Chapter 4
Preparation for Reusing, Recycling, Recovering, and Landfilling: Waste Hierarchy Steps After Waste Collection

Abstract The less useful operations in accordance to waste hierarchy principle will be driven in this section. Reusing, recycling, treating, and landfilling are all operation options for waste, which need to be considered regarding its impact on the environment and how their management can potentiate a better use of resources. A brief review on the concepts is presented, in the light of European waste management definitions and existing technologies.

Keywords WHP · MSW · Upcycling · Downcycling · Incineration · Biological treatment · End-of-waste criteria

4.1 Waste Hierarchy Principle: All After Becoming Waste

The management options when products become waste are vast, although the hierarchy is quite similar between them. In the "hierarchy of resource use" of Gharfalkar et al. (2015), waste should be managed following the preference order:

- Preparing for reuse is referent to options of cleaning, checking, repairing after the product has become waste, and making the object be used again as for the same purpose (like in definition of Waste Framework Directive 2008/98/EC).
- Reuse via resale of used, repaired, refurbished, reconditioned, or remanufactured products; reuse via renting, leasing, or servitization of products; and reuse without any further operation (secondhand, thirdhand, always with owners changing).
- Reprocessing: upcycling, recycling, and downcycling.
- Other recovery: recovery of energy and recovery of other substances or materials to be used as fuels or for backfilling.
- Rectification: considered for treatment before disposal.
- Return: disposal of waste.
- Waste exports: waste exports are seen as waste trafficking, considered by Bartl (2014) where waste exports are not in light with the global system with finite resources and where countries may divert waste from their landfills and send them to less developed countries.

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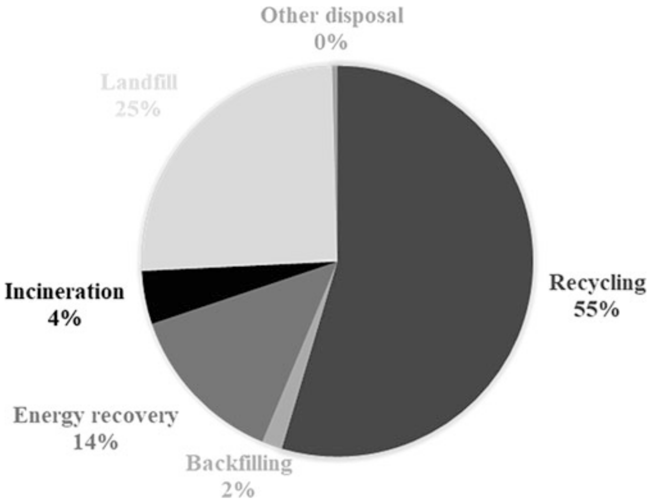

Fig. 4.1 Municipal solid waste generated and type of treatment, in 2014. (Source of data: Eurostat (2017))

For food waste management, Papargyropoulou et al. (2014) defined a waste hierarchy to help on its sustainable management, regarding avoiding food waste and food loss in the life cycle of food production. The waste hierarchy proposed presents the following order of operations (Papargyropoulou et al. 2014):

- Reuse: which includes food for human consumption, for people affected by food poverty through redistribution networks and food banks.
- Recycling: recycle food waste into animal feed and via composting.
- Recovery: treat unavoidable food waste and recovery energy, including anaerobic digestion.
- Disposal: dispose unavoidable food waste into the sanitary landfill with landfill gas extraction and recovery.

The diversity of waste hierarchy options shows how essential and discussible is the definition of the most sustainable correct direction to follow when managing waste. To better present the treatment options possible to waste, the defintions on waste hierarchy at Waste Framework Directive will be followed in the next sections.

Waste Framework Directive divides waste hierarchy into management for waste in preparing for reuse, recycling, and disposal. The management of waste generated at European Union is presented in Fig. 4.1. The analysis shows that there is no statistical information on waste send for “preparing for reuse,” being mixed with the recycling operation, which will be the dominant operation. Also, 54.6% of municipal waste (excluding imports and export of waste) for the 28 countries of European Union is sending for recycling, 25.3% for landfilling, 13.6% for energy recovery, 4.4% for incineration (without energy recovery), 1.7% for backfilling, and 0.4% for other disposal operation (Eurostat 2017). Recycling is, in fact, the leading solution for waste, but landfill has a relevant role in the integrated waste management. More than half of the countries are preferring recycling operation in opposition to the other waste management operation options, being the recycling leaders the countries Belgium, the Netherlands, and Slovenia, with recycling rates above 70%. Landfilling is still the preferred destination for countries like Bulgaria, Estonia, Greece, Spain, Cyprus, Hungary, Malta, Romania, and Slovakia.

4.2 Preparing for Reuse

The definition of preparing for reuse from Waste Framework Directive includes the "checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing." The definition considered in European Union legislation requires that the product has become waste, i.e., it has entered a collection system to be discarded or delivers it to another entity to get rid of it. The frontier of the owner defines the difference between being a waste prevention measure and preparing for reuse measure.

There have been different approaches to promote preparing for reuse. European legislation (and subsequent transpose to the national law of Member States) includes targets of preparation for reuse together with recycling for several waste materials, plastic, paper, glass, metal from and households, and for construction and demolition waste. Market-based instruments applied to preparing for reuse are deposit-refund systems and extended producer responsibility instrument. For several years in Portugal, before the entrance of compliance management for packaging waste, glass bottles were subjected to deposit-refund systems, to be collected and refilled again. Under the responsibility inherent at extended producer responsibility, the manufacturers can develop their products under design for disassembly, making products adequate to be, at waste phase, reparable to others to use them, at second-hand market or donations. Information campaigns on preparing for reuse also occur through the elaboration of indicators and awareness campaigns. Voluntary instruments such as norms, standards, and guidelines to conduct verification and guarantee for the electric and electronic waste are also being applied in European countries. In the UK, the PAS 141:2011 standard sets out the requirements for preparing waste electrical and electronic equipment (WEEE) for reuse, including suggestions for handling, tracking, segregating, storing, and protecting the appliances and its components for the preparation for reuse (Lu et al. 2018). In Flanders region of Belgium exists the standard for reuse of WEEE from Public Waste Agency of Flanders (OVAM), where environmental criteria are also considered, namely, the energy labeling to improve the environmental performance of reused appliance (Lu et al. 2018). In Germany, the standard *VDI 2343 – recycling of electrical and electronic equipment* – also allows promoting the benefits of reuse. Bovea et al. (2016) have developed a protocol specific for small WEEE from households, classifying appliances by potential reuse and the tests to be conducted, being based in other protocols

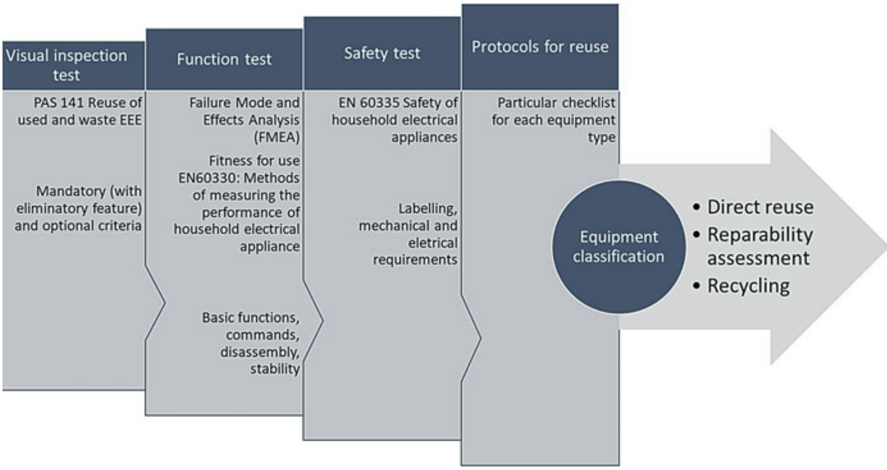

Fig. 4.2 Proposed methodology for the preparation for reuse of small WEEE. (Source: Adapted from Bovea et al. (2016))

already existing. In Fig. 4.2 the protocol is presented. The first step is the visual inspection, which should be done following PAS 141; the function test verifies if the appliance is operating according to its functions; the safety test verifies the aspects related to electrical, mechanical, and thermal risks; and the reuse protocols will define the reuse potential and which operations to be made to the appliances are to be reused (Bovea et al. 2016).

4.3 Recycling

Recycling means "any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations" (European Waste Framework 2008/98/EC). Looking at Fig. 4.3, European countries most devoted to recycling (i.e., where waste generated is mostly sent for recycling) are Belgium, Czech Republic, the Netherlands, and Slovenia, just to name a few, and countries with low waste recycling are, for example, Bulgaria, Estonia, and Romania.

Three types of recycling can be described: upcycling, recycling, and downcycling. The main difference of those definitions will be addressed in the next subsections.

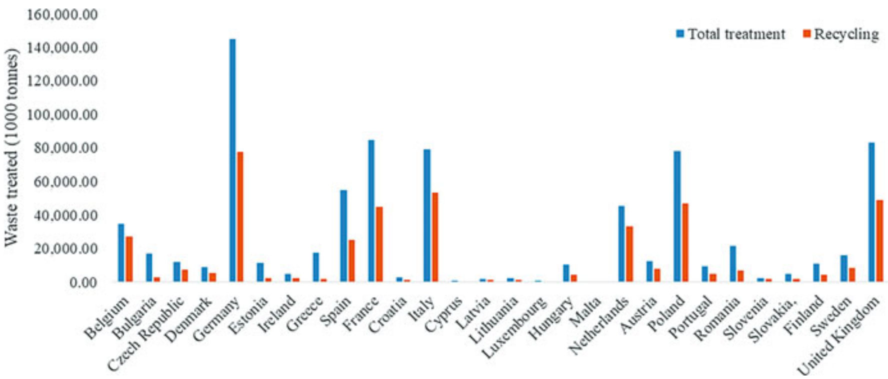

Fig. 4.3 Recycling of municipal solid waste in European countries. (Source of data: Eurostat (2017))

4.3.1 *Upcycling*

According to Cohen and Robbins (2011), upcycling was firstly introduced by William McDonough and Michael Braungart on the book “Cradle to Cradle: Remaking the Way We Make Things” as “the practice of taking something that is disposable and transforming it into something of greater use and value (McDonought and Braungart (2002)).” Other definitions also go on the same concept, increasing value. Upcycling is referent to processes that can increase the value of the recycled material over time, where the recycled material is reemployed for a more significant use or with a higher environmental value (Chandler and Werther 2014). Another view of upcycling is the one brought by Huysman et al. (2017), occurring when, for example, the plastic is of good quality but is used to replace another material that presents a higher environmental burden when compared to the virgin plastic.

To achieve upcycling concept, the industry needs to avoid the use of harmful substances and materials, recycle and upcycle for the continuous life of the products manufactured, decrease the consumption of energy and water, and also pay fair wages to employees (DeLong et al. 2017). Cases of upcycling are making purses out of used tires or used spare parts from end-of-life vehicles (McKenna et al. 2013), turning curtains into garments, or making old pair of jeans into a bag (Hjelmgren et al. 2015). In this cases, upcycling imposes the conversion of the product into other more valuable products. However, upcycling may also occur inside the same product. In the case study presented by Niero et al. (2017), a methodology to promote eco-efficiency and eco-effectiveness for aluminum cans of Carlsberg intends to upcycle the can continuously, in which every time that the can is recycled, it improved.

One of the areas of upcycling is being discussed in the textile sector. Waste textiles have been considered a waste stream needing better-dedicated management. Hjelmgren et al. (2015) identified the barriers to a large-scale upcycling of clothing in Swedish clothing sector as the shortage of suitable production facilities which are located outside Sweden and the need for significant amount of waste materials to make production and transportation efficient, just to name a few (Table 4.1).

Table 4.1 Barriers to upcycling textile waste

Products	Production facilities
Costs due to capital tied in inventory	Transportation costs and lost/reduced value that is created from an environmental perspective due to the transportation of finished products, or high manufacturing costs due to small-scale
Costs for producing clothes which are not in demand	Costs of inventories
Reduced perceived value of products using the same brand name as the product made of waste material	When using a highly specialized production facility, production of products made of waste material has a significant negative impact on the utilization of the facility. The need for distributors to change their purchasing routines. Concerns about sanitation of used clothes
Fibers origin	The lack of transparency and traceability in the supply chain concerning the fibers origin (the input material), to deal with potential perceived risks that traces of hazardous substances

Sources: Hjelmgren et al. (2015); Meyers (2014); Watson et al. (2017)

4.3.2 Recycling

In recycling, the process used to recycle the waste maintains its value over time. Recycling cases occur when the waste materials are recycled again into the initial products, i.e., in the cases of closed-loop recycling. Cases of recycling or also of closed-loop recycling are glass recycling, where the glass can be recycled several amounts of times without losing its properties. Herat (2008) compared a recycling (closed loop) and a downcycling (open loop into a lower-value product) of cathode-ray tube (CRT) glass. The closed-loop solution for CRT glass was glass-to-glass recycling, where the process allowed to obtain leaded and unleaded CRT glass. The open cycling tested was glass-to-lead recycling, where CRT glass was subjected to a smelting process, recovering lead and copper. Glass-to-glass recycling has barriers such as the difference in CRT glass composition due to different producers, high labor cost of dismantling, cheap and ready availability of other recycled glass, and high collection costs from significant barriers (Herat 2008).

4.3.3 Downcycling

Downcycling is a recycling process where the value of the recycled material decreases over time, being used in less valued processes, with lesser quality material and with changes in inherent properties, when compared to its original use (Ashby et al. 2007; Chandler and Werther 2014; Geyer et al. 2015). Cases of downcycling are recycling of printing paper into toilet paper (McKenna et al. 2013). Most of the time, the actual recycling of municipal waste streams (e.g., paper/cardboard, plastic) is considered more like a downcycling and not recycling. Such is related to the poor design of products, which are not conceived to be recycled and disassembled, and end-of-life management of products and materials, getting contaminated with other substances or materials, leading to recycled materials with low quality, limiting the applications of those materials (de Aguiar et al. 2017; Reuter et al. 2013).

A particular case of downcycling is the one related with recycled aggregates from construction and demolition waste. Recycled aggregates are results from concrete crushing, sieving, and decontamination (if needed), being adequate for use as bulk fill, fill in drainage, sub-base or base material in road construction, and also aggregate for a new concrete (Florea and Brouwers 2013; Hansen 2002). The first three operations use downcycling, being the most applied operation to recycled construction and demolition waste in Europe (Florea and Brouwers 2013; Hansen and Lauritzen 2004). Countries like Belgium and the Netherlands are facing the problem of aggregate market saturation, where the use of such recycled material is no longer applicable, due to its low quality, and the applications of such low quality material is ceasing (viz. road construction) (Di Maria et al. 2018; Hu et al. 2013). The only way to move from downcycling into recycling is by improving the quality of recycled aggregates, by removing impurities by advanced recycling techniques, or by selective demolition of buildings, which includes the progressive dismantling of the buildings, although the high costs of such procedure are not promoting it (Di Maria et al. 2018).

4.3.4 Recycling Challenges

One of the main drawbacks of the recycling is the difficulty in promoting a homogenous market for recyclates and other products made of waste (including other recovery at Sect. 4.4), in such a way that the industry could have trust on the waste products and where the bureaucracy related to waste transportation and management could be softer. Waste Framework Directive intended to promote the introduction of waste products in the economy by defining the end-of-waste criteria for specific waste, where waste products could respect specific requirements to ensure that they are secondary raw material for the industry. These requirements are (European Parliament and Council 2008):

- "the substance or object is commonly used for specific purposes;
- a market or demand exists for such a substance or object;
- the substance or object fulfills the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; and
- the use of the substance or object will not lead to overall adverse environmental or human health impacts."

End-of-waste criteria are to be applied to specific waste streams, being the Joint Research Centre responsible for its selection. The ones selected so far are (Villanueva et al. 2010):

1. Streams used as feedstock in industrial processes, a pathway that most often controls the risks of health and environmental damage via industrial permits. The streams identified in this subcategory are:
   - Metal scrap of iron and steel, aluminum, copper
   - Plastics
   - Paper
   - Textiles
   - Glass
   - Metal scrap of zinc, lead, and tin
   - Other metals
2. Streams used in applications that imply direct exposure to the environment. In these cases, the EoW criteria to be developed in the further assessment shall probably include limit values for pollutant content or leaching, taking into account any possible adverse environmental and health effects. The streams in this subcategory are:
   - C&D waste aggregates
   - Ashes and slag
   - Biodegradable waste materials stabilized for recycling
3. Streams that may be in line with the EoW principles. However, it is not clear in all cases that (a) their current management in the EU takes place via recycling or (b) that recycling is a priority compared to controlled energy recovery or landfilling in suitable facilities. More detailed information is needed about their subfractions and their available outlets before they opt for selection. By the results collected, the waste streams proposed for this category are solid waste fuels, wood, waste oil, tires, and solvents.

4.3.5 Remarks

An aspect that should be highlighted when identifying those recycling measures is the missing concept of value. What is a more significant value than the initial one? Is the market value of final products made with recycled materials? Alternatively, are regarding environmental impacts? Alternatively, in the destination regarding market, but not regarding market value but regarding demand – a more valuable product can be made of recycled materials, but the demand for it can be too low, not allowing an adequate avoidance of virgin resources by replacing them with the recycled material. For that reason, maybe it is better to mention quality and not value.

Identifying which is the route of the waste being managed can be hard. Even end-of-waste criteria defined by the Waste Framework Directive only want the waste to be a product and define its features, although it is not helpful in this area. Again, the hierarchy of recycling options probably requires other methodologies to help to understand the more sustainable ones and such recycling process compared to the other waste operation from the waste hierarchy.

4.4 Other Recovery

Other recovery management option means (European Parliament and Council 2008):

> Any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfill a particular function, or waste being prepared to fulfill that function, in the plant or the wider economy.

In other recovery, the most spread technology is waste-to-energy (WtE). Depending on which side of the world, the type of technologies included in WtE varies. In Asian countries, WtE includes physical, thermal, chemical, and biological techniques (Pan et al. 2015). Concerning municipal solid waste, the most devoted WtE techniques are co-combustion, co-digestion, and fermentation/compost, being generated by biogas, heat- and refuse-derived fuel, presented in Fig. 4.4.

There are particular situations on recovery technologies at European Union, in the light of waste hierarchy. One case is defining when energy recovery vs. incineration is occurring, and the second case is when biological treatment (in this case by anaerobic digestion) is recovery or recycling. Those situations are particularly relevant when targets need to be fulfilled by European countries, this way, respecting the European legislation.

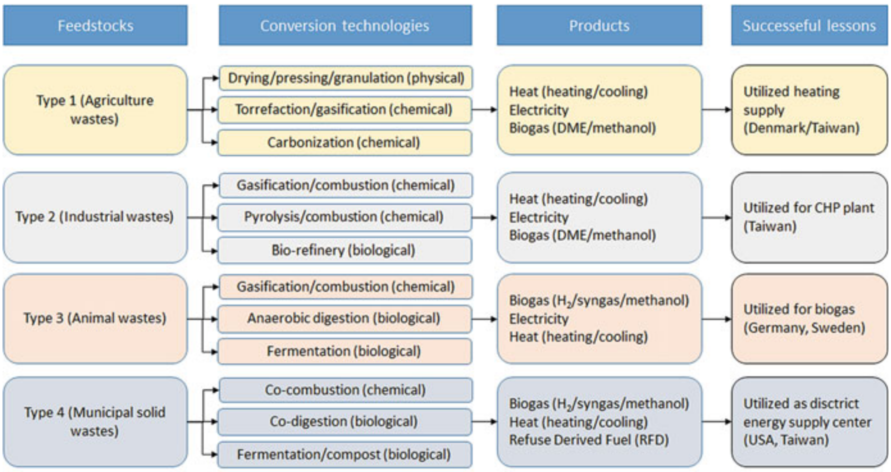

Fig. 4.4 Technology tree for WtE techniques. (Source: Pan et al. (2015))

Table 4.2 Average energy recovery efficiency, according to R1 formula, by type of plant in Europe

Type of plants	Average energy recovery efficiency (R1 formula)	Average waste flow (t/y)
CHP plants	0.71	230,000
Mainly electricity-producing plants	0.49	150,000
Mainly heat-producing plants	0.64	90,000

Source: Grosso et al. (2010)

Looking at incineration, the Directive 2008/987EC defines that it is a case of energy recovery through the definition of efficiency by R1 formula (Eq. 4.1). The units in operation before 1 January 2009 capable of reaching 0.60 of energy efficiency (equal or above) and units permitted after 31 December 2008 capable to reach 0.65 of energy efficiency are units where energy recovery occurs. The rest of the units not capable of doing it are making incineration (a disposal operation). This situation has made several incineration plants that do not recover the heat directly but for electric energy use without being capable of meeting the energy efficiency, which is the case of incineration plants in Portugal. In 2014, the energy recovery of municipal solid waste was 471 thousand tons, when incineration was 998 thousand tons (Eurostat 2017), showing the difficulty in increasing efficiency of electricity-producing plants in reaching the required efficiency. According to Table 4.2, the average energy recovery of efficiency by the R1 formula for electric energy production units is 49%. The R1 formula is given by Grosso et al. (2010):

$$\text{Efficiency} = \frac{E_p - (E_f - E_i)}{0.97 \times (E_w - E_f)} \quad (4.1)$$

"where E_p is the annual energy produced as heat or electricity. It is calculated with energy in the form of electricity (E_{el}) being multiplied by 2.6 and heat produced for commercial use (E_{th}) multiplied by 1.1 (GJ/year). In formula it results:

$$E_p = 1.1 \times E_{th} + 2.6 \times E_{el}$$

E_f is the annual energy input to the system from fuels, contributing to the production of steam (GJ/year); it is obtained by summing the products of each fuel flow by its net calorific value (NCV):

$$E_f = \sum m_{\text{fuel},i} \times \text{NCV}_{\text{fuel},i}$$

E_w is the annual energy contained in the treated waste calculated using its lower net calorific value (GJ/year):

$$E_w = m_{\text{waste}} \times \text{NCV}_{\text{waste}}$$

E_i is the annual energy imported, excluding E_w and E_f (GJ/year); 0.97 is a factor accounting for energy losses due to bottom ash and radiation."

The issue of anaerobic digestion is concerning the capability of digestate to meet the recycling definition, i.e., in producing a product. Here, also the composting is included in the discussion. The products of composting and anaerobic digestions are compost or digestate which, according to the Commission Decision 2011/753/EU (Commission 2011), is used as recycled product, material, or substance for land treatment resulting in a benefit to agriculture or ecological improvement (European Commission 2017). The issue here is on when the anaerobic digestion or composting processes are included in mechanical-biological treatment units, which are treating residual waste or mixed waste, i.e., municipal waste which has not been source separated. In those units, only if the owner of the unit can prove that the produced compost or digestate brings a benefit to agriculture or ecological improvement can it be seen as a product and, in that case, a recycling operation (European Commission 2017). The way to prove such benefit is made through the compliance with national norms and standard for compost and digestate, which is defined by each European country.

Eurostat is focusing on the presentation of recovery as the main incineration including energy recovery. The recovery rates vary from 1% from Bulgaria and Greece to more than 30% for countries like Denmark, Germany, Luxembourg, Finland, and Sweden (Eurostat 2017).

4.5 Disposal

Disposal definition considered is "any operation which is not recovery even where the operation has as a secondary consequence the reclamation of substances or energy." The disposal is the last option for waste, in the light of waste hierarchy but also of the circular economy, because the waste material will get lost to the economy but also the environment, not being available to replace virgin materials. Ways defined to avoid the disposal management option of waste have been defined by policy instruments, like bans of materials from landfill, higher landfill and incineration fees for recyclable materials, and the use of policy instrument to promote the other waste management hierarchy options.

The two most known and spread disposal techniques are engineering (also sanitary) landfills and incineration (without energy recovery). Figure 4.5 shows the countries Spain, the UK, Poland, France, Italy, Germany, and Bulgaria with considerable annual amounts of municipal waste sent to landfill and incineration without energy recovery in 2014. On the other hand, other countries like Luxembourg have no landfilling, no incineration without energy recovery, and no other disposal.

The dependence of landfilling has made countries to divert waste from this operation, namely, by landfill taxes and taxes for specific waste features going to landfill. Another perspective to reduce the environmental impact from landfills is its mining. Landfill mining has been used all over the world in the last 62 years; it started in 1953 in Israel and rapidly spread to the USA, Canada, India, and several

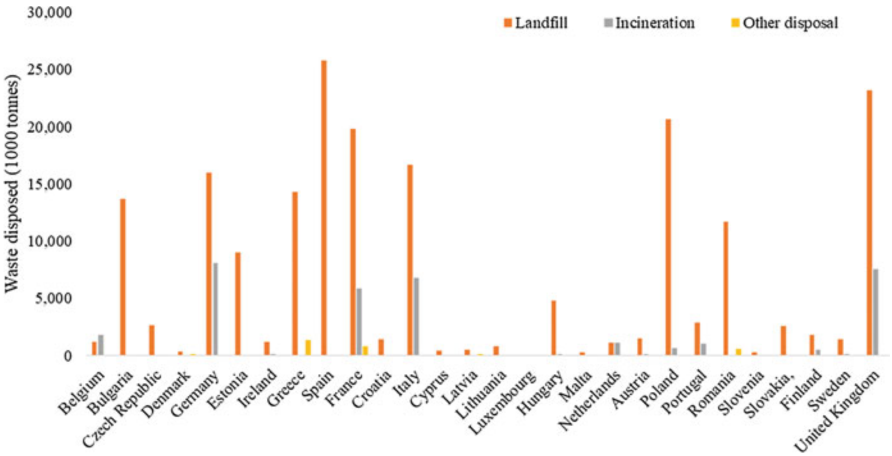

Fig. 4.5 Waste disposal destinations in European countries. (Source of data: Eurostat (2017))

countries in Europe like Germany, Sweden, Belgium, and Italy (Hogland et al. 2004; Kurian et al. 1999; Jones et al. 2013). Landfill mining is being addressed as the new source of raw materials for Europe. However, landfill mining can have other drivers that have justified it. The needs to recover the land for added value activities like construction, to remove waste and stabilize hazardous fractions, to extend landfill capacity, to generate revenues from materials obtained and fuel for energy production, and to reduce landfill closure costs are drivers to the landfill mining (Collivignarelli et al. 1997; USEPA 1997).

Although all the drivers promoting landfill mining, most of the time, this operation is not economically feasible, leading to the concept of "temporary stage," where materials without value to be mined are conditionally stored (Breure et al. 2018; Jones et al. 2013). Besides the pragmatic economic affordable issue, other barriers such as misleading and missing legislation, shortage of environmental standards for the materials to be explored, shortage of best available techniques that support the technical operation of a landfill mining activity, lacking of standardization of safety and health, public skepticism, the missing of studies and life cycle assessment showing the environmental benefit of landfill mining, and the decreasing of recoverable waste in landfills are to be solved to enable landfill mining to be a reality (Pires et al. 2016).

4.6 Final Remarks

Using the waste hierarchy ordination of waste operations to manage municipal solid waste (or another type of waste) may be a challenge and can be costly, and the environmental benefit can be questioned. Aspects related to infrastructure location, features of material to be recycled, and quality of recycled material as well as of waste-derived fuel can dictate different destinations that may impose different impacts on the environment, different financial resources, and different revenues that have made researchers doubt the waste hierarchy. One thing is sure: waste hierarchy helps to save resources. Although waste hierarchy seems static, the concepts of the waste operations prioritized are not closed and in continuing update, as long as technology also evolves.

Research on waste hierarchy and how the waste collection can contribute to the hierarchy is needed. European regulations are based on the scientific evidence that source separation of waste is a requirement to ensure recycling, being this aspect more determinant of the biodegradable municipal waste. If biodegradable municipal waste is not source separated, the quality of compost of digestate is questioned, not ensuring the occurred recycling but recovery only. For other materials, the mechanical processing of mixed waste is capable of bringing high amounts of recyclable waste that citizens are not source separating, making more material available for recycling, although with a loss of quality. An analysis of the entire life cycle of the waste – from the source of the waste as a product until the last destination – is required to ensure that the best destination is given regarding sustainability.

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