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Natural Resources: Applied Basic Research

Recycling, a Challenge for the Circular Economy

Coordinated by
Michel Cathelineau

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Introduction

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I.1. Sustainable management and the circular economy

The circular economy aims to increase resource consumption efficiency, reduce environmental impact and therefore reduce resource waste and the ecological impact of the materials cycle. The role of the latter in the economy had already been considered, but it emerged as a concept around 2000 and has since been widely spread in Europe by the McArthur Foundation. It relies on the sustainable production of goods and services by limiting consumption, reducing resource waste and waste generation. This perspective contrasts a linear economy, in which resources are used, consumed in the form of goods, and then disposed of in the form of waste after use. In France, the French Agency for Ecological Transition (*l'Agence de l'Environnement et de la Maîtrise de l'Energie*, ADEME) supports the initiatives aimed at improving the circular economy and keeps up-to-date statistics concerning waste destination. The cycles of materials are complex and involve many players including manufacturers, private persons or communities, within a developing legal context and according to the economic requirements governing our societies. This effective approach is complex but compelling in light of this integrated perspective involving many interactions (Figure I.1).

The circular economy relies on:

1) supply and the economic players interested in the sustainable procurement of renewable or non-renewable resources, the eco-design of goods and services, the development of industrial and territorial ecology, and implementation of the functionality economy (using services rather than owning goods, e.g. renting

electric vehicle batteries instead of purchasing them, for better management of collection and recycling);

2) consumption (demand and behavior), which covers responsible purchasing, proper use of products, reuse and repair;

3) waste management, though waste must be reduced as much as possible, the objective being responsible consumption that promotes recycling and, if needed, energy recovery.

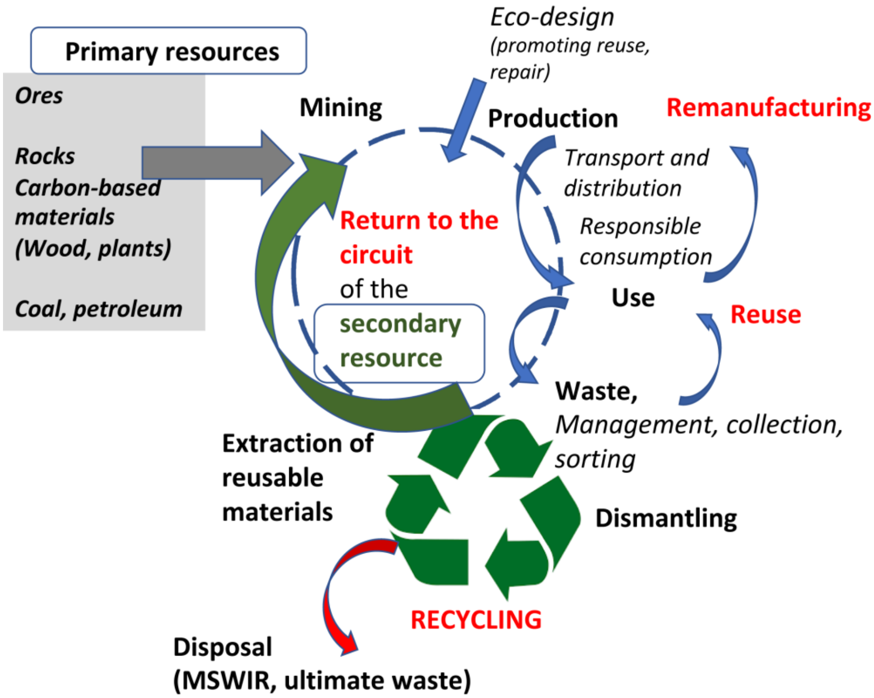

Figure I.1. *Principle of the circular economy. For a color version of this figure, see www.iste.co.uk/cathelineau/recycling.zip*

In France, the recycling industry is represented by around 4,800 companies involved in the recovery of waste composed of ferrous and non-ferrous materials, plastic, paper and cardboard, textiles and glass materials. This book focuses on the challenges in the industry of recycling non-ferrous materials – used in high-tech and thus play a strategic role in a country's activity – like cardboard, plastic materials and building materials, to reduce the environmental impact of our activities and manage our resources sustainably.

Recycling is backed by the principle of sustainable development, according to which today's waste is not mere resources but reserves that can technically and economically be used in the future. For this reason, everything mined from natural resources to meet human needs must, from now on, enter the circle of the circular economy and never leave it. This goal must guide the development of new materials and technologies. In general, the materials and technologies upon which our societies heavily depend were originally created with different goals in mind. Adapting them to align with the principles mentioned above presents various technological challenges, which can be tackled through the development of specialized recycling technologies. Indeed, irrespective of the industry in which they are employed, the complexity of the materials designed and manufactured seems to be inexorably increasing, in correlation with increasingly advanced functionalities. Unfortunately, the complexity of functional materials seems directly correlated with difficulties in terms of feasibility and effectiveness of the various recycling stages. This complexity can be interpreted as an "energy (and economic) barrier" justifying or not the implementation of complex processes for the treatment of materials to be recycled. For example, because the demand for rare earths dropped, while fluorescent bulbs were replaced, and Chinese exports of rare earths returned to normal, Solvay group ended its production of rare earths from used low-energy lamps.

The economic model of our Western societies is probably the most important obstacle to implementing the circular economy. Companies are, in fact, expected to maintain profitability, as required by their shareholders. The latter are essential in implementing services or goods manufacturing, as they provide the initial funds (startup capital). Implementing a new plant for manufacturing semiconductors or batteries (gigafactories under construction in Europe for manufacturing batteries are, in certain cases, backed by recycling plants) requires startup capital of several billion euros. But running such activities implies maintaining economic equilibrium and growth. Considering the high cost of local production (labor costs, financial impact of social and environmental standards), companies opted for large-scale delocalization. The cost of purchased raw materials could be reduced by choosing to source from the best suppliers in the global market. Such a choice has short-term financial advantages, but also long-term fundamental drawbacks. This led to losses spanning from know-how to the entire value chain, and also to the delocalization of mining operations, then of metallurgy and finally of finite objects manufacturing. These developments particularly concern the sectors of permanent magnets and semiconductors. The greatest beneficiaries are Asian countries, particularly China. Finally, collection, local recycling limiting the energy cost of waste transportation, is not included in the economic model of the recycling industry, as it is not economically viable. The costs are thus partly borne by territorial populations and communities.

I.2. Various categories of recycled materials

The main substances can be classified depending on the nature of the source materials. Figure I.2 can be used to identify most primary sources of materials, their use and their potential destination in recycling.

Chapters of this book are dedicated to these various substances: metals, materials resulting from the use of sands and gravels and sedimentary rocks (glass (silicon oxide obtained from quartz), cement (derived from clay-limestone sediments), organic products and their carbon-based derivatives): organic materials (wood, agricultural products, household waste, cardboard and paper resulting from animal and plant fibers) and products resulting from the use of fossil carbon-based materials (derivatives such as plastic materials and also hydrocarbon molecules including plastic materials mainly resulting from petro-chemistry).

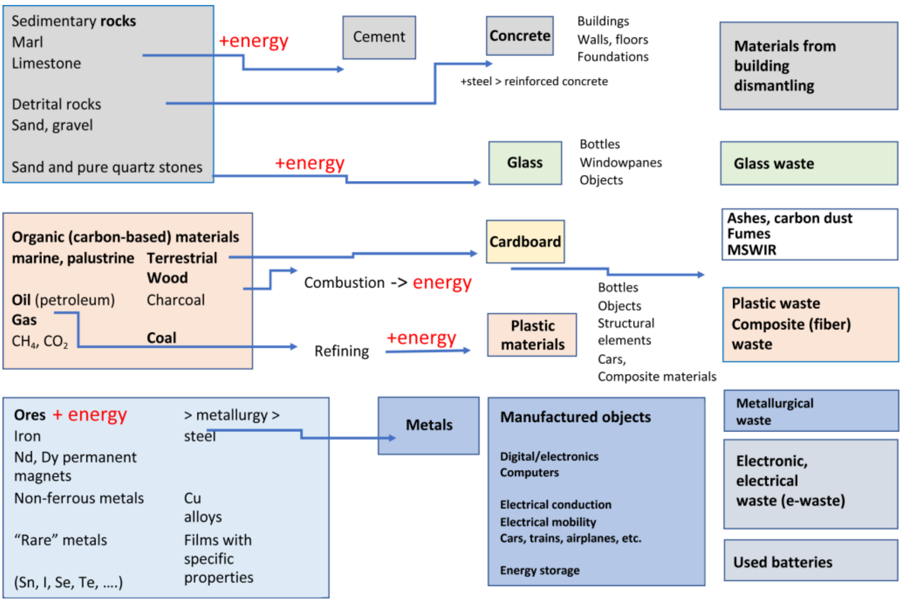

Figure I.2. *Natural raw materials, use and associated waste to be recycled.*
For a color version of this figure, see www.iste.co.uk/cathelineau/recycling.zip

I.3. Current and future challenges for society

Addressing the problem of municipal and industrial waste is one of the most urgent environmental problems of our times, second to reducing greenhouse gases, as part of the management of energy sources.

In France, the transition to the circular economy is officially acknowledged as one of the objectives of the energy and ecological transition, and as one of the sustainable development goals by the Ministry of Ecological Transition, whose site mentions several areas in which progress should be made:

– *sustainable procurement*: considering the environmental and social impact of the resources employed, particularly those associated with their mining and use;

– *eco-design*: considering the environmental impact on the entire life cycle of a product and integrating it from design;

– *industrial and territorial ecology*: synergizing and sharing by several economic players material, energy and water flows, infrastructures, goods or services in order to optimize the use of resources on a territory;

– *functionality economy*: opting for use rather than ownership, selling services rather than goods;

– *responsible consumption*: considering the environmental and social impact at all stages of the life cycle of the product in the purchase choices of both public and private buyers;

– *extended duration of use* of products by repairing, selling or buying second-hand or giving, in the context of reuse;

– *improved waste control, management and recycling*, by reinjection and reuse of materials resulting from waste in the economic cycle.

Recycling is one of the key parameters of these objectives. It has many advantages. The following are made possible by recycling:

– *reduction of imports* and therefore of the dependence on certain manufacturing countries. In the field of metals, though Europe was self-sufficient until the 19th century, with France producing metals until the end of the 20th century, it is currently highly dependent on external procurement. China has the monopoly for over 40 substances, while other countries also have this monopoly status (the Democratic Republic of the Congo for cobalt, Brazil for niobium and tantalum). Most European countries had to close their mining sites due to various reasons, such as competitiveness problems related to labor costs or environmental considerations. This is the case for the three largest metal consuming European countries: Great Britain, France and Germany. The contribution of European manufacturing countries (Northern Europe, Spain and Portugal) amounts only to a few percent of the global metal consumption;

– *job creation*: the recycling of metals requires labor and technological development, source of skilled trades;

– *reduced environmental impact*, which also requires the development of particularly clean and energy-efficient processing plants for recycled products, generating a certain number of regulatory constraints. Shredding a computer hard drive disk remains a challenge however, so the use of energy for shredding and separating the parts of electronic waste should be considered, and the metal recovery rate remains very low, with the exception of the readily recoverable elements such as gold, silver and platinum;

– *reduce the disposal of metals*, or the export of materials to be recycled to countries where the social and environmental conditions of waste treatment are not acceptable, which is still the case;

– *optimize the management of household waste*: poor waste management has a direct negative impact on the quality of all the elements of the environment, therefore on ecosystems and human health. Underground or air emissions from poorly managed disposals may impact the quality of water, soil and air, and affect farmland surfaces. It is essential to increase the level of recovery (including recycling) of industrial waste by means of regulatory and/or fiscal policies, and to develop modern management of municipal waste in order to increase recovery and thus reduce the volume of waste disposal.

I.4. Structure and features covered in this book

This book does not aim to exhaustively cover all aspects of recycling, but provides a series of examples of cycles of the circular economy presented in Figure I.2.

After raising awareness on everyone's role in reducing the volumes of individual waste (Chapter 1), Chapter 2 provides a historical perspective on the consumption of metals and energy and on the potential role of recycling in meeting the future needs of society, for metals in particular.

The following chapters are dedicated to technical aspects, difficulties and future perspectives on recycling:

– batteries and permanent magnets, two key elements of the energy transition (Chapter 4);

– recovery of metals contained in electronic and electrical waste, particularly electronic cards, symbols of the digital revolution (Chapters 5 and 6);

– recycling of plastics in two ways (recycling of polymers, and short recycling circuits for 3D printing). Plastic recycling is a world of its own, given the great diversity of materials, integrating organic molecules and hydrocarbon derivatives;

– recycling of wood that has already been used in construction or other sectors and whose characteristics result from their anthropogenic cycle;

– glass recycling;

– recycling of elements used in public works and civil engineering, particularly concrete.

The last chapter offers new perspectives on the recovery of metals from natural or polluted land using agromining methods.

I.5. Acknowledgments

This book on recycling requested by Ph. Boulvais and Y. Lagabrielle (Geosciences Rennes) could be completed thanks to the logistical support provided by Institut Carnot Icéel and LabEx RESSOURCES21 (ANR-10-LABX-21-RESSOURCES 21) for organizing meetings. It covers the recycling know-how gained in Lorraine by these two organizations.

1

Waste Prevention

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1.1. Introduction

"Show me your trash bin and I'll tell you how you consume". This could be the adage that summarizes the close link between a person's way of living and the waste it generates. In the 1960s, The French-born American artist Arman made a series of works entitled "*poubelles*" (trash bins) related to waste, exposing the abuses of the emerging consumer society (Figure 1.1). Arman poured the content of a trash bin into a Plexiglas case and used epoxy resin to "freeze" it. This is a series of works he made at various places and times.

Sociological studies were dedicated to his works, which were used to demonstrate the pernicious effects of excess consumption. Indeed, hyper consumption, to which modern society turned, directly impacts our waste. Due to the illusion of waste *management*, energy from waste or waste *recycling*, the consumer was lured into a no-blame, no-responsibility bubble with respect to this waste and their conscious awareness of the environmental risk it generates is gradually diminishing.

Section 1.2 of this chapter presents all the negative effects of waste on the ecosystem and the risks they pose to humanity. This is followed by an evaluation of our individual contribution to waste production and a presentation of sustainable solutions for waste reduction.

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coordinated by Michel CATHELINEAU.

Figure 1.1. "Poubelle organique" *(Organic trash bin) by Arman. Museum of Contemporary Art, Marseille (photo E. Langlois). For a color version of this figure, see www.iste.co.uk/cathelineau/recycling.zip*

1.2. Facts

1.2.1. *The ecological footprint of human activity*

Sustainable development was defined in 1987 by the International Institute for Sustainable Development, as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

Indeed, the presence of humans on Earth and their activity impact environmental equilibrium. The notion of sustainable development covers a set of concepts aimed at reducing this impact as much as possible and rendering the footprint of anthropic activity as neutral as possible. Nowadays, there are many indicators for measuring the impact of human activities and they can be globally classified into the following four broad categories:

– Greenhouse gas emissions mainly from combustion and associated industrial activities and the movement of motor vehicles. The presence of these gases in the atmosphere, carbon dioxide being predominant, causes heating at the Earth's surface, thus disturbing the equilibrium of biosystems. While the European contribution to CO_2 generation is currently decreasing (about 15%), that of the main contributors (Asia and the United States) is still growing. In France, according to the governmental studies on which the law on energy transition for green growth relies, in 2020, the greenhouse gas emissions should be six times lower in order to reach carbon neutrality by 2050.

– Pollution of water, soil and air caused by the discharge into these three media of objects or chemical molecules that can have a harmful and often irreversible effect on living organisms and plants.

– Natural resource depletion: the natural reserves of materials used for the manufacture of construction or consumer goods are significant but not infinite. Hence, certain natural materials are now being depleted, which is particularly true for crude oil, the basis of all fuels and the chemistry of plastics, polymers, pesticides, cosmetics, etc. There are also concerns related to the future availability of metals. But this depletion is even more concerning for some minerals used in a large number of manufactured objects: silver, gold, tin or zinc. Chapters 5 and 6 focus on the concept of reserve/resource particularly for metals.

– Biodiversity loss: due to the expansion of surfaces humans can use as living space and farmland or for manufacturing activities, the natural reserve and the living and reproduction areas of plant and animal species are significantly reduced. This reduction is inescapably accompanied by the disappearance of some species, the rarest, the most fragile or those considered the most harmful to human beings.

The industrialization and globalization of manufacturing activities and commercial exchanges led to a strong and rapid deterioration of these indicators in recent decades. The "living comfort" of the mass consumer society has an ecological cost that has unfortunately been ignored or underestimated for too long, and its effects are harmful to the environment, to the integrity of the natural environment, to climate and the evolution of species. Nowadays, there is no need for arguments or proof, as these effects are noticeable and a huge majority of countries are aware of them. The reversal of this trend would be possible through changing habits, but this is still met with strong resistance.

While all the observers and specialists agree that the point of no return has not yet been reached, it is also widely accepted that there is an urgent need to act effectively to, at a minimum, curb the trend, since the effects of climate change are becoming more and more visible today. This being the case, the question on everyone's mind is what means, actions and behaviors should be implemented to reach this virtuous objective of being able to continue living in relative comfort while preserving the environment, resources and plant and animal species, and allowing the human species to peacefully enjoy what the Earth has to offer.

Given the existing global disorder, it might quickly become discouraging to imagine that individual behaviors may change this slow evolution. The solution is however at hand, and it is individual before it is collective. This solution will be presented in this chapter. Waste reduction is a particularly interesting support tool for this individual change, as it can be used to rapidly act on all the indicators of sustainable development, and this will be studied in detail. For this purpose, our individual contribution to waste, its impact and especially its origin must be brought to light.

1.2.2. *Our contribution to waste*

An extremely well-organized activity in industrialized societies is waste logistics. Indeed, our waste quickly disappears from our hands and our eyes as users, giving us the illusion of a "cleaner" society. As the logistics chain is well organized, data are quite readily available.

In France, the French Agency for Ecological Transition (*l'Agence de l'Environnement et de la Maîtrise de l'Energie* (ADEME)) leads the environmental protection network that gathers and uses the information on waste management. According to its annual report published in 2020, ADEME[1] estimates that, during 2017, communities collected over 39 million tons of waste. Considering the number of residents in the area, this figure represents an amount equal to 580 kg/resident/year, which is an extra 12 kg per resident compared to 2015.

Of the 580 kg/year/resident, 440 kg corresponds to household waste, while the difference corresponds to waste generated by small companies and administrations,

1 See the key figures in the ADEME document "Report of the public service on the prevention and management of household and assimilated waste".

and also to municipal waste related to works, schools and other activities. This 580 kg is composed of 255 kg/resident/year of door-to-door household garbage collection and 325 kg/resident/year of voluntary contributions: 136 kg at drop-off centers, 30 kg of glass, 49 kg of packaging and paper, 18 kg of green waste and 10 kg of bulky waste.

At this stage, it is important to realize that 580 kg/resident/year represents only our directly attributable share of waste, the visible part, waste we have directly touched, put into the trash bin, sorted or brought to drop-off centers. There is however an invisible part, which is much more important, that is attributable to all activities of resource extraction, refining these resources, processing and assembly of all our consumer goods. Across the French territory, ADEME estimates that the waste generated by companies and by the building sector represents the equivalent of about 5 tons/resident/year. By adding the waste resulting from farming and health care activities, the Zero Waste France association (CNIID) estimates that the invisible share of waste produced in the national territory is at nearly 14 tons/resident/year. Considering that the very large majority of clothing, consumer goods, electrical and electronic goods are manufactured outside of France, often in China or other Asian countries, the share of invisible waste per resident and per year largely exceeds 20 tons for a French citizen. This is the sad reality of our contribution to the waste generated by living in a consumer society.

It is important to note that, in terms of environmental impact, this section refers only to the waste generated, but we should add to this total energy consumption related to mining raw materials, their processing and the transportation of these products to our location.

This is the first important point in raising awareness on our individual contribution: even before being unpacked, used or eaten, the material good that we purchase has a record in terms of waste, energy consumption and use of natural resources. Indeed, the manufacture of any consumer good follows the same rule and requires three essential ingredients: raw materials, energy and water. Raw materials belong to the Earth's resources: they must be mined, then refined or purified. Then they must be transformed, shaped and assembled. All of these operations are energy and water intensive. Moreover, they require transportation between operations and generate a significant amount of unrecovered waste. Certain organizations looked into this environmental impact accounting to illustrate this phenomenon. For example, when a worn out plastic toothbrush is thrown in the garbage bin, this adds several dozen grams at most. But if the waste generated during its manufacture is added, the toothbrush has a record of about 1.5 kg of waste before entering your home. In the case of a laptop, which weighs only several kilograms, the generated waste all along its manufacturing process weighs 1,500 kg, the equivalent of 310 L of oil used to generate energy, 22 kg of chemical products used during various manufacturing stages and 1,500 L of water. On average, 300 additional liters of fuel should be considered for shipping to your sales outlet. To quantify this excessive use of resources in a comprehensible manner, the Global Footprint Network organization developed a calculation model known as "overshoot day". This day of the year corresponds to the day when humanity consumed more natural resources than the Earth is able to produce in 1 year and emitted more greenhouse gases than the Earth is able to absorb during 1 year. In 2019, the overshoot day was July 29. In 2020, due to the Covid-19 pandemic and to the drop in manufacturing activities, the overshoot day took a 3-week leap forward and was estimated as August 22, a date which had not been reached since 2005. As a reference, the overshoot day in 1970 was assessed as December 29, which means that our way of living was nearly "sustainable". While the reliability of this indicator and the hypotheses on which its calculation relies are still under debate, it actually highlights the need to improve our energy and consumption frugality in subsequent years.

1.2.3. *The future of our waste*

Let us return to our direct waste. A substantial part of it is not collected and ends up in nature. In a report published in 2019, the World Wild Fund for Nature (WWF) estimated that 80,000 tons of plastics are lost in nature every year in France, which is over 1 kg per person[2]. On a global scale, the contribution of countries in which there is no collection or the existing one is not as well organized as it is in France, this is much more significant. It is estimated that over 200 kg of plastics are discharged into the Earth's oceans and seas every second, which means 1 ton every 5 s and 720 tons every hour.

Once they have entered the oceans, plastic materials are carried along by sea currents and under the action of sunlight, agitation and oxidation caused by water, they are split into increasingly smaller fragments. They are eroded until they form microspheres that are ingested by fish and consequently by sea birds, or continue to split by friction and form nanoparticles, which are absorbed by the plankton. This plastic material causes the death of over 100,000 sea animals and over 1 million sea birds per year. In 2009, in the Midway Atoll in the Pacific, the photographer Chris Jordan took a series of photos of albatrosses that had died having ingested too much plastic material (Figure 1.2). Since the nearest inhabited coasts are at least 2,000 km away from the Midway Atoll, albatrosses found these plastic fragments in the sea, carried by the current.

2 WWF (2020). Plastics: the costs to society, the environment and the economy. Report [Online]. Available at: https://wwflv.awsassets.panda.org/downloads/wwfintl_tcops.pdf.

Figure 1.2. *Chris Jordan's photograph: "Midway: Message from the Gyre", showing the stomach of a decomposing albatross containing plastic objects. For a color version of this figure, see www.iste.co.uk/cathelineau/recycling.zip*

Plastic and its fragments then accumulate in ocean gyres. Gyres are centers of whirlpools upon which large currents converge, huge vortices caused by the Coriolis force. There are five large ocean gyres, the most important of which is the South Pacific Gyre. The latter, whose size is equivalent to a third of Europe's surface, contains five times more plastic material than plankton. Plankton is the first link in the ocean food chain and it is also at the origin of the production of over 50% of atmospheric oxygen. Plankton contamination and extinction is therefore doubly damaging.

Let us return to solid ground and explore the journey of collected waste. The essential part of domestic waste is recovered, in the sense that it is incinerated after collection to generate calories for district heating or hot water. The incineration of household waste generates calories and gas. The combustion residue, known as clinker, contains ashes with some highly toxic pyrolitic compounds. The clinker is used in sublays for soil stabilization in civil engineering, when building roads or works of art. This use authorizes the direct contact between clinker and natural environment and is at the origin of the migration of residual pollutants and therefore the contamination of soils and water sources.

Most gases generated by incineration are water vapor and carbon dioxide, the main anthropogenic greenhouse gases. Other highly toxic gases are generated in variable amounts, resulting essentially from the combustion of plastic materials.

Most of them are filtered and condensed by reaction with lime or sodium bicarbonate before being discharged into the atmosphere. This collected fraction, known as MSWIR (Municipal Solid Waste Incineration Residue) fly ash, contains a large number of substances toxic to humans and the environment. Its contaminating potential must therefore be stabilized: MSWIR fly ash is passivized, vitrified or coated, before being stored in centers for dangerous waste, MSWIR fly ash becomes industrial waste and is stored in class I landfills. Part of this MSWIR fly ash is buried in former mine cavities, in former salt mines, particularly in Germany.

There is no magic to make our incinerated waste completely and permanently disappear. Incinerating 1 ton of waste releases between 0.7 and 1.7 tons of CO_2[3], and generates between 250 and 300 kg of residual clinker and between 20 and 50 kg of MSWIR fly ash. Once incinerated, our waste contributes to global warming through carbon dioxide emission and to the pollution of air, soil and water.

Concerning polymer recycling, the figures vary depending on the considered material and must therefore be interpreted in different ways. For example, the plastic recycling rate is calculated by dividing the weight of the materials entering the recycling process by the quantity launched on the market, for metals; this is the reuse rate during recycling. Table 1.1 presents the recycling figures for 2019 in France, listed in the Citéo/Adelphe[4] report.

	2019 deposit in kilotons	2020 deposit in kilotons
Steel	257	275
Aluminum	88	90
Paper cardboard	1,149	1,192
Bricks	69	70
Plastic	1,165	1,189
Glass	2,559	2,607
Total deposit	5,200	5,383

Table 1.1. *Data cumulated by Citéo and Adelphe on the deposits collected in France from recyclable products in 2019 and 2020*

3 The combustion of organic matter, composed mainly of carbon and hydrogen, drives the production of CO_2 by adding oxygen to carbon, which is much heavier than hydrogen, and therefore the possibility of generating a mass of CO_2 that exceeds the initial mass of organic matter.

4 Citéo and Adelphe activity report (2020). [Online]. Available at: https://bo.citeo.com/sites/default/files/2021-07/CITEO-Rapport-activite-2020.pdf.