Power plant waste and emissions

Definitions and distinctions

What is waste?

Waste or waste materials are generally understood as solid remains that are freely transportable substances or things that accumulate in private households, in industrial and public processes, or in the service industry. This also includes chemical and radioactive residues in solid form. According to the legal definition, waste also includes solid or liquid substances as long as they are in rigid containers. Circulation and waste management laws make a distinction between “waste for recycling” and “waste for disposal” that is either incinerated to generate power or heat or stored in landfills.
In any case, the producer and/or holder of the waste is obligated to ensure lawful disposal or recycling according to defined waste categories. Substances that are not listed as waste in the corresponding laws, implementation provisions, or regulations are not legally waste but rather a commodity. A general principle of modern legislation is “avoidance is better than recycling, and recycling is better than disposal.”

What are emissions?

The term “emission” is derived from Latin (“emittere”) and means “to discharge, send out.” In the context of energy, emissions are differentiated according to physical and technical aspects.

Emissions in the physical sense:

- Light emission from illuminated bodies
- Emission of other electromagnetic radiation (for example, x-rays, gamma rays)
- Emission of individual particles (for example, alpha and beta particles, neutrons) during radioactive decay and other nuclear processes
- Emission of electrons:
  Thermionic emission from metals and oxides due to high temperature (applied in electron tubes and cathode ray tubes of television receivers) and photoemission (light) in photocells (applied in photovoltaics)

Emissions in the technological sense:
This category includes the emission of solid particles (for example, dust) as well as liquid and gaseous substances that end up in the environment – that is, in the atmosphere, bodies of water, or soil – due to industrial plants or technological processes. These emissions change the natural composition of the atmosphere, the bodies of water, or the soil and usually lead to contamination that can disrupt the ecological balance.
Emissions from incineration plants (like power plants) and combustion engines (like motor vehicles) for solid, liquid, and gaseous fuels primarily include the combustion products sulfur oxides SO_x, nitric oxides NO_x, and carbon oxides CO_x as well as the solid particulate emissions ash, soot, fly ash, and particulate matter.
These technical emissions, released primarily in flue and exhaust gases, are usually indicated in ppm, g/m³, or mg/m³. The permissible limits are also specified in these units of measurement. Furthermore, “energy emissions” can be detected in both the technical and physical areas, including noise, vibrations, and heat radiation. A term exists for electromagnetic radiation in the low-energy

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range, “electrosmog,” which mostly refers to environmental pollution due to magnetic fields from radio and modern communications technology.
In principle, each type of emission pertains to a specific source.

How does a substance become a pollutant?
Substances that can potentially damage people and the environment due to their chemical or physical effects are often technologically indispensable. They do not become a pollutant until they are released in an uncontrolled manner and cause disruptions in Earth’s ecological balance or adversely affect people’s health. For instance, nitric acids in the reactor of a chemical factory or ammonia in the boiler feed water of a steam generator are undeniably dangerous substances, but not pollutants. They are not pollutants until they end up in the air we breathe due to leaks in the system. By contrast, carbon dioxide is inherently a harmless substance, but because of the accumulation in the atmosphere, it promotes the greenhouse effect and is therefore now classified as a pollutant.

Solid, liquid, and gaseous is insufficient information for classification!
At first glance, the state of aggregation seems to play a role in the legal classification of waste and emissions. Governments consider more than just the consistency of the waste substances and emissions. Although “waste” is defined as “solid substances,” it also includes “liquids in containers.” However, if the solid “dust” is part of exhaust air or exhaust gas, like gaseous substances it is defined as emissions in the legislation for “air” (in Germany, “Technical Instructions on Air Quality Control”). If the dust is filtered out of the flue gases, it is subject to waste legislation as a solid. If the inherently solid components of the dust are dissolved in water during flue gas scrubbing, waste water legislation applies. The cooling water polluted with heat is partly handled like waste water, and additional legal regulations apply to some extent.

Waste and emissions in power generation

In this document we will limit ourselves to the emissions and waste that accumulate directly as combustion products during the power generation process in power plants. For an overall ecological and energy balance, coal mining, oil and gas extraction, and uranium mining and processing, for example, would also have to be taken into consideration.

Solid waste products of power generation

Ash
When wood, lignite, coal, coke, bitumen, and heavy oil are burned, only the organic components of these fuels combust. Therefore, the residues in the form of ash mainly consist of the inorganic parts of the respective fuel used, the minerals. These are primarily the oxides and carbonates of various metals such as aluminum, calcium, iron, magnesium, manganese, phosphorous, potassium, silicon, or sodium (for example, Al_2O_3, CaO, Fe_2O_3, MgO, MnO, P_2O_5, K_2O, SiO_2, Na_2CO_3, and $NaHCO_3$), which can be partially processed into fertilizers. Ash from biomass power plants can be used, for example, as potassium and phosphate fertilizers in agriculture and forestry without being treated.
If the combustion temperatures are between approx. 900°C and 1,200°C (ash softening point), the ash becomes viscous, soft, or dough-like. When this viscous ash cools, it forms a porous yet solid mass that is sometimes further processed as “vitrified” slag.

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Slag

Slag is the vitrified portion of mineral combustion residues. It isn't inherently a pollutant, but it may contain pollutants, like heavy metals. If the slag is water-insoluble, for example, as a result of complete vitrification, pollutants may be embedded in it. Slag was previously used directly for road construction or disposed of. Today, many countries have legal provisions regulating the processing and use of slag. For example, if the slag is used as a raw material for cement production under the defined conditions, the resulting end product is environmentally neutral.

Radioactive substances

The treatment of radioactive waste is prescribed separately and in detail in specific laws according to which the producer of radioactive waste products must ensure that they are recycled harmlessly or disposed of in a controlled manner as radioactive waste. Radioactive waste is divided internationally into three categories, depending on the level of heat it generates: low-, intermediate-, and high-level radioactive waste.

Roughly 90 percent of radioactive waste is low- and intermediate-level radioactive substances like auxiliary and operating supplies (such as filters) as well as cladding and structural materials (such as ^{90}Zr, ^{60}Co). High-level radioactive fission products and spent fuel elements that generate high levels of heat make up approximately 10 percent of radioactive waste.

Typical fuel rods like those used as "fuel" in nuclear power plants contain approximately 96 percent uranium 238 (^{238}U) and approximately 4 percent enriched fissionable uranium 235 (^{235}U). During nuclear fission, ^{235}U is used and converted into various fission products. A small portion of the ^{238}U absorbs a neutron and is converted to plutonium 239, which is fissionable like ^{235}U and likewise yields energy. After about three to five years, when the proportion of fissionable ^{235}U has "burned off" to approximately 1 percent, the fuel rods must be replaced with new ones.

Spent fuel rods still contain about 94 percent ^{238}U, less than 1 percent of still fissionable ^{235}U, and less than 1 percent of fissionable plutonium 239. The remaining approximately 4 percent is a mixture of highly radioactive fission products – the most common are isotopes of iodine, cesium, strontium, xenon, and barium – as well as transuranium elements such as neptunium, americium, and californium, which formed when the atomic nuclei of uranium and plutonium captured neutrons without undergoing nuclear fission. The fuel rods are initially stored for a few years in the cooling ponds of the nuclear power plant for reduction of the quick-decaying isotopes. The half-lives of some of the contained radioactive substances are in the range of seconds, minutes, days, or a few years. Other half-lives last many thousands of years, which necessitates safe final storage for an extremely long time. For this reason, the fuel elements are transported to an interim storage facility or to a reprocessing plant in special "CASTOR" (cask for storage and transport of radioactive material) containment vessels. The highly radioactive fission products are chemically dissolved out of the spent nuclear fuel, melted with highly chemically stable glass, poured into stainless steel containers, and transported back in CASTOR containers for subsequent final storage. In one year, a 1,000 MW nuclear power plant generates 3.5 to 4 m³ of solidified, highly radioactive waste for final storage. The uranium recovered during reprocessing is re-enriched to approximately 4 percent ^{235}U and used to produce new fuel elements, and thus it's reintroduced into the nuclear fuel cycle. The separated plutonium is reprocessed together with depleted uranium into uranium-plutonium mixed oxide fuel (MOX fuel). However, due to the dangerous radioactive "waste materials" that get separated, the reprocessing of spent fuel rods is extremely complicated and risky, and also very expensive. Reprocessing is therefore no longer carried out in the United States and Germany (since 2005).

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For low- and intermediate-level radioactive waste with low heat generation, many countries – such as France, the United Kingdom, Spain, Czechia, and the United States – have used near-surface disposal facilities (up to 100 m below the surface) until now.
However, according to current safety standards, they are not considered safe as final storage facilities. In Germany, three “repositories” exist for low- and intermediate-level radioactive waste: Morsleben, Asse, and Konrad. In the 1980s, flooding and collapses occurred at the former salt mine in Morsleben. As a result, work to rehabilitate this repository has been ongoing since 1998, costing several billion euros. The same applies to the former Asse salt mine, where 126,000 barrels with radioactive waste were stored. The barrels are now rusting through, and the ingress of water into the mine has resulted in a radioactive brine that is threatening to penetrate near-surface layers of soil and groundwater. For this reason, the Asse repository must be rehabilitated at a huge expense, originally estimated in 2008 to be 2 billion euros, but by 2016 it had increased to over 10 billion euros. In 2002, the former Konrad ore mine near Salzgitter was licensed as a repository at 800 to 1,300 m deep and the license was reapproved one final time in 2006. The repository is now being converted as approved in the license. It had been expected to be ready for the final storage of radioactive waste starting in 2013. However, according to information from the German Federal Office for Radiation Protection, the official opening has now been postponed until approximately 2022 due to necessary rehabilitation work.
To date, none of the 31 countries using nuclear energy has a completed repository for high-level radioactive waste, although corresponding planning has been ongoing for decades; a repository is in the approval process in the United States, and a location has been designated in Finland. In Germany, the final storage of high-level radioactive waste has been planned and undertaken in Gorleben since 1977. However, for reasons similar to those for Asse, this former salt mine appears to be ill suited and a search is now being conducted for a new repository location. It is expected that a location will be found by 2030 – at the latest, by 2050.
So what is the specific problem of radioactive waste from nuclear power plants? Compared with the radioactivity of the natural uranium originally used in the fuel rods, the spent fuel rods contain several thousand times the radioactivity, in terms of both the amount and the number of isotopes. The proponents of nuclear power point out that according to state-of-the-art technology, safe final storage in the long term is possible. However, the problem is the high costs, which are estimated to exceed 100 billion euros by 2100 for German nuclear waste alone.

Emissions from power generation

Sulfur oxides (SO_x)

Nearly all living beings contain sulfur-containing amino acids. Their conversion products lignite, coal, coke, oil, and natural gas therefore inherently contain greater amounts of sulfur compounds. When they are burned, primarily sulfur dioxide (SO_2) and sulfur trioxide (SO_3) develop. These compounds react with water to form acid (“acid rain”), which caused large areas of forests to die off in the low mountain ranges of Central Europe and other locations in the 1970s and 80s. Sulfur dioxide is also harmful to the human bronchial system. Thanks to stricter legal regulations and new technologies, today natural gas is desulfurized to 10 mg/m^3 and heating oil, diesel, and gasoline are desulfurized to 10 mg/l or less. Power plants that burn coal or worse types of heating oil now operate with highly efficient flue-gas desulfurization. This process neutralizes the sulfur oxides using lime, resulting in gypsum (calcium sulfate $CaSO_4$), a substance that is used in construction. A modern power plant technology is coal gasification, a process in which potential pollutants like sulfur and heavy metals are removed before combustion.

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Nitric oxides (NO_x)

The majority of the nitric oxides in flue gases and exhaust gases comes from combustion with air (nitrogen/oxygen mixture). If combustion were to take place with pure oxygen, nitric oxides would not form, but that process would generally be too expensive. To some extent there is also nitrogen contained in the fuel that can react to form nitric oxide during combustion. The reaction is highly temperature-dependent and hinders higher combustion efficiencies. Nitric oxides also react with water to form acid. Major economic and ecological damage is caused by the overfertilization of forests by rain containing nitric oxide, which results in growth disorders in many trees. In interaction with ozone caused by exposure to UV light from the sun and hydrocarbons, nitric oxides also form a number of smog substances that irritate peoples' respiratory and circulatory systems. For this reason, the legal limits for nitric oxides have since been reduced in Germany, the EU, and the United States. Optimized process control and catalysts for converting nitric oxides to nitrogen now ensure that exhaust gases from power plants contain less than 40 mg/m^3.

In automobile exhaust gases, especially from diesel vehicles, the emission of NO_X is a major problem and under normal driving conditions, catalytic converters currently cannot completely remove NO_X. While nearly complete catalytic purification of vehicle exhaust gases to remove NO_X is possible, it's extremely complex and expensive. The latest findings show that high proportions (up to 50 percent) of N_XO_y originate from nitrogen-based fertilization in agriculture. (A significant proportion of the nitrogen in the fertilizer breaks down into N_20, a greenhouse gas that is 310 times more potent than CO_2 and is released into the air.)

Dusts

Unburned carbon (soot) is still a problem with diesel engines, but it is negligible with optimum process control in modern combustion power plants. To a certain extent, metal oxides and salts (especially chlorides) are always contained in exhaust gas from combustion plants as particulate matter. After it became apparent that particulate matter is harmful to health, similar to asbestos, many countries also reduced the limits for particulate matter. Modern power plants achieve exhaust gas levels far below 20 mg/m3 with cyclones (centrifugal separators), electrostatic precipitation, and wet scrubbing. In gas power plants, exhaust gas levels are considerably lower, even without additional precipitation.

Carbon monoxide (CO_x)

Since ultimately carbon is burned in all combustion power plants, carbon dioxide (CO_2) is also constantly formed. Conventional power generation based on fossil fuel is currently the main source of CO_2 greenhouse gases at 42 percent.

CO_2 emissions in grams per generated kWh: lignite ≈ 950 g/kWh; coal ≈ 750 g/kWh;
oil ≈ 720 g/kWh; natural gas ≈ 540 g/kWh; natural gas combined cycle ≈ 350 g/kWh.

Since these concentrations of CO_2 are not toxic or burdensome to plants, animals, or people, CO_2 emissions were not initially recognized as a problem. However, more than 150 years of global industrialization have led to a stark increase in the global economy's energy requirement and, accordingly, the CO_2 emissions from the combustion of fossil fuels. As a result, today's increase in the CO_2 content (as a greenhouse gas) of the atmosphere has led to an increase in the temperature on Earth. Population growth has caused additional strains, with increased CO_2 emissions just from cooking and heating. The increasing deforestation of primeval forests to obtain firewood (in Europe) or to cultivate plants for animal feed or energy in Asia and South America has drastically increased CO_2 emissions. In addition, food production (including rice cultivation and cattle farming) is generating increasing amounts of the greenhouse gas methane (CH_4). The burning of fewer fossil fuels is therefore not just a matter of conserving resources, but also of mitigating the green-

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house effect. Modern technology helps boost the efficiency of combustion power plants and optimize the use of renewable energy sources.

Water

Water (H_2O) is inevitably released during the combustion of hydrocarbons (oil, natural gas) (for example, $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$). To a certain extent, it can influence the microclimate around a power plant, but it is assumed that the water only negligibly pollutes the environment. Increased cloud formation may lead to local climate fluctuations, but ultimately the water in the atmosphere is precipitated very quickly as rain or snow, meaning that there is no long-lasting accumulation in the air. We can observe this fact based on the increasing cases of torrential rain and flooding worldwide. It is true that global warming leads to increased evaporation of (sea) water and cloud formation. However, global warming also causes increased precipitation in some regions of the globe while deserts are expanding in other locations.

Radioactive emissions

In a boiling water reactor, the gases dissolved in the reactor water and highly volatile substances flow together with the steam through the turbine and into the condensers. From there they are fed to an off-gas treatment system, where the gases are routed through a delay line, an activated carbon delay system, and an absolute filter before they are released through the off-gas stack together with internal air. Most of the radioactivity decays within the delay routes, for example, ^{133}xenon (half-life 5.3 days) decays to 0.1 percent of the original activity after a delay time of 40 to 60 days. For pressurized and boiling water reactors, radioactive gases can also find their way into the ambient air of the reactor building through irradiation of the air in the annulus surrounding the reactor pressure vessel and through leaks in the piping systems. The ambient air is also released to the environs in a controlled manner via the off-gas treatment system. Waste water from nuclear power plants is collected in large containment pools, the activity of individual nuclides is determined, and the waste water is released in a controlled manner if it complies with the limits. The actual emissions of German nuclear power plants (NPPs) are consistently far below the values set by government authorities. A dense network of measuring stations monitors the area surrounding every nuclear power plant. However, there are critical voices that attribute an observed increased risk of leukemia for children in the vicinity of NPPs to power plant emissions (see the keyword “radiation”).

Radiation

On the outside of a nuclear power plant, virtually no amount of direct radiation (alpha, beta, and gamma radiation) can be measured due to the short range and the strong shielding. The situation is different for the transport of spent fuel elements in CASTOR containers, which is why specific safety precautions have been established for them. It should be kept in mind, though, that the real hazard is not the radiation measured at a particular distance because neither a Geiger counter nor the human body detects anything a few centimeters away from an alpha-radiating dust particle. However, if the dust particle enters the body through the lungs or dissolves in drinking water, a range of 2 cm is too close. Over the years, this absorbed radiation can definitely cause cancer.

Heat

Using the heat generated in the combustion process to the best possible extent is essential to the efficiency of power plants. In many types of power plants, steam is used as a heat transfer medium. Only conventional steam engines (for example, steam locomotives) simply release the unused exhaust steam into the environment. By contrast, there are benefits to condensing the exhaust steam and feeding it back into the boiler. In steam turbines, the condensation generates negative

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pressure at the exit, which additionally increases efficiency. The boiler feed water must be relatively pure and contain very specific additives to prevent calcification and corrosion. Thus it would be extremely inefficient to forgo condensing the steam and feeding it into the closed cycle. (In nuclear reactors, the primary water circuit must be completely closed for safety reasons alone.) Thermal power plants generally work with cooling towers and a secondary cooling water circuit, using river water in most cases. This causes significant amounts of river water to evaporate and leads to an increase in the temperature of the river. In regions where water is not available for cooling, power plants today are cooled purely with air. However, air cooling is considerably more expensive than water cooling and is therefore seldom implemented. Given that traditional thermal power plants lose up to 65 percent of their primary energy as waste heat, large-scale thermal power plants thus represent a significant burden to the environment. In Germany, for instance, the Isar 2 nuclear power plant requires 42,000 l/s of cooling water; the Biblis B nuclear power plant, which has since been shut down, removed 210,000 m^3/h from the Main River.
The use of modern technologies, like combined cycle power plants that integrate the use of waste heat as district heating, is therefore vital in terms of both efficiency and ecology.

Noise
Large-scale power plants generally do not cause problems with noise emissions due to the massive construction and the distance from residential areas. In small-scale power plants and block-unit heating power plants, the noise emissions greatly depend on the structural design, as is also the case with biogas plants that rely on large diesel engines to convert gas directly to electricity. In wind power plants, the extent to which the noise emission is a burden depends on the distance from residential areas.

Odors
Until the 1990s, poorly filtered lignite-fired power plants in Central Europe (for example, former German Democratic Republic, Czechoslovakia, and Poland) generated clouds of stench reaching a distance of up to 100 km depending on the weather conditions. In the EU today, relatively strict exhaust gas treatment requirements have worked effectively so that large-scale plants normally do not cause odor pollution. Smaller biogas and wood chip plants that rely on older technology currently have a bad reputation.

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