1 Introduction

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Today, nearly half of the world's growing population lives in urban areas, causing enormous pressure on the local environment. Particularly in the large agglomerations of the developing countries, inadequate waste management is the cause of serious urban pollution and health hazards. Affluent industrialized economies are facing an ever-increasing load of wastes and declining landfill space to dispose of these materials. Sustainable management of waste with the overall goal of minimizing its impact on the environment in an economically and socially acceptable way is a challenge for the coming decades.

Different countries have adopted different strategies for reaching their goals, be it by applying advanced environmental technologies, by extending recycling and re-use, or by reducing the material intensity of their economy. Sustainable waste management will have to consider all possible options for the reduction of the negative impacts of consumption. Waste is a source of pollution as long as we don't learn how to better use the material and energy resources contained in waste: "Don't waste waste!"

1.1 The Problem with Waste

When a useful material good, such as a car or a newspaper or a computer reaches the end of its life cycle, it loses its economic value and turns into waste material. The car may turn into waste because its engine breaks down through wear and material failure, or because it crashes into a tree. Today's newspaper will turn into waste after it has been read and/or because the information it carries will be obsolete tomorrow. The computer might turn into waste if it breaks down, or, what is more likely nowadays, because its technology is outdated by the development of new and more powerful machines.

The transformation of a useful product into waste strongly depends on the function it has for the owner and its economic value. Waste is, so to say, in the eye of the beholder: the used car might still serve as a shelter for a homeless person, yesterday's newspaper might be useful for wrapping up some fish-and-chips and the outdated computer might still be sufficient for use in a primary school class. Waste is not just waste! It can be transformed back into a valuable material by a different user and be useful for another life cycle. When the car starts to get so rusty that it can no longer keep the rain out, it will be abandoned by the homeless person. When the fish-and-chips are eaten up, the newspaper will have turned into a greasy and soggy bit of paper that will be dropped on the pavement by the thoughtless consumer.

As it will take years for the newspaper to transform into topsoil and as it will soon become evident that the rusting car body pollutes the roadside with corrosion products and poisonous liquids, there will be citizens who will object. They will want to have the car removed from the side of the road and the newspaper picked up from the pavement because litter interferes with their esthetic preferences, or because they are concerned about the ecological consequences of potentially dangerous emissions.

At this stage waste clearly reaches the state in which it has a negative value, e.g. it will give rise to costs because it will have to be removed and treated so that it does not cause additional costs in the future. *Waste management* is about all the options society has to manage the transition of the value of goods and materials from positive to negative. Ideally, waste management will ultimately turn waste into a zero-value good (e.g. appropriately treated residues which can be left in a safe landfill for indefinite durations) or recycle it by transforming it physically and/or chemically so that it becomes valuable again as a raw material for new products.

From the above, we can conclude the following:

1. Waste management is inextricably linked to economy, as waste is defined by its relative economic value;
2. Waste management is likewise linked to ecology, as, left on its own waste is likely to affect the environment;
3. Waste management is a social issue, as waste is mainly a social construct (what is perceived as waste depends to a large part on life-style and social rank) and it raises the questions about the responsibilities of individuals towards society.

The short introduction should illustrate that all three aspects of sustainability (economic, environmental and social) have to be considered in waste management.

1.1.1 Economic Aspects of Waste

The economic problems of waste are due to the fact that, by definition, waste is material with no value. Classical economic mechanisms of supply and demand controlling the flow of goods, therefore, fail for waste materials. As a consequence, they tend to accumulate in the natural environment if no countermeasures are taken by authorities. Countermeasures include regulations prohibiting the uncontrolled disposal of waste and prescribing minimum standards for treatment and deposit. Controlled disposal or recycling involves costs, i.e. waste materials are assigned a negative economic value in the form of a disposal fee. In exchange for the disposal fee, the economic value "absence of pollution" is created. The central economic problem is allocating the costs for a clean environment to the stakeholders. Waste management used to be the responsibility of the public domain and financed by taxpayers, with little or no incentive for the consumer to diminish the rate of waste production. In order to create incentives for waste reduction, the "polluter pays" principle has been introduced and increasingly used.

Mining of ores and fossil fuels leads to the depletion of resources and to irreversible (at least in human, as opposed to geological time spans) dissipation of material (entropy increase). One would expect that the dissipation of concentrated mineral resources will eventually lead to increased economic value of the materials in question (increased prices for a given raw material) and thus to an efficient reduction in their use, or their substitution. So far, however, the economic value of most, if not all, mined raw materials has decreased over the past centuries and there is hardly any indication of a reverse trend. Although the concentrations of, for example, Cu in mined ores has continually decreased, the copper industry has been successfully dealing with this trend by employing new extraction technologies (and improving existing ones), even with declining prices. While the primary world production of copper increased from less than 8.8 million tons to more than 13.3 million tons between 1976 and 1996, the average price (corrected by the consumer price index) dropped by 50% within the same period [7]. The percentage of recycling to total copper consumption has leveled close to 40% in the same time span. Of this 40%, about half has been recycling of manufacturing waste. This means that about 20% of the total copper consumption is recovered from post-consumer waste. It is quite clear that this share of recycling will not be increased as long as prices from primary production sources keep declining. Clearly, the motivation for tapping municipal solid waste (MSW) as a source of mineral raw materials is not given at the time being. The currently proved reserves of copper will last for another 40 years, the resources for another 105 years [7]. Imposing taxes on non-renewable resources to encourage more efficient management of such resources or their substitution has been proposed (see Chapter 8).

1.1.2 Ecological Aspects of Waste

Industrial civilization relies on materials that are mined from enriched deposits (ores and fossil fuels) and are hence very different in composition from the resources that natural systems (i.e. the biosphere) draw on. Producing, using and discarding these materials will ultimately lead to their dissipation and accumulation in specific compartments of the environment with potentially harmful consequences. The waste resulting from the high carbon intensity of our industrial civilization has led to the well-known surge in CO_2 concentrations in the atmosphere with potentially disastrous consequences for the world climate. Metallurgical activities of humans have left footprints in the global environment as well: the analysis of Greenland ice cores has revealed that human activities have resulted in enhanced concentrations of, for example, Pb in the precipitation already more than 2000 years ago, with the spread of Graeco-Roman metallurgy exploiting lead containing silver ores [9].

Our industrialized civilization clearly leaves chemical footprints in the environment, i.e. it changes the chemical composition of some of the sensitive ecological compartments (such as air, water, soil, etc.). Whether or not an increase in the concentration of a given compound or chemical element in an environmental compartment is ecologically harmful or not, depends very much on the activity it exhibits with living systems. Many of the trace deposits of heavy metals found in the different environmental compartments are detectable but need not be harmful; others clearly have an impact globally or locally due to their quantities and or quality. The assessment of contemporary ecological impact and, in the long-term, of the irreversible dissipation of materials to the environment is the subject of Chapter 6.

Materials (compounds, elements), which are not found in nature, can cause particularly harmful effects on ecosystems and human health. Such xenobiotic materials can be damaging at very low concentrations. Examples from domains of chemistry, physics and biology include the following:

- Xenobiotic chemicals: persistent chemical compounds entering the food chain, such as the infamous pesticide DDT turning up in unexpected places and concentrations – or the release of very stable chloro-fluoro-carbons (CFCs) leading to the destruction of the stratospheric ozone layer in polar regions.
- Radio-nucleids: radioactive isotopes formed by artificially induced nuclear reactions (atomic bombs, reprocessing of nuclear fuels, etc.) with unknown and/or difficult to assess hazards to the environment and human health.
- Bio-hazardous material: there is increasing concern about the release of traces of bio-active substances, such as hormones and/or antibiotics, mainly via the water cycle. These substances can be biologically active in very low concentrations. The unknown risk associated with the release of transgenic organisms is the most recent example of potential dangers arising from the interaction of the "artificial" with the "natural" environment.

From an environmental perspective, sustainable development means that the chemical footprints of civilization should be reduced to a level where they are not

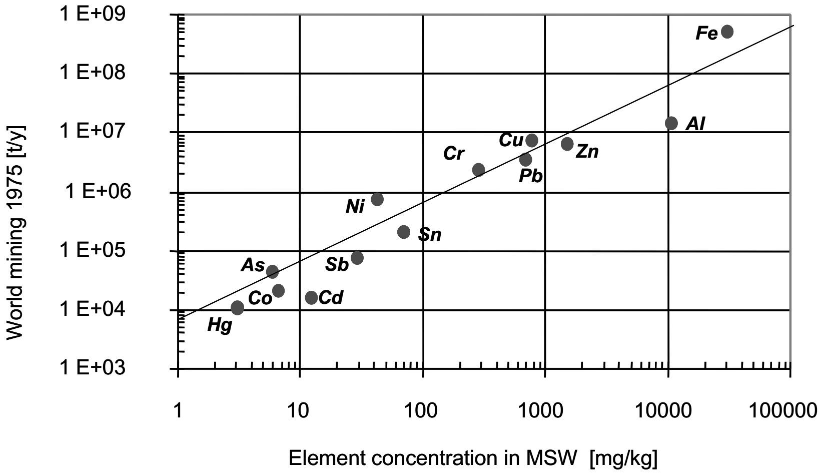

Fig. 1.1. World mining productivity plotted vs. the average concentration of elements in MSW. Concentrations reveal a correlation to the production rates for a number of metals

harmful for future generations. The elemental composition of average solid discards from households and local small business (MSW) differs from the background composition ("earth crust") by an order of magnitude for a number of heavy metals. Clearly, the solid residues of MSW, if discarded, will show an environmental footprint, the extension of which depends on the rate of dissipation into sensitive compartments such as aquifers. A number of chapters and case studies in this book focus on the recovery of metals from MSW treatment plants, with emphasis on avoiding any long-term pollution of aquifers by toxic metals.

The elemental composition of MSW reflects the spectrum of products that enter the consumption chain. This is illustrated in Fig. 1.1, which shows the correlation between the production rate of mining products and the mean concentration of elements in MSW. This means that, at least for a number of elements, MSW is a representative sample of what is being consumed. In order to devise efficient means of guiding the flow of materials and/or avoiding hazardous pollution to the environment, the flows of materials need to be analyzed in the entire system. Material flow analysis, i.e. methods used to establish the material balances of the inputs and outputs of human settlements ("the anthroposphere"), has contributed to our understanding of the material flows and material accumulations in human-made systems [1]. This analysis is essential in assessing the relative importance of the material flows and the suitability of waste management options available for influencing these flows. For an example of such an analysis, see section 8.3.2.

1.1.3 The Social Problem of Waste

The minimum requirement that solid waste management has to fulfill is the removal of solid discards from the immediate vicinity of settlements. This task is being solved in more-or-less efficient ways in most societies. As soon as waste is out of sight it is no longer perceived as a problem. This attitude becomes more of a problem, the better the consumers are shielded from the consequences of their consumption. According to [10], the transition to consumer society after World War II has been connected with a high degree of division of labor and an increasing separation of production and consumption. “The price for this separation has been a loss of immediate perception and control of the individual over the material and energy fluxes associated with his or her activities, and a growing difficulty to keep track of what is going on in the world.” [10]. The relative prices for the raw materials and energy have come down tremendously during the same period. Consumption has become more and more effortless as a consequence. In order to provide unspoilt consumption pleasure, the chores of dealing with the resulting wastes have also been taken away from the consumer. Efficient waste management systems which deal with the material output at the end of the pipe are in place: waste water is dealt with from the moment you push the flush button; solid waste is removed efficiently from the side of the street by public waste collection workers, and the further processing of this material has little or no implications for our daily lives.

Therefore, as long as waste management operations do not lead to emissions which immediately interfere with the pleasures of consumer life we are enjoying, the consequences of the highly increased material output of our consumer society are not generally perceived. The better the management of wastes, the less the public is aware of our high-throughput economy. The vision of a zero-waste society can therefore only become a reality if the immediate material flux consequences of consumerism can be made transparent or tangible again.

Current waste management practices are mostly based on centralized operations: waste is collected and brought to a landfill or a central processing plant (e.g. incinerator). Social acceptance problems arise mainly from local opposition to the erection of such plants because of real or feared negative impacts, such as noise, odor, air pollution, traffic (see Ch 7).

1.2 History of Waste Management

Waste has been an issue of public concern ever since humans started to live in towns, i.e. in an area which was smaller than the land area needed to sustain their food production. Most European countries introduced legal regulations regarding waste management only in the second half of the 19^{th} century [3]. It is no coincidence that this time coincides with the population explosion in central Europe of the same century, which led to the growth of big cities. It was also during this time that growing scientific evidence showed that epidemics related to overpopulation, most prominently cholera (e.g. the 1832 epidemic of London), were related to hygienic problems. Waste management was, therefore, first of all a hygienic issue: preventing the spread of diseases through rotting waste.

In industrialized countries the decades after the end of the 2nd World War were characterized by a sharp increase in the per capita consumption of energy and material resources. Between 1950 and 1990, as an example for a European country, the consumption of fossil fuels in Switzerland rose by a factor of 5, the production of MSW by a factor of 4.3, and the number of cars by a factor of 19 – with a population growth of 44% for the same period [10]. By the end of the 1970s, this unprecedented out-of-control surge in material throughput had fuelled fears that we may not be able to master the associated waste avalanche. The publication of the "Limits of Growth" [12] by the Club of Rome in 1975 made clear that the resources the consumer age depended on were not unlimited and that therefore waste management had to change its focus from "efficient removal" to waste avoidance, minimization, and recycling as options with higher priority. New guidelines had to be developed to manage the material flows of consumer society. For example, in Switzerland the Swiss Guidelines for Waste Management were published in 1985 [5], as a highly visionary set of guidelines, which have since influenced the Swiss waste management policies (see Box). To enforce these policies, environmental legislation and specific regulations regarding waste management were drawn up as a result. In European countries, most of the actual waste management regulations came into force in the early eighties [4]. Different countries have adopted different strategies for reaching their goals of reducing the ecological and economic burden of wastes.

Summary of Swiss Guidelines for Waste management

Scientific and technical guidelines:

- Waste disposal systems should generate materials which can be recycled or deposited in a final disposal site.
- Hazardous substances must be concentrated, not diluted.
- Organic substances are not compatible with final disposal sites.

Political guidelines:

- Waste management is guided by the objectives of the environmental protection laws.
- Waste disposal systems must be environmentally compatible.
- Waste should be disposed of within Switzerland.
- Regional responsibility for planning of landfill sites is applicable.
- Public authorities play a subsidiary role in waste management.

Economic guidelines:

- Public authorities should not subsidize waste disposal systems.
- The *polluter pays* principle is to be adhered to.

- Waste should be recycled if the result is less environmental pollution than disposal and production from virgin materials. Recycling must be profitable.

1.3 Directing Material Flows

Waste is an inherent result of economic activity, as it is of any metabolic system. The ultimate goal of waste management is the absence of waste, i.e. to get rid of it, to use it as a resource, or not to have it in the first place. Preventing the production of waste materials is not usually considered a part of waste management in its strict sense. The term 'Integrated Waste Management' (IWM) has been coined to include front-end measures such as design for recycling, exclusion of problematic materials in products, etc. as integral parts of waste management (see Ch. 8).

Waste management in the narrower sense directs the flows of materials so that their impact on the environment, the depletion of resources, and the resulting costs are minimized. Various strategies to achieve these conflicting goals have been adopted by different countries. Strategies include technical fixes 'at the end of the pipe' as well as recycling schemes and prevention of waste at the source, i.e. on the drawing boards of production. According to Buclet and Godard [4], three main "myths" underlie most of the strategies adopted in Europe, and probably in developed countries all over the world. These principles are referred to as "myths" because, implemented individually, they will not work.

1. **The myth of a dematerialized post-modern society** maintains that the material intensity of the consumer society can be drastically reduced so that fewer material goods end up in the waste management cycle. Consumption shifts from using and discarding material goods to the consumption of immaterial "services."

   While it is true that an increasing share of the economic throughput today is made with immaterial goods, the overall material throughput itself has not declined, only its relative value (i.e. the contribution of material products to the GDP). The much praised substitution of the flows of material goods by flows of information ("moving bytes instead of tons") [14] has thus far not been successful. Information and communication technologies have not done away with travel – mobility demands are steadily increasing. The computer has not brought us the paper-less office; it has rather enabled us to increase our printer outputs tremendously. It is, however, undisputed that the material efficiency (and energy intensity) of the economy could be increased by factors [15].
2. **The myth of perpetual material cycles** maintains that the material cycles of the "artificial" human civilization can be closed completely, as can the materials cycles in "natural" ecosystems. Any waste material can be reused or recycled. Dissipation of materials from the "artificial" to the "natural" can be neglected and has therefore no environmental impact ("zero waste" vision).

The zero waste vision has been inspired by the fact that, apparently, in natural ecosystems there is no waste, i.e. all refuse is recycled by specialized organisms in an ecosystem. Industrial ecology has been dreamed up as an artificial equivalent to natural systems [8]. However, no ecosystem can persist without a throughput of materials and energy drawn from and discarded to sufficiently large reservoirs. Complete recycling is not possible, as any material cycle will include irreversible losses (entropy production) which cannot be prevented without excessive energy input. Energy use and materials recycling ultimately need to be put into their right balance in order to optimize the life cycle performance of products.

3. **The myth of mastery and containment** maintains that waste can be treated and deposited safely; that landfilling can be mastered so that any spilling of pollutants into the environment can be prevented in any timescale, or is environmentally irrelevant.

   Potential leakage from a landfill can be minimized by adopting appropriate technology of treatment and landfill construction. However, no one can guarantee the long-term safety of landfills with respect to emissions. Incinerators greatly contribute to reducing the risk of groundwater contamination by landfills; nevertheless, the products of incineration still contain toxic elements unless subjected to further treatment. Purely technical solutions to the waste problem easily run into acceptance problems with respect to costs and operational risks (“not in my back yard!”).

The “three myths” discussed above aim at reducing the flow of materials on different levels in the life cycle of goods (see Fig. 1.2): prevention at the front end; recycling at the end of life of a useful product, before disposal; and finally end-of-pipe treatment and safe disposal (avoiding any uncontrolled flows to the environment). In integrated waste management (IWM), one assumes that there is not simply one unique way of dealing with material flows in a sustainable way, but that there should be control mechanisms on all levels. Realizing that any material flows and conversion processes involve potential emissions to the environment (see horizontal arrows in Fig. 1.2), it is clear that control measures further upstream are more efficient in preventing environmental damage and in saving resources. Avoided waste is the cheapest, the most efficient and most effective method of ‘disposal’! This has lead to the hierarchy of integrated resource management options that has been adopted as a guideline in many countries: prevention > reduction > recycling > disposal. A pragmatic way of setting priorities is to minimize the total impact of waste on the environment, i.e. the impacts on water, air, soil have to be minimized as well as the consumption of energy, materials and landfill space.

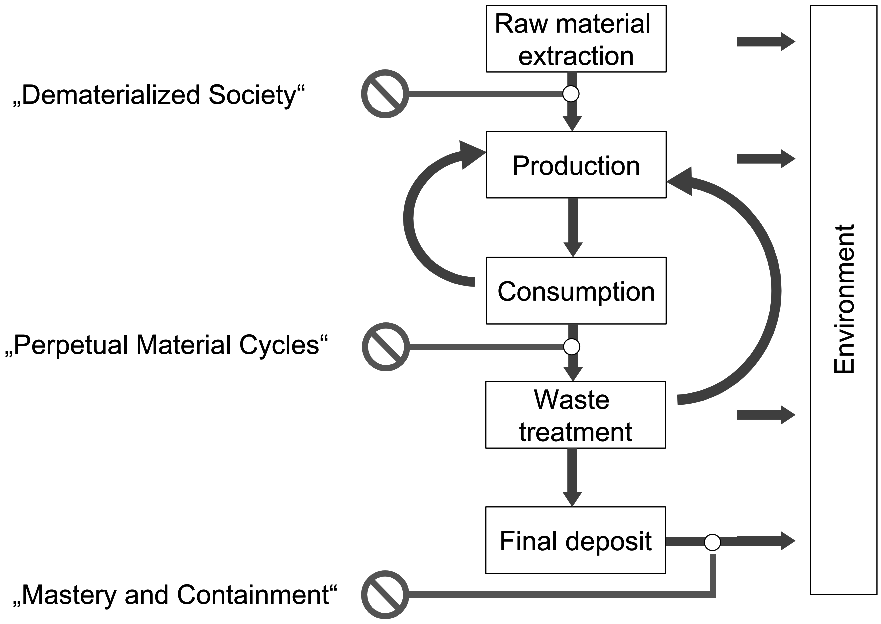

Fig. 1.2. From the cradle to the grave: product life cycles and the “myths” of controlling material flows

1.3.1 Preventing and Reducing Waste

Waste can only be prevented at the front end of the material cycles by changing the way goods are produced and consumed. The rapid rise in material and energy throughput of western economies is clearly not sustainable (“… it is simply impossible for the world as a whole to sustain a Western level of consumption for all. In fact, if 7 billion people were to consume as much energy and resources as we do in the West today we would need 10 worlds, not one, to satisfy all our needs” [2]). This means that reducing the throughput for a given set of services is a primary goal of sustainable production and consumption. Realizing that the ecological efficiency of the way goods are produced and consumed today is far below what it could be, some leading industrialists have come to the conclusion that the efficiency of material usage has to be improved along the life cycle of products (“doing more with less”). ‘Eco-efficiency’, a way of balancing ecological and economic efficiency, has been coined by the World Business Council for Sustainable Development as a strategy for advancing production towards sustainable goals [13]. The eco-efficiency strategy has tried to achieve an economically competitive advantage by reducing the material intensity of products and production processes, which, at the same time, lead to an overall reduction of waste production. The ideas of Schmidheini and his colleagues have been successfully implemented by a broad range of companies and have contributed to a general “greening" of industry over the past 10 years, although they have been criticized as doing little more than slowing down the current trends and perpetuating the paradigm of consumerism [11]. Clearly, new concepts for the development of products and services need to be discussed and put to work if waste prevention is to become more than just another myth. While this is essential, a thorough discussion of sustainable production and consumption is beyond the scope of this book. Important strategies that can be adopted in this area are the subject of a recent book [6].

1.3.2 The Great R's: Re-use, Recycle, Recover

Recycling is the second level in the hierarchy of waste management options. The myth of closed material cycles relies on using all waste as a raw material for production. Waste can be used as a resource for a great number of materials. Separate collection schemes have been very successful in enabling cost effective recycling of materials such as paper and cardboard, glass, aluminum, etc. (see chapter 3.). Recycling can be done at different levels of material complexity:

- Re-using products or parts of products for the same application (e.g. re-using parts of a machine after disassembly), or for a different application (e.g. using a newspaper as packing material);
- Recycling of complex materials (e.g. producing recycled paper from waste paper, recycled plastic from waste plastic);
- Recovering raw materials and energy from waste (e.g. metals from scrap, monomers from polymers, heat from combustibles).

The higher the level of recycling, the lower the technical complexity of the recycling process usually is and the lower the required energy input. At the same time, the recycling of products and of complex materials leads to the deterioration of the resulting recycled product with each recycling loop. This phenomenon, which limits the number of potential recycle loops, has been referred to as "downcycling," which means that the quality of the secondary material or product is usually inferior.

The situation is different in the case of raw material recovering, which can be done in a way that does not impair the product quality, because the material is broken down to the level of its building blocks (i.e. metals or metal salts from inorganic residues, or synthesis gas from organic material). The recovery of raw materials usually involves thermal processing steps (smelting and metallurgical processing; gasification; purification steps), which are intrinsically more energy intensive. The energy input economically limits the degree to which raw materials can be recovered.

The Swiss Guidelines for Waste Management [5] state that recycling should be favored only if the recycling process leads to less environmental damage overall than production from virgin raw materials. This means that decisions regarding recycling should be based on a full life cycle analysis of the underlying processes, including energy consumption.

1.3.3 Recovering Materials and Energy from Waste

However much waste prevention there is at the front end, and however many improvements in the cycles of consumption and production, waste managers will never become redundant: At the end of the cycle there always remains a material flow which needs to be taken care of. In its classical sense, waste management is about dealing with those materials and, accordingly, the main part of the present book deals with end-of-pipe technologies and their implications.

MSW contains high fractions of organic compounds, which, in a thermodynamic sense, are not in equilibrium. The organic matter in MSW will eventually get transformed in the landfill by biological and chemical processes. The rate of these transformations depends on conditions in the landfill. The chemistry of these processes is very unpredictable and so are potential emissions resulting from such a large chemical reactor (2.2). MSW landfills have been recognized as potential hazards to aquifers and therefore need long-term monitoring and emissions management (treatment of leachate water and collection and use of landfill gas).

Incineration of MSW gets rid of the organic carbon in MSW (via the flue gas, in the form of CO_2) and produces solid residual materials (bottom ash and fly ash), the chemistry of which is more predictable. The environmental performance of early incinerators was highly questionable, as untreated flue gases contain pollutants (SO_2, NOx, dust, heavy metals, dioxins, ...) which might be more damaging than the potential emissions resulting from the slow decay of the same mix of materials in a landfill. This particular drawback of incineration has, however, been overcome by applying highly sophisticated filtering technology. Modern air pollution control technology removes air pollutants of waste-to-energy plants to levels that are comparable with equivalent power plants fuelled by fossil fuels (see Ch. 6). The age of environmental technology, starting with the eighties, has solved the negative impact of incinerators on the local environment, and a modern MSW incinerator can be regarded as a sink, not a source of pollutants (see chapters 3, 5).

The inorganic solid residues from incinerators and from flue gas treatment equipment (fly ash, scrubber residues) are a mixture of materials with a composition which differs from average rock materials (“earth crust”) for a number of elements, notably for the heavy metals. Much of recent research and development has tried to separate minority components, such as heavy metals, from ashes by thermal, mechanical or even biological treatment, or to optimize the incineration processes with respect to its separation efficiency. The goal of these new developments has been to produce residues which can either be used as secondary raw materials, or deposited safely in a long-term landfill. The processes usually involve one stage at temperatures above the melting point of the ashes and produce glassy residues with much improved leaching stability. The major competitors in the environmental technology business have developed new processes with greatly improved residue quality over the past 10 years. They are being introduced to the market in Japan (5.3).

1.4 Conclusions

Waste is an inherent product of economic activity. The surge in productivity and connected consumption in the second half of the past century has led to a massive increase in material flows in the anthroposphere, creating environmental problems of sinks and (re-)sources. Solid waste management is relevant in directing the flow of some of the materials, especially heavy metals as essential ingredients of modern civilization, and as persistent toxic elements. There are various strategies to control the flow of materials through the economy. The overall goal of IWM must be the reduction of the total environmental impact resulting from waste, its handling recycling, treatment or final disposal. Reducing the input to the waste management system by increasing the material efficiency of the economy is the preferred option in the long term. Recycling of materials can substantially contribute to minimize the amount of material, which needs to be deposited. At the end of the pipe there is, and there will be no alternative to treating and depositing the remains. Technologies for doing this in a way that does not charge the burdens to our children and grandchildren are available. They take a good fraction of the following chapters.

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