to use environmental data to spur a *change*

Citizen science projects on fossil fuel exploitation are often initiated to stimulate *change* – in industrial operations, political regulations, and civil society. Thus, the knowledge acquired in these contexts gains a dimension beyond academic purposes: it can empower citizens, support local communities in legal battles, and help resolve environmental conflicts. This section explains what "*actionable knowledge"* means and offers tips on how to turn citizen science projects into real-world change.

5.1 What is *actionable knowledge*?

Actionable knowledge refers to the insights and information generated through scientific research that create the condition for positive change. It means translating scientific data into information that can be used in public debates, education, and awareness campaigns, thus informing decision-making and empowering citizens.

Unlike academic research, the effectiveness of actionable knowledge depends on a complex interplay of factors. In other words, having professionals collect data in a technically sound way is not enough. For projects to create real change, they must be clearly linked to real-world applications and involve community members and policymakers already at the planning stage. Adopting various funding mechanisms is also crucial for the long-term sustainability of the project and to maintain an active partnership among all actors. Including *all participants* in planning, data collection, and data validation is fundamental to ensure **"knowledge democracy"**: that is, to produce information that is legitimated by diverse members of the civil society, not only knowledge authorities. Involving the local community in collecting data through different methods – *any* data, not only pollutants' concentrations! – is also a form of **"cognitive justice"**, as it gives relevance to knowledge systems that have historically been devalued or ignored (for example, Native Americans').

To be effective, *actionable knowledge* must address the complexity of the problems it seeks to solve, and the variety of data involved. In this context, correctly **dealing with uncertainty** is key. Data uncertainty must be clearly defined and communicated to all actors – some scholars even suggested organizing activities to develop a "sensibility to uncertainty". At least in part, uncertainly must also be embraced. This can be achieved by adopting a **"post-normal" science approach**, where uncertainty is recognized as a defining factor in knowledge related to complex issues such as environment and health. Uncertainty can also be mitigated by adopting some of the strategies outlined in the next section.

5.2 How can one *activate* environmental data?

This section summarizes best practices to maximize the production of *actionable knowledge* in citizen science projects. These practices fall into two categories: **socio-technical** (related to technological improvements and organizational changes) and **socio-political** (focused on social norms, behavior, and politics).

Socio-technical best practices include three key actions (Figure 9, left).

1. Improve **communication and project visibility** by using existing platforms, engaging with traditional and modern media of communication, and organizing face-to-face meetings to foster interactions.
2. **Connect** project results **to policy goals** by involving policymakers in the project's design and aligning the outcomes with policy priorities.

3. Ensure **data accuracy** through training and support from professionals.

Socio-political best practices focus on three main themes (Figure 9, right).

1. Choose the **best way for citizens to participate** – projects with higher citizen involvement are more likely to create *actionable knowledge*.
2. Adopt a **justice-oriented approach** by ensuring all communities have access to the relevant knowledge and aiming to achieve "knowledge democracy".
3. Ensure that **data is socially robust** by including traditional knowledge, ensuring that data is co-produced, and managing uncertainty thoughtfully.

SOCIO-TECHNICAL

1. Enhance visibility and good communication

1.1 Set up an online information portal on citizen science, including a knowledge base on initiatives across Europe, topics covered, tools, and resources.
1.2 Communicate transparently on used methodologies and adhere to good practices.
1.3 Promote availability of citizen science data on existing or new open platforms and ensure that official reporting mechanisms can accept and integrate these data.
1.4 Engage successfully with traditional media (newspaper, TV) as well as science communicators; use social media networks and platforms.
1.5 Organize face-to-face meetings allowing social interaction and rewarding success.

2. Link results and policies priorities

2.1 Target environmental policy frameworks at different scales. Make explicit the relationships between citizen science projects, themes of the Green Deal, and Sustainable Development Goals.
2.2 Increase the awareness of decision makers, in particular local authorities, about the relevance of of citizen science results – for instance, organizing match-maker events to foster exchange and knowledge transfer.

3. Data quality as accurate

3.1 Provide training and resources on data quality management methodologies and standards of good practices.
3.2 Illustrate how data reliability has been achieved, in order to be trusted and to align with environmental regulation and monitoring requirements from governments.

SOCIO-POLITICAL

4. Define the appropriate mode of participation

4.1 Acknowledge the best mode of citizen engagement considering the four levels defined by Haklay (2013): crowdsourcing, distributed intelligence, participatory science, extreme participation.
4.2 Use strongly participatory sciences ('extreme') in environmental controversies to allow polluted communities to have a voice.

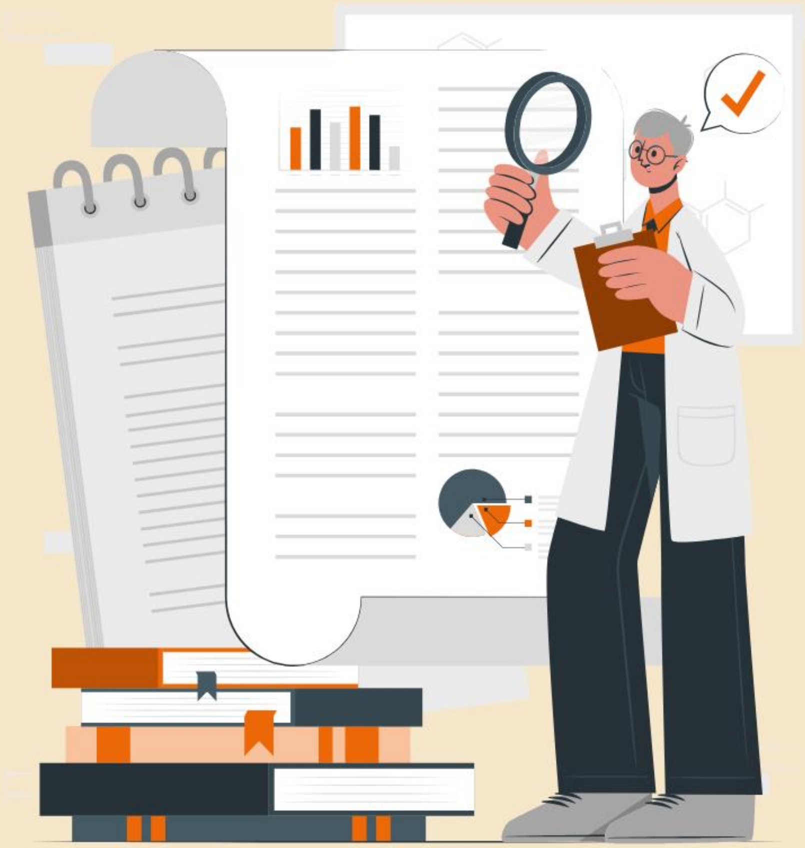
5. Adopt justice-oriented approaches

5.1 Embrace knowledge justice—ensuring that all communities, especially those marginalized or more impacted by environmental issues, have access to relevant scientific and technical knowledge, considering the existence of different knowledge systems.
5.2 Aim at achieving knowledge democracy through validation of public knowledge in the public domain.

6. Data quality as socially robust

6.1 Enhance the legitimacy of data by involving a wider circle of people in the discussion of knowledge (not merely those with institutional accreditation), and forming extended peer communities (e.g., citizen juries, focus groups, consensus reference).
6.2 Co-produce knowledge by including a plurality of legitimate perspectives and inclusive dialogue.
6.3 Adopt credibility-building strategies by implementing different techniques at different stages of the project, prioritizing training, scientific advising, publication, and management use.
6.4 Illustrate that citizens engaged in monitoring have a level of training and experience that allow them to be defined as experts.
6.2 Manage uncertainly by acknowledging the complexity of knowledge co-production and promoting a 'sensibility to uncertainty' through a series of activities, e.g., seminars engaging stakeholders.

Figure 9 *Summary of socio-technical and socio-political practices to maximize the production of actionable knowledge in citizen science projects.*



Illustrations by Storyset

6. Some examples to get inspired, in Europe and beyond

This concluding section describes citizen science projects initiated by communities concerned about the impacts of local fossil fuel exploitation. These initiatives engaged citizens at diverse levels and were all successful in unique ways – while only some led to tangible changes, all helped raise awareness, educate citizens, or provide initial evidence of pollution. These experiences highlighted the importance of including *everyone* – policymakers, community members, and academics – and contextualizing knowledge. Some of the most successful projects relied on simple observations – like reporting unpleasant odors or gas flares – further emphasizing how firsthand knowledge can be as valuable as data from expensive instruments.

Our review identified 8 European citizen science projects on fossil fuel exploitation, targeting primarily refineries and petrochemical plants in Western Europe (Figure 10).

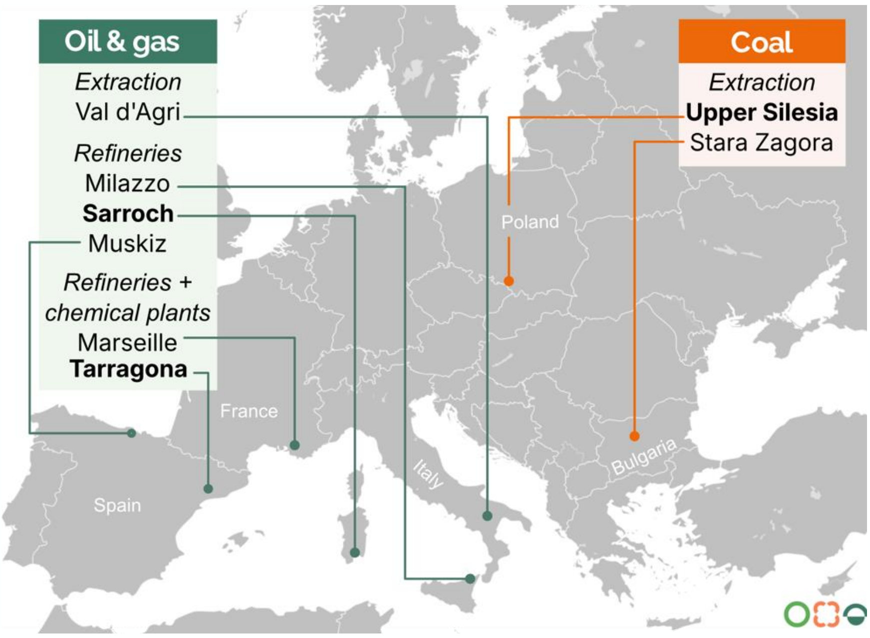


Figure 10 *Locations of European citizen science initiatives on fossil fuel extraction and processing. Projects further described in the text are highlighted in bold; see Section 7 for more information on the other initiatives.*

Below, we discuss in detail only three initiatives: those around the petrochemical complex in Tarragona (Section 6.1); the Saras refinery in Sardinia (Section 6.2); and coal mines in Poland (Section 6.3). Section 6.4 concludes with successful examples outside Europe that we hope will inspire future initiatives on environmental justice.

6.1 The petrochemical complex in Tarragona

6.1.1 The problem

Tarragona, on the northern Mediterranean coast of Spain, is home to the largest petrochemical complex in Southern Europe. Operative since the 1960s, the complex includes about 30 companies and covers over 1’200 hectares. One of the main companies is Repsol, which owns a refinery and several petrochemical plants. Fuels and plastics are the primary goods produced in Tarragona.

Although there have been a few environmental disasters – like the discharge of toxic wastewater into the Francolí River (2008) and the spill of 40’000 tons of naphtha to underground water (2013) –, residents have long complained about the persistent bad smell around the industrial complex. Since a plastic pellet spill in 2018, there has also been growing concern about microplastic pollution along the nearby coastline.

6.1.2 The initiatives

In 2008, residents near the petrochemical complex created Plataforma Cel Net, a citizen-led organization aiming at gathering independent air quality data. With the support of other organizations, in 2014, Plataforma Cel Net commissioned a study to the Universitat Politècnica de Catalunya, which found over 200 NMVOCs in the air around the petrochemical area. Some chemicals – like 1,3-butadiene and ethylene oxide – are concerning because they are carcinogenic but not yet regulated in Europe (Section 3.2).

These findings led to grassroots awareness campaigns like "Something smells bad", "Do you know what you breathe?", and "You breathe it too" organized by Plataforma Cell Net in partnership with GEPEC-EdC, the Study Group for the Protection of the Catalan Ecosystem, and La Canonja3. Enginyeria Sense Fronteres, the Catalan group of Engineers Without Borders, has also organized similar activities. Altogether, these initiatives promoted more data collection, educated the public, and advocated for new regulations. The local University has also conducted further air quality studies to identify the NMVOCs responsible for the bad smell, identify other toxic unregulated chemicals, and pinpoint the companies emitting these compounds.

After a plastic pellet spill in 2018, the non-profit Good Karma Project launched MEDPELLETS, a citizen science initiative that investigates the dynamics of plastic pellet pollution in the western Mediterranean Sea with the support of the local surfing community.

6.1.3 The results

While Plataforma Cel Net and collaborators have been pivotal in raising awareness, their work is far from complete. A partial success came in 2015 with the creation of the Territorial Air Quality Board, which includes citizen platforms, administrations, research centers, and companies and aims to create a new system of control, regulation, prevention, and protection in the petrochemical area. However, since many NMVOCs are not yet regulated, the Board is facing challenges in achieving concrete results.

In 2023, the Catalan Parliament approved a motion to increase the air monitoring points around the petrochemical complex and include 1,3-butadiene to the pollutants to be monitored. Other achievements include the installation of two real-time air monitoring stations in El Morel and benzene leak sensors around the petrochemical complex;

the formation of the Tarragona Air Quality Group, an industry-led initiative to fund air quality studies; and the work of Colectivo Ronda, who took Repsol to court for causing cancer to a worker. The industry has also shown some self-regulation, with 1,3-butadiene emissions dropping by 40 – 80% since 2013. At the time of writing, Plataforma Cel Net is still pushing for regulations on 1,3-butadiene and ethylene oxide, which remain unregulated in Europe (Section 3.2.2).

Concerning microplastics, findings by the Good Karma Project led to more inspections in manufacturing companies, resulting in penalties and the initiation of proceedings for malpractice. In the upcoming waste legislation, the Catalonia Parliament has also included a section on plastic pellet management. If enacted, this would establish Catalonia as a pioneer in Europe in addressing this issue.

6.2 The Sarlux oil refinery

6.2.1 The problem

Active since 1965, Saras S.p.A. operates the Sarlux refinery in Sarroch (Sardinia), one of the largest in Europe. The refinery produces liquified petroleum gas, gasoline, naphtha, diesel, and aviation fuel, mainly for Italy and Spain. Sarlux has a story of environmental disasters and chronic impacts that local associations like Donne Ambiente Sardegna and Sardegna Pulita have been reporting for years. In the early 2000s, optimal socio-political conditions allowed these efforts to shape into a cohesive project.

6.2.2 The initiative

In 2006, the Sarroch municipality partnered with the University of Florence and Cagliari to launch "Sarroch Ambiente e Salute". This initiative was triggered by a 2006 study by the University of Florence that demonstrated an increased incidence of some types of cancer and respiratory illnesses in residents near the Sarlux refinery. Local air pollution was identified as one of the underlying causes of these health conditions. During the first phase of the initiative (2006 – 2008), the partners organized dissemination activities, published guidelines on respiratory illnesses in kids, and carried out two epidemiological studies on children and one on air quality. The municipality also bought a mobile station to measure air pollution around the refinery. Collectively, the studies confirmed an increased incidence of respiratory illnesses in kids and strengthened the link between health issues and high levels of SO_2, PAHs, and heavy metals. The second phase of the project started in 2009 with further epidemiological and air monitoring studies and the creation of a biobank, where biological samples from residents could be stored for future studies. The biobank opened in 2010 and operated until 2016.

6.2.3 The results

During its "gold years" (2006 – 2009), the project achieved several meaningful results. The most notable was the reduction of the SO_2 attention threshold from 500 $\mu g/m^3$ to 100 $\mu g/m^3$ (hourly averages), which was agreed upon in 2008 during a round table with the national authority. During this meeting, the Ministry also cut Sarlux annual SO_2 emissions from 14'000 to 7'000 tons and required the refinery to monitor PM_{10} emissions and install filters. In 2014, the municipality reported SO_2 levels consistently below the legal limits (this result has been achieved each year since 2009) and decreased hospital admissions for respiratory problems – though other illnesses remained above the regional average. Recent reports from Sarlux (2022 – 2024) and the University of Cagliari (2022) confirmed that SO_2 levels are constantly below the threshold set by Italy and the WHO.

While "Sarroch Ambiente e Salute" was crucial in raising environmental awareness at the refinery, it also highlighted how crucial a strong political support is for enabling change. If on one hand the municipality's involvement was pivotal in starting the project, the lack of interest from later administrations undoubtedly contributed to its decline. According to a letter from Donne Ambiente, as of 2021, there have been no further epidemiological studies, and the biobank has disappeared.

6.3 Coal extraction in Poland

6.3.1 The problem

In late July through August 2022, the Oder River in Poland suffered a massive pollution event that resulted in the death of 360 tons of fish and other organisms. Investigations by Polish, German, and EU authorities all pointed to a bloom of the toxic algae *Pyremnesium pavum* as the cause. The proliferation of this organism, which thrives in brackish waters, was caused by an abnormal increase in the salinity of the river water. Though no single pollution source was identified, all investigations agreed the cause was largely anthropogenic.

This event – the worst river disaster in modern European history – brought new attention to the environmental impacts of coal mining in the Upper Salesian region. In this area, coal mines generate extremely salty wastewater – during extraction, groundwater enters the pit and dissolves halides, minerals made of water-soluble salts present with coal (see Section 2.3). In November 2022, Greenpeace Poland carried out an independent study revealing dangerously high salt concentrations in several coal mine wastewater discharges – not only in the Oder but also in the Vistula, Poland's biggest river. While investigating possible reasons for this malpractice, Greenpeace described the questionable behavior of the national government, which renewed permits without requiring Environmental Impact Evaluations. This loophole allowed companies to continue operations as they did before the 1990s, when modern environmental regulations were not in place. While the Polish law has now been aligned with EU directives, mines that renewed their permits during this "favorable" time window still operate as 40 years ago.

6.3.2 The initiative and the expected results

Alongside the activities of Greenpeace Poland, the Polish Angling Association launched #WPŁYWOWI, a citizen science initiative run in collaboration with the bank BNP Paribas, the company Expert Float, and the University of Warsaw. The project aims to continuously monitor the river water conductivity using the "AGUARD float", a fish float that measures temperature and conductivity in real-time. Launched in April 2024, the initiative aims to reach 2,000 people by December 2024 – this is the number of floats made available as part of BNP Paribas' #WPŁYWOWI campaign. So far, the initiative has gained widespread media support, including from the platforms Onet Group and Noizz.pl.

Although the disaster is too recent to have produced *change*, the ongoing initiatives are well poised to "stir the waters" around coal mining practices in Poland. #WPŁYWOWI is contributing to educating locals and raising awareness of water pollution. At the same time, Greenpeace Poland is keeping its attention high on Poland's mining practices by advocating for environmental impact evaluations for all coal mines, the implementation of desalination technologies, the harmonization of legislation, and the creation of a national park along the Southern Oder River.

6.4 Virtuous examples outside Europe

This last section describes two examples of "extreme" citizen science initiatives related to the fossil fuel industries outside Europe: one in Ecuador (Section 6.4.1) and one in Myanmar (Section 6.4.2). Other noticeable examples include the work of the "Louisiana Bucket Brigade", a non-profit that used the "Bucket Monitor" (Section 4.1.3) to advocate for residents of the "Cancer Alley" in Louisiana; and "Citizen Sense", a UK-based academic initiative helping communities around the world to monitor environmental health – for example, they developed the Frackbox (Section 4.1.2) for residents near a fracking plant in Pennsylvania. Beyond the United States, we mention the "Media Awareness and Justice Initiative" in Nigeria, which has played a key role in promoting environmental justice in the Niger Delta, one of the world's most oil-polluted areas.

6.4.1 Banning gas flaring in Ecuador

In 1989, UNESCO established the Yasuní Biosphere Reserve to protect the unique biodiversity and cultural heritage of the Ecuadorian Amazon. Unfortunately, parts of the reserve overlap with oil and gas fields that have been exploited since the 1970s. Chevron-Texaco has been the main company operating in the area, causing serious environmental degradation with its extraction activities. Despite the company has already been sued and found guilty, Chevron-Texaco's extraction practices – gas flaring in particular – are still raising concerns for their significant environmental impacts.

The citizen science project A.M.A.Z.O.N.Y.A. – "Mapping gas flaring from below" – was launched in response to two independent triggers: local grassroots movements and academics. In 2020, researchers from the University of Padova (Italy) used satellite data to identify gas flares active between 2010 and 2017 in the Ecuadorian Amazon. This work revealed active sites also in the Yasuní Reserve and provided evidence of 34 new sites, of which 12 were in the Tiputini field, a protected area. Building on these findings, A.M.A.Z.O.N.Y.A. involved local indigenous and farmer communities in a participatory ground-mapping exercise. This project had several objectives, including the validation of satellite data, the identification of new flaring sites, and the generation of independent open information that the community could use to promote environmental justice. A.M.A.Z.O.N.Y.A. identified 295 previously unmapped flaring sites, some of which were in the integral protection area of the Reserve. The community further provided evidence of unreported gas *venting* and other environmental impacts, like harm to insects and soil. Beyond the University of Padova, A.M.A.Z.O.N.Y.A. involved the "Unión de Afectados y Afectadas por las Operaciones Petroleras de Texaco" and the "Fundación Alejandro Labaka", a non-profit dedicated to research, cultural promotion, and support for Indigenous communities in the northern Amazon.

In February 2020, these results triggered the campaign "¡Apaguen Los Mecheros!", which involved a legal action presented to the Court of Nueva Loja to stop gas flaring in Ecuador. Although initially rejected, an appeal in January 2021 succeeded, giving companies 18 months to close all gas flaring sites near populated areas and until 2030 to end all flaring. Despite the legal success, as of 2024, Ecuador is still struggling to get the sentence enforced.

6.4.2 Improving coal mining practices in Myanmar

In 2011, after discovering coal deposits in the Ban Chaung area, the Myanmar government granted East Star Company a 25-year license to extract coal. By 2015, residents started noticing smoldering in a large waste pile at the extraction site. Beyond combustion-related pollution, this phenomenon caused residents serious distress due to the associated risk of wildfires. Following repeated reports, in 2017 the government ordered East Star Company to improve its waste management practices. The company responded by covering the waste pile with a one-meter layer of soil and banana leaves, which started eroding shortly after. During the following year, local volunteers reported 47 incidents of smoldering or combustion, highlighting the ineffectiveness of the company's remediation action.

In early 2019, a scientist from Naresuan University (Thailand) teamed up with local volunteers to involve the community in risk management decisions. The resulting citizen science project started in the summer of 2019 with two field surveys that gathered ground-based evidence of smoldering using thermal and visual cameras. The team also used portable devices to detect gases associated with coal burning, including VOCs, SO_2, H_2S, and carbon monoxide. Chemical analyses of water and soil samples confirmed contamination from acid mine drainage – with water having a pH of 2.3 – 3.1 (Section 3.2.2). Finally, they analyzed photos and reports of past incidents, results of independent sampling, and health assessments that the local population gathered between 2015 and 2019.

After collecting data, the researcher trained residents on state-of-the-art coal waste management and guided the discussion. Although locals preferred grouting and fire suppression followed by off-site disposal, they were also open to surface sealing – the company's choice – if a long-term monitoring system was implemented. This community-informed input was intended to be forwarded to the local government to evaluate East Star Company's corrective actions.

Illustrations by Storyset

7. Selected references and further readings

Section 2

This section draws from educational material from the Italian Hydrocarbons Authority ("Conosciamo il gas e il petrolio"), the Smithsonian National Museum of Natural History ("What are fossil fuels?"), and the Union of Concerned Scientists ("How coal works"); the book *Petroleum formation and occurrence* (Tissot and Welte, Springer, 1987); the publication "Petrolio e biodiversità in Val d'Agri" by A. Diantini (2016); and the EMEP/EEA Air Pollutant Emission Inventory Guidebook (2023). Information on gas flaring (Box 1) is from Facchinelli et al. (2020), the Earthworks' website, and the World Bank's website.

Section 3

Section 3.1 is based on the EMEP/EEA Air Pollutant Emission Inventory Guidebook (2023), specifically on parts 1.B.1.a, 1.B.2.a.i, 1.B.2.b, 1.B.2.c, and 2.B. For more details on the natural radioactivity of produced waters see the USGS Fact Sheet FS-142-99 (1999) and Hosseini et al. (2012). The information in Boxes 2 and 3 was primarily from *TPH Risk Evaluation at Petroleum-Contaminated Sites* (Chapter 4, 2018) and from a manufacturer's manual.

Air quality guidelines are from the WHO Global Air Quality Guidelines (2021) and the Air Quality Guidelines for Europe (2nd Edition, 2000). Reference values from total VOCs were from the German Federal Environmental Agency (300 µg/m^3; value for indoor air) and the EU Industrial Emission Directive (Directive 2010/75/EU) (2'000 µg/m^3). Water quality guidelines are from the Guidelines on Recreational Water Quality, Volume 1: Coastal and Fresh Waters (2021). Other useful documents not discussed in the booklet are the Guidelines for Drinking Water Quality (4th Edition, 2022) and the Guidelines for Drinking Water Quality: Small Water Supplies (2024).

Environmental quality standards are from the most recent EU Air Quality Directive (Directive 2008/50/EC) and the Environmental Quality Standards Directive (Directive 2013/39/EU). Other relevant legislation that we do not discuss include the EU Industrial Emission Directive, the Drinking Water Directive, the Water Framework Directive, and the Groundwater Directive. For compounds not regulated in the EU, we refer the reader to the American Environmental Protection Agency (e.g., for air), the Canadian Council of Ministers of the Environment, or agencies of individual states.

For further information, see our background review on existing tools and technologies for environmental monitoring.

Section 4

When not provided directly in the text, information and technical details on selected instruments are in our background review on existing tools and technologies for environmental monitoring.

The Aeroqual S500 sensors data in Figure 5 are from the manufacturer's website. Detection limits (DL) in ppm were converted to µg/m^3 with the formula DL [µg/m^3] = DL [ppm] * MW [g/mol] * 1000 / 24.45, where MW is the molecular weight. For total VOCs, we used MW = 100 g/mol, which is an estimated average value.

The Radiello data in Figure 7 were provided by the manufacturer. Detection limits are 0.05 – 0.1 µg/m^3 for benzene, toluene, ethylbenzene, and xylenes (BTEX; 7-day exposure); 0.3 µg/m^3 for 1,3-butadiene (8-hour indoor exposure); 1 ppb (= 1.4 µg/m3) for H_2S (1-day exposure); 1 ppb (= 2.6 µg/m^3) for SO_2 (7-day exposure); and 1 ppb (= 1.9 µg/m^3) for NO_2 (7-day exposure). Data for Aeroqual S500 are from Figure 5.

Section 5

The socio-political best practices of Figure 9 were derived mainly from Marres (2018) (the concept of "knowledge democracy"), Visvanathan (2005) (the concept of "cognitive justice"), and Functowicz and Ravetz (1993, 2003; the "post-normal science" framework). Other relevant authors are Barbara Allen, promoter of the citizen science project in Marseille (Section 6) and author of books and articles on citizen science for environmental justice (e.g., Allen, 2003; Allen, 2017; Allen, 2018), and Leona F. Davis, who analyzed citizen science projects that produced a societal change (Davis and Ramìrez-Andreotta, 2021). The complete list of references is in our background review on best practices for actionable data.

Socio-technical best practices were summarized from the document Best Practices in Citizen Science for Environmental Monitoring (European Commission, 2020) and two academic publications: Turbè et al. (2019) and Hecker et al. (2018).

Section 6

For more information on the citizen science initiatives in Figure 10, see COVA Contro's website and Diantini (2016) for Val d'Agri; Coordinadora Anticoke's website for Muskiz; Jeanjean et al. (2023), VOCE's website, and the EPSEAL-FOS's website for Marseille. For detailed information for all other initiatives mentioned in Figure 10 and Section 6 see our background review on citizen science for environmental monitoring.

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