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ORIGINAL PAPER

Transforming Waste to Wealth, Achieving Circular Economy

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Abstract

Wastes are usually thought of as unwanted or unusable materials. Waste is any substance which is discarded after primary use, or considered worthless, defective, and of no use. The term is often subjective, as not every application has identical raw material requirements and sometimes even objectively inaccurate. A starting point towards managing waste is the division in basic categories, ranging from municipal and agricultural waste to radioactive and explosive waste. Through proper collection of municipal solid waste, very important metals and other valuable sources can be recovered and used in new products, thus achieving significantly lower production cost and environmental impact. Success stories in waste management are reported in countries around the world. These typically showcase optimal waste transformation to wealth. Furthermore, applied waste management methods are specified. These actions should be adapted by every organization handling waste. At a managerial level, these must be considered as potential resources, commodities with significant economic, environmental and sociological added value. This paper attempts to identify and present the valuable resources and products that exist in waste streams, focusing mainly on their monetary value, based on data recovered from literature and raw materials stock markets. Municipal solid waste and non-hazardous commercial and industrial wastes are considered in this context. The methodology followed was based on identification and analysis of cities-communities and countries that have successfully adopted waste management policies towards circular economy and waste to wealth transformation.

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Introduction

Waste is any substance which is discarded after primary use, or it is worthless, defective, and of no use. The term is often subjective, because what is waste to one need not necessarily be waste to another. Sometimes, the matter is objectively inaccurate, for instance, to send scrap metals to a landfill is to inaccurately classify them as waste, because they are recyclable.

Municipal wastes include the following:

- Household waste, commercial waste, and demolition waste
- Agricultural waste
- Electrical and electronic wastes (many of them considered hazardous)
- Hazardous waste

    Industrial waste
    Biomedical waste-clinical waste

- Special hazardous waste

    Radioactive waste
    Explosive waste

Typical composition of industrial non-hazardous wastes is similar to municipal solid waste (MSW) in different percentages with the addition of waste oil and sludge. A typical composition of electronic waste includes plastics, metals, PCBs, glass, and hazardous wastes. Concentration of each material is varied among countries worldwide. Globally, wastes generated are causing several environmental impacts, from generation and transportation to their disposal in landfills. Increased amounts of solid municipal wastes are expected due to the increase in population. Nowadays, almost 80% of global municipal solid wastes are disposed of in landfills, and only a 20% are disposed in sanitary landfills. Moreover, environmental and energy issues are under intense investigation. Fossil fuel reserves as well as natural resources across the world are decreasing; CO2 emission levels are extremely high due to extensive use of fossil fuels whilst increased amount of municipal solid wastes further impact climate change due to CH4 emissions from landfills. Consequently, additional problems seem to be arising such as economic and social [1].

Furthermore, climate change constitutes a major environmental issue bearing a heavy impact in various aspects of human life and other organisms. In order to face energy supply problems as well as climate change impacts, the European Union has enacted several directives including 2009/29/E.C. [2], 2009/28/E.C. [3], 2009/31/E.C. [4], and Decision No. 406/2009/E.C. [5].

Considering that the last few years both economic activity and raw material consumption have increased, it can be concluded that the in-force development model is unsustainable. However, one of the EU’s fundamental objectives is to contribute in sustainable development through its policies, as initially included in the Treaty of Amsterdam in 1997. In 2001, at the Gothenburg summit, EU sets the base for a sustainable development strategy (EU S.D.S.). Two targets of this strategy were defined**:** Initially take measures towards restriction of activities that contribute to unsustainable development and secondarily propose that all EU’s policies, either economic, social, or environmental, should be issued in such a manner that they reinforce each other. Thus, the overall aim is to improve life quality and public health of citizens, among the member states, indicating several fields as the most crucial that policies should be focused on. These include climate change and clean energy, sustainable transport, sustainable consumption and production, conservation and management of natural resources, public health, social inclusion—demography and migration—as well as global poverty and sustainable development challenges [6]. However, any attempt on having a positive impact on sustainable development must demand the participation of citizens, throughout any shift required in their daily habits. Furthermore, political and economic decisions on behalf of member states or worldwide are mandatory. Thus, the exploitation of other valuable energy sources such as wastes instead of conventional fuels—coal, oil, gas, nuclear—as well as the use of materials recovered from wastes is more than important, enhancing the concept of circular economy.

Further exploitation of MSW as feedstock in waste-to-energy (WtE) facilities and the overall upgrade of the latter may constitute a solution that could have a great contribution both in environmental protection and the energy sector, satisfying objectives and aims of EU’s policies and directives. In the basis of the two principle EU strategies, Europe 2020 and Strategy for Sustainable Development, the development and the integration of WtE facilities as the main waste treatment method can be an effective alternative energy option, leading to reduced CO2 and CH4 emissions while saving limited fossil fuel and natural resources. The text is organized as follows. Waste is analyzed as resources, wealth and as a commodity. All the above facets are presented so as to identify the justified placement of waste in a circular economy approach. Furthermore, energy recovery from relevant processes is considered. The final section of the text is dedicated to the identification of communities, cities, and countries that have successfully implemented such policies. The databases contributing to this effort were the EU databases and Waste ATLAS.

Wastes as Resources

Manufacture of products demands raw materials and energy. Metal, wood, plastic, leather, and glass are the most valuable materials widely used in manufacturing processes. For everyday modern living, human beings need food (agricultural products, meat and its products, fisheries) and energy. Thus, energy in any of the available form (electricity, thermal energy, energy for cooling) is vital.

In the novel globally accepted approach, one’s waste can be the other’s raw material. That roughly describes the concept of circular economy. The most representative example is found in waste water treatment plants. What is thrown away from our houses is transformed to water, for agricultural use, energy, and fertilizers. Furthermore, many useful materials and minerals are collected which reduce the need for new raw materials and reduce the monetary and environmental cost for reprocessing [6]. Recycled and recovered materials can be reengineered, reducing the energy and water demand for repurpose, and at the same time create valuable supply chains for these materials increasing the revenues associated with them. Significant amounts of materials, including pieces of equipment, can be recovered and repurposed to drive the concept "wastes as resources" in multidimensional pathways from simple raw materials to full parts (spare parts, used parts of equipment, used or reengineered parts, etc.) creating multilevel resources for equipment and production [7].

Wastes as Wealth

In wastes, one can find valuable raw materials. Metals cost money and vast amounts of energy to be recovered from earth through mining and industrial procedures. Fertilizers require energy intensive chemical industries and raw materials. Moreover, construction raw materials (gravel, etc.) require mining procedures which are energy intensive. All these procedures require significant amounts of water in addition to raw materials and energy if the materials processed are not presenting high purity. Furthermore, in waste streams, metals are also included. Steel, copper, aluminum, and zinc are typical metals found in wastes [2]. These metals in waste streams present purity that can reach up to 100%, such as aluminum cans. The production of new Al cans, from empty collected Al cans, and other Al goods such as window frames requires 95% less energy and 97% less water [2–6]. Thus, through proper collection, valuable metals can be recovered and used in new products with significantly lower production and environmental cost. Moreover, waste streams include organic wastes. The organic portion of wastes is full of useful ingredients for agriculture and farming, providing nutritional elements to vegetables and fruits. Low energy intensity and simple procedures (simple aerobic digestion) even for domestic use transform organic wastes to natural fertilizers—compost for use in soil improvement for agriculture and planting. More complex procedures, such as anaerobic digestion, transform larger amounts of organic wastes to fertilizers and energy, electricity, and heat. Plastics, rubber, leather, wood, and packaging materials found in waste streams are materials with high calorific value. These materials can replace other energy sources in industrial or power processes, improving process energy efficiency and reducing use of non-renewable sources [5–7]. Construction and demolition waste (CDW) is one of the heaviest and most voluminous waste streams. It consists of numerous materials, including concrete, bricks, gypsum, wood, glass, metals, plastic, solvents, asbestos, and excavated soil, many of which can be recycled. There is a high potential for recycling and reuse of CDW, since some of its components have a high resource value. In particular, there is a reuse market for aggregates derived from CDW waste in roads, drainage, and other construction projects. Technology for the separation and recovery of construction and demolition waste is well established, readily accessible, and inexpensive in general. The procedures require raw materials that are considered as waste and avoid significant amounts of mining-oriented materials with energy intense methods.

Following these assumptions and considering the aforementioned multidimensional creation of resources from raw materials to complete parts of equipment, through disassembling and reengineered components, creates value from the parts themselves to complete supply chains, allowing the creation of additional markets also for used components in addition to the raw materials market, and develops new specialized professions. These issues are also of paramount importance and create an indirect market, thus wealth based on materials, energy and components from different types of wastes generated in our communities (Figs 1 and 2).

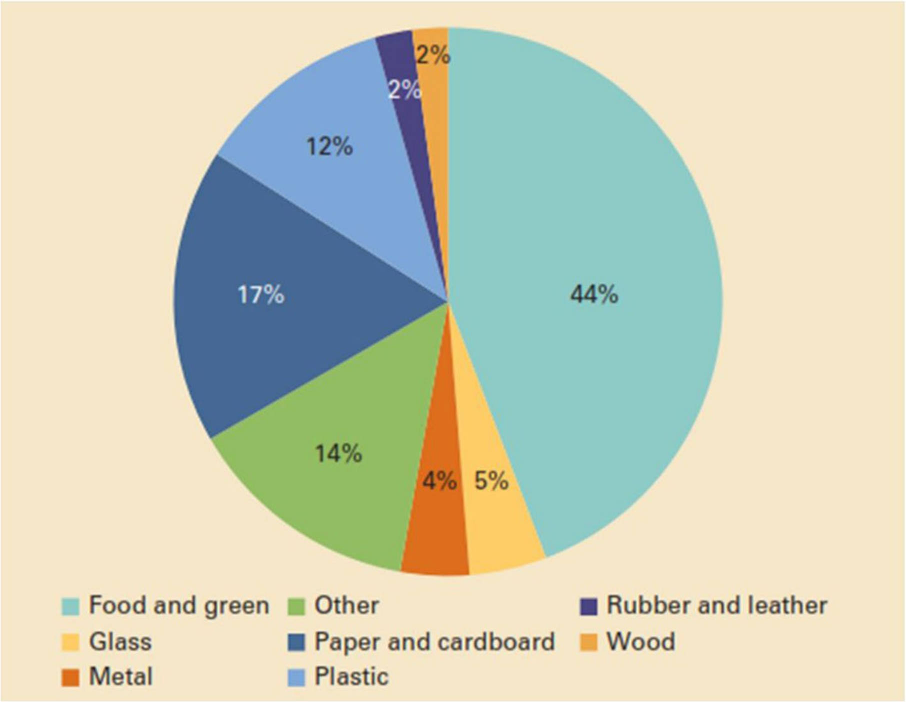

Fig. 1 Global waste composition [8]

Fig. 2 Electrical and electronic waste (e-waste) [9, 10]

Waste Management

The strategic approach depends on what is being collected. The collection strategy defines the path to transform waste to wealth. The systematic source separation of solid wastes is the simplest way to wealth (Fig. 3).

On the other side, and the most known collection system is based on black bag collection. In Fig. 4, the systematic black bag collection is presented, revealing the steps followed leading to the final product. As it may be easily realized, in any of the proposed steps, several materials may be recovered.

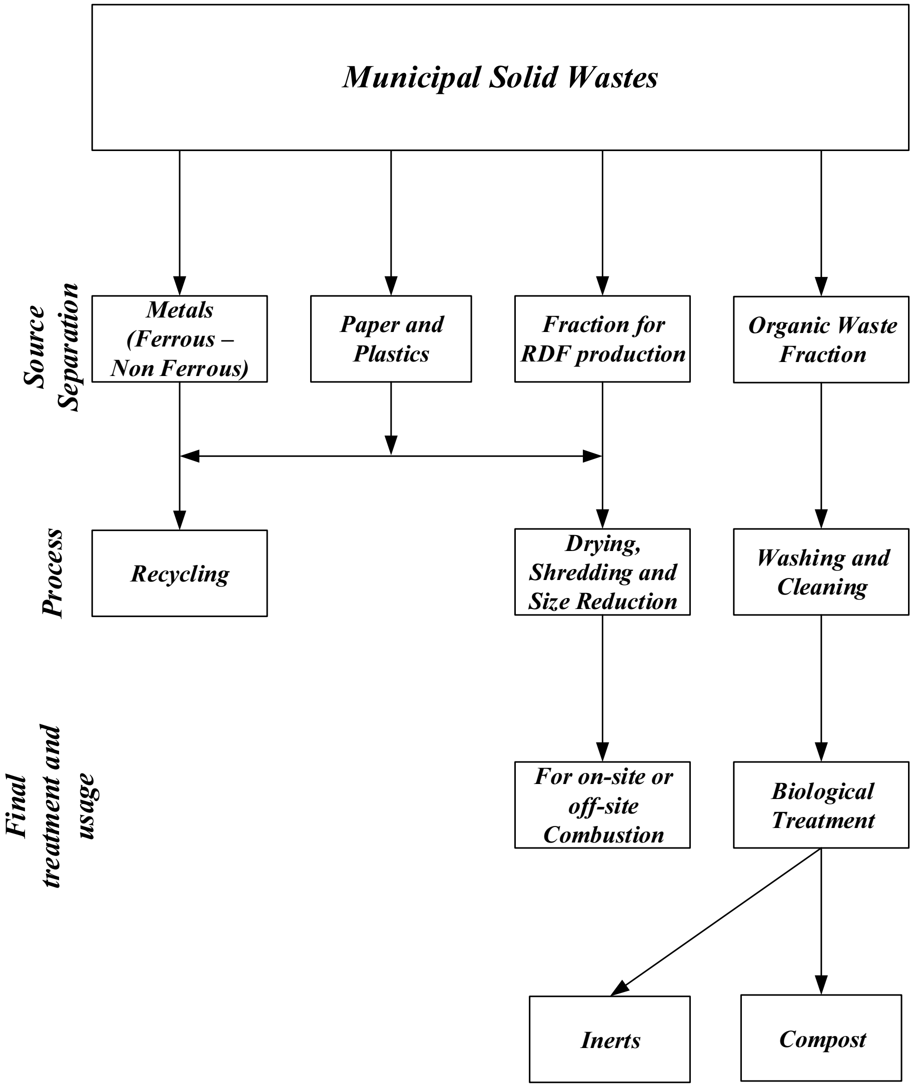

Fig. 3 MSW management. A strategic approach [11]

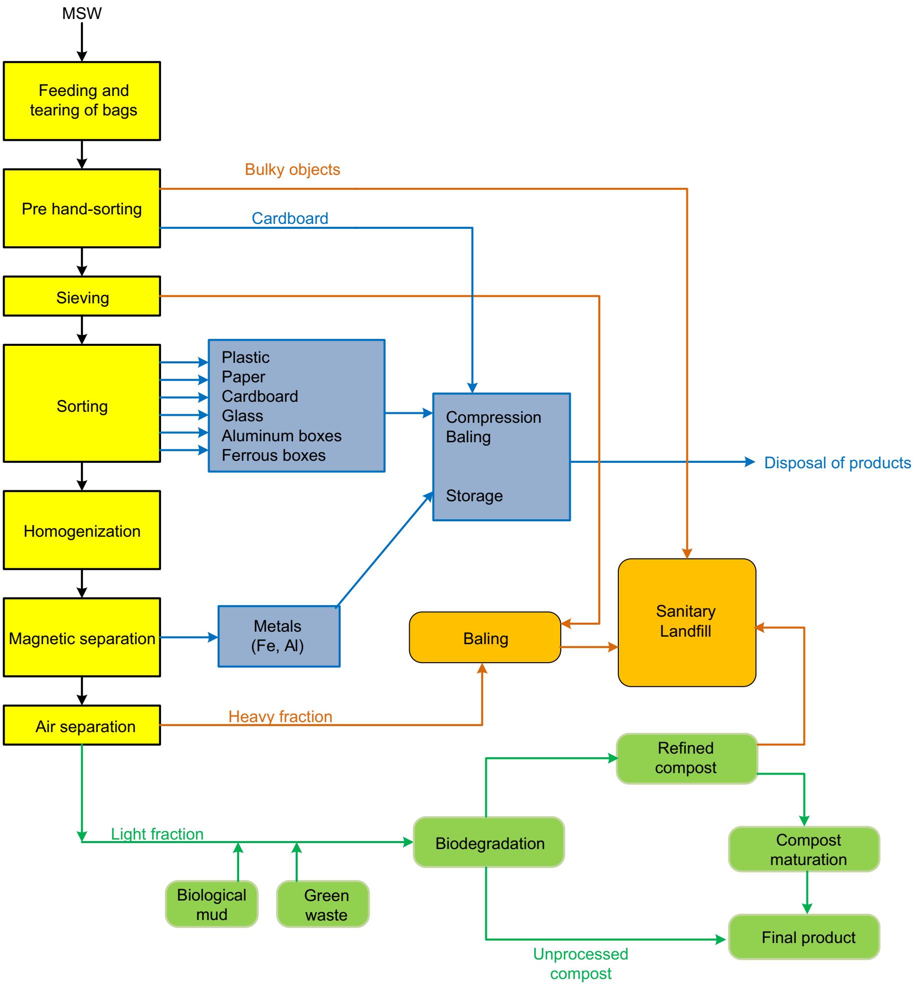

Fig. 4 The systematic black bag collection [7]. The process is illustrated in detail, where every step towards reclaiming various materials can be seen. These include sieving, sorting, and separation

Waste as a Commodity

Steel, copper, aluminum, and zinc are the typical metals that can be found in wastes and are internationally trade commodities (Table 1). Moreover, other materials such as paper, plastic, and glass can also be recovered, enhancing the recycling rates.

From Table 1, what should be emphasized is the price of recovered materials. This could also underline the significant role of recycling, and its contribution in wealth creation from wastes. Paper, plastics, organic fraction, wood, textiles, rubber, etc. present significant calorific values. Thus, it can be converted to fuel for power production.

Table 1 Prices of international trade commodities [12]

Material	Price per ton (€)
Cu from scrap	2300 (average)
Al from scrap	850 (average)
Steel from scrap	750 (average)
Paper (from separated collection)	107
Clear PET	263
Color PET	60
Natural HDPE	580
Mixed HDPE	455
Mixed polymer	130
LDPE	325
Plastic PRN	414
Compost (clear, organic without other fractions)	308

Energy Recovery

An alternative option in waste management can be energy recovery/energy from wastes. Energy recovery from wastes can be achieved through two processes: biological and thermo-chemical processes. The first one includes anaerobic digestion and fermentation, while the second includes combustion, pyrolysis, and gasification [13, 14]. However, the majority of waste-to-energy (WtE) facilities are focused on thermal treatment technologies and particularly on combustion processes [10]. MSW that cannot be recycled or landfilled can be used as a fuel in waste to energy facilities. According to Table 2, significant heat content can be recovered from both biogenic and non-biogenic materials.

As seen in Fig. 5, recycling is hierarchically above energy recovery. However, it has been proven that wherever a waste-to-energy facility is operational, the recycling rates increase as well [16]. WtE facilities can enhance the recycling rates instead of reducing them. Furthermore, most of the materials included in MSW such as plastic and paper possess a specific potential for recycling, and reaching their maximum value can be turned into combustible materials [17]. Moreover, WtE facilities can reduce the weight and volume of municipal solid wastes by 75% and 90%, respectively, avoiding land occupation for

Table 2 Heat content per material [15]

Biogenic	Heat content (kWh/t)	Heat content (GJ/t)	Non-biogenic	Heat content (kWh/t)	Heat content (GJ/t)
Newsprint	4689.1	16.88	Rubber	7883.6	28.38
Paper	1963.6	7.07	PET	6008.0	21.63
Containers and packaging	4835.7	17.41	HDPE	5714.9	20.57
Textiles	4044.4	14.56	PVC	4835.7	17.41
Wood	2930.7	10.55	LDPE/LLDPE	7063.0	25.43
Food waste	1524.0	5.49	PP (polypropylene)	11,136.7	40.09
Yard trimmings	1758.4	6.33	PS (polystyrene)	6008.0	21.63
Leather	4220.2	15.19	Other plastic	5304.6	19.10

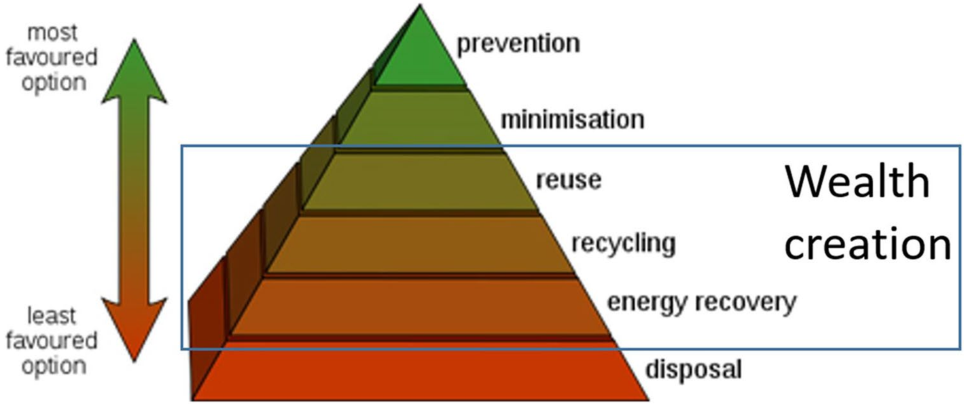

Fig. 5 Waste hierarchy pyramid [19]

Table 3 Energy and R.E.S. content of several fuel types [20]

Fuels type	Energy content M.J./kg	Total emissions CO_2g CO_2/kg	RES content % RES	Emissions CO_2 Mg CO_2/TJ
Lignite	8.6	955	0%	111
Brown coal	29.7	2762	0%	93
Oil	35.4	2620	0%	74
Natural gas	31.7	1775	0%	56
Municipal solid wastes	9–10	1170	55%	45
Refuse derive fuel/solid recovered fuel from MBT	14–16	1067	67%	24

Table 4 Comparison of air emissions of WtE and fossil fuel power plants [23]

Fuel	Air emissions (kg/MWh)		
	CO_2	SO_2	NOx
MSW	379.66	0.36	2.45
Coal	1020.13	5.90	2.72
Oil	758.41	5.44	1.81
NG	514.83	0.04	0.77

sanitary landfills [18]. On the other hand, WtE facilities can produce energy in the form of electricity and heat. According to the US Department of Energy, energy from wastes is recognized as a renewable source of energy in the form of biomass due to the large percentage of included organic materials, in contrast to materials derived from fossil sources (Table 3). Nowadays, the development of renewable energy is high in the public agenda compared to other forms of energy to protect the environment and human health.

The Europe 2020 strategy or alternative target 20–20-20, which has been set according to the energy directive 2009/28/E.C., introduced specific goals in a number of different sectors. A reduction of 20% of GHG (greenhouse gas) emissions compared to 1990 levels, 20% share of energy production by renewable energy in EU, and finally 20% improvement in energy efficiency are the goals among the member states. More specifically, considering the power sector, GHG emissions reduction must be 21% lower compared to 2005 levels. Treating MSW in such a manner that could lead to the simultaneous production of renewable energy can lead WtE facilities to the top ranking in waste management methods, satisfying current EU environmental and energy directives. What should also be emphasized is that renewable energy production derived from energy recovery from wastes can support the effort in securing energy supply and independence. Although security of energy supply is provided by renewable sources [21], the intermittent energy production from other renewable energy sources due to their stochastic nature have resulted in lower capacity factors in contrast to energy recovery, reaching a capacity factor of over 70% [22]. Finally, the energy content of MSW should be highlighted compared to total emissions. According to Table 3, energy content of MSW as received reaches 9–10 MJ/kg, while RDF (refuse derived fuel)/SRF (solid recovered fuel) may reach almost 16 MJ/kg. Compared to conventional fuels and mainly to lignite, energy content of wastes may be higher. However, it is worth noticing that air emissions are significantly lower (Table 4), while in comparison to other activities, Dioxin emission is by far lower (Table 5).

Table 5 Toxic emissions comparison [11]

Dioxin emission sources	Comparison scale	Dioxin emissions
Modern waste-to-energy facility	1	0.01 ng/m^3
Modern hazardous waste thermal treatment plant	1	0.01 ng/m^3
Open non-controlled burn (e.g., domestic fire places)	1000	10.00 ng/m^3
Fireworks	10.000	100.00 ng/m^3
Burning landfill	100.000	1000.00 ng/m^3

In order to prevent or reduce, as far as possible, the negative effects of landfill wastes on environment and human health, the EU has also enacted the directive 1999/31/E.C. or landfill directive, which contains provisions for acceptable or unacceptable wastes and the corresponding processes, while laying down the conditions for the authorization, operation, closure, and aftercare of landfills. Moreover, the directive imposes the gradual volume reduction of biodegradables deposited in landfills. Considering the 2008/98/E.U. directive where waste to energy plants have been upgraded as waste treatment in hierarchy waste treatment can be considered an advanced solution in order to meet the increased volume of wastes.

Successful Implementation

Success stories in waste management are typical cases where wastes are transformed into wealth for the countries. Some of the most sustainable cities [24] in the world are presented in Table 6.

Success stories in waste management and the world's most sustainable and wealthy cities are applying specific waste management methods. One of these is composting the separated fraction of organic wastes. Recycling of different types of wastes derived from separated collection systems reaches high rates. In many of the cities presented above, recycling

Table 6 Most sustainable cities in a global scale [25]

Cities	Population (Millions)	Waste quantities (Mt)	Recycling	Composting (separated fraction)	Waste to Energy	Landfilling
Singapore	5.0	6.1	57%		41%	2%
Berlin	3.4	0.7	50%	10%	40%	N/A
Vienna	1.6	1.0	23%	11%	63%	3%
Munich	1.4	0.6	44%	6%	49%	1%
Copenhagen	0.9	0.6	62%	4%	25%	9%
Malmö	0.7	2.1	20%	6%	69%	5%
Lee County Florida	0.6	2.0	46%	3%	51%	N/A
Zurich	0.4	1.1	29%	9%	62%	N/A
Marion County Oregon	0.3	0.3	45%	9%	34%	12%

accounts for more than 50% of the total wastes produced. Waste treatment through landfilling has decreased appreciably. On the other hand, energy recovery from wastes reaches high rates. Data appearing in Tables 3 and 4 reveal the significant contribution of waste to energy (incineration, R1). Today in the EU, there are 452 WtE facilities in operation and over 800 globally. In 2009, more than 70 Mt of wastes were incinerated in WtE facilities, 38 Mt of fossil fuels were avoided, 28 million MWh of electricity were generated for 13 million citizens and 70 million MWh of thermal energy for 12 million citizens were also produced (Table 7).

One (1) ton of MSW can generate 650–750 kWh, leading to the avoidance of mining 350 kg of hard coal or 200 lt of oil. Also, avoidance of 32.4 kg/ton CH_4 emissions (GHG 21 times more affecting than CO2 GWP of $CH4 = 21$) as well as other volatile organic compounds is produced in landfills. In a modern landfill with CH_4 capture and burn/usage, only the 70% is collected and destroyed safely. WtE protects the land, as one unit of 1×10^6 ton/y requires for the total systems around 10 ha (0.1 km^2), with an operational lifetime of 30 years, while the equal amount of wastes 30×10^6 ton requires around 300 ha (3 km^2). An upgrade of the unit (same area) will allow an additional 30-year operation [10]. There are several pathways to recover energy from non-recyclable wastes and from the composting and recycling residues. The diagram in Fig. 6 shows different approaches that can lead to successful implementation (Table 8).

Barcelona's Example

Barcelona is the city selected as an example, based on the types of utilization of the energy recovered by WtE facility which is one of the few trigeneration facilities as well as it is located in the Mediterranean coast of Spain presenting the typical climate conditions that includes hot summers and medium cold winters. In addition, the city presents significant changes in waste generation due to seasonal changes in tourist flows, while the waste streams contains high portions of food wastes and high moisture. The combined tri-power WtE Plant unit of Barcelona transforms wastes to wealth, commodities, and services as follows: A capacity of 350,000 tons of wastes or waste derived fuels generates annually almost 150 GWh of electricity and 68,000 ton of steam for district heating and cooling systems. Bottom ash is used in roads construction, while the flying ash is extracted for heavy metals and rare earth extraction. The gate fee, which is the cost payed by citizens for the treatment of their waste, is around 30 €/ton. Finally, the lowest price of all EU electricity is sold at a fixed price of 70 €/MWh [24].

The district heating and cooling system serve hotels, one hospital, office buildings, houses, and malls. Furthermore, the WtE Plant unit of Barcelona has indirect benefits.

Table 7 Share of MSW treatment methods in EU28 for the years 2008–2017 [25]

EU28	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Landfill (%)	40.21	39.63	37.62	35.24	32.94	31.06	28.57	26.46	24.35	23.00
Incineration R1 (%)	15.52	16.14	17.05	19.80	21.12	23.58	24.62	24.19	26.04	26.81
Incineration D10 (%)	6.34	6.33	5.29	4.78	3.80	2.82	2.65	3.50	2.13	1.32
Recycling (%)	23.96	24.83	25.07	26.35	27.46	27.43	28.56	29.51	29.87	29.89
Composting (%)	13.98	13.88	13.34	13.84	14.71	15.37	15.86	15.98	16.83	16.86

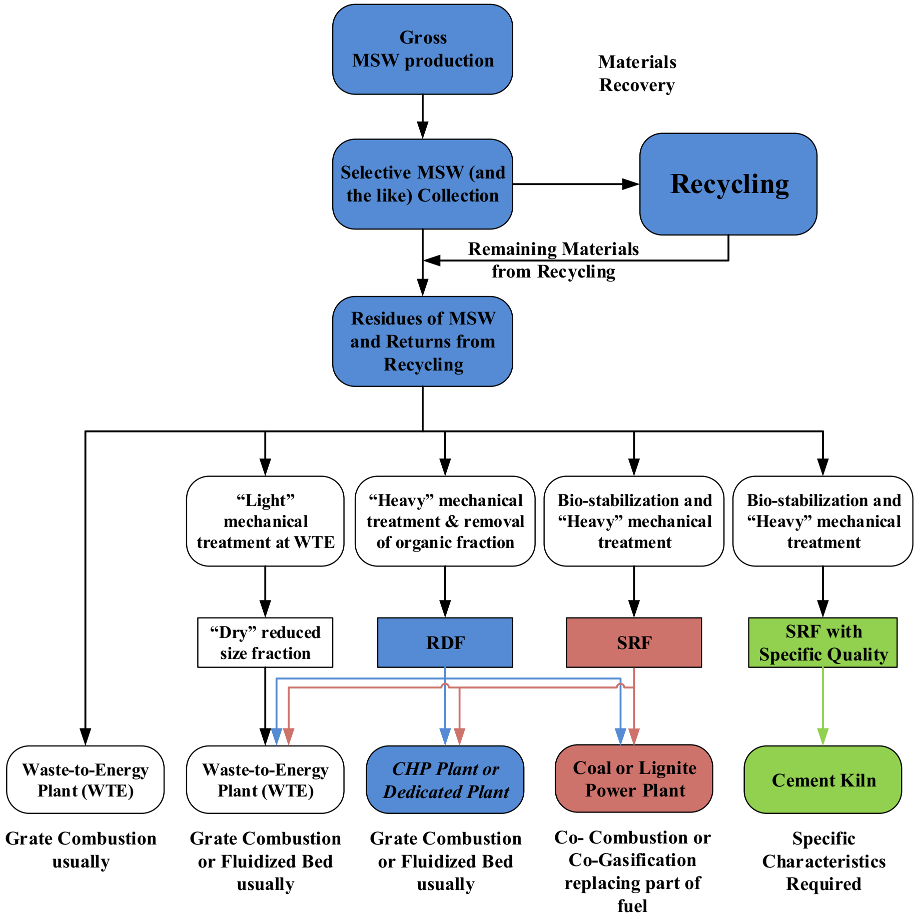

Fig. 6 Schematic diagram for RDF/SRF derived from MSW utilization alternatives [24]

The additional investment cost of district cooling was 50 M€. District heating and cooling network is 13.1-km long and accounts for contracted heating over 44 MW and contracted cooling over 68 MW. Additional advantages are reduced pollution (no heating oil or natural gas is used), reduced noise (no cooling systems-compressors are used), and reduced water consumption (the water circulation network is closed). The system uses two hot water pipes (feeding in 90 °C returned in 60 °C) and two cold water pipes (feeding in 90 °C returned in 60 °C) [24].

The example of Barcelona proves the multidimensional possibilities from transforming waste to energy in hot climate cities for covering the demand of electricity, heating and cooling, and creating wealth from wastes, providing low cost clean energy and reducing the waste streams in the city, with the lower cost for the citizens. This lower cost creates additional indirect income to the citizens as they have to pay less for their wastes. It should be noted that the lower cost for energy and waste management are of paramount importance for supporting the lower income families allowing them to avoid energy poverty.

Table 8 Benefits of waste-to-energy facilities [10]

Capacity of wastes for thermal treatment MSW/RDF/SRF (t/y)	400,000	700,000	1,000,000
Heating value average (MJ/kg)	11.5	11.5	11.5
Net electricity production (GWh)	260	455	650
Land requirements (ha for 30 years)	0.095	0.1	0.1
Population served	141.530	247.677	424.336
Number of families served	47.177	82.559	141.445
CO_2 Emissions reduction ($MgCO_2$/y)	348	608	1042
Weight and volume reduction 75–80% (remaining from thermal treatment in t/y)	< 100.000	< 175.000	< 250.000
Bottom ash: inert materials ~ 20% (basic use in road construction and prefabricated cement products) (t/y)	80,000	140,000	200,000
Flying ash: hazardous materials ~ 1.5–3% (recovery of heavy metals and rear earths) (t/y)	6000–12,000	11,000–21,000	15.000–30,000
Contribution on R.E.S. production (GWh)	130	227,5	325
% Generation (based 2010, 57.39 TWh for Greece)	0.45%	0.79%	1.13%
% RES generation (based 2010, 10.56 TWh for GR)	1.23%	2.15%	3.08%
Reduction on energy imports (GWh/y, | MW)	260 | 35	455 | 60	650 | 95
Reduction on energy imports (total, in M€)	40		
Direct employment positions during operations	~ 60–70	70–80	80–100
Indirect employment positions during operations	> 120	> 140	> 160
Direct employment positions during erection/construction	~ 500	~ 700	~ 1000
Direct investment (unit cost) (in M€)	200–250	300–350	400–450
Per 1M€ income of the unit returned investments to the local community (M€)	1.60–1.90	1.65–1.85	1.70–1.95
Continuous investments (operational cost) (M€)	16–20	25–32	30–40

Sweden's Example

Sweden is a typical Scandinavian EU country, with high quality environmental standards and long experience in circular economy and waste to wealth transformation. Sweden imports a significant fraction of Norway's wastes to utilize them in electricity and heat, having invested extensively in infrastructure (Fig. 7). This decision allows Sweden to convert the wastes of Norway to wealth for the country and its citizens. Thus, it collects money from Norway to treat its wastes, uses the wastes of Norway to cover the needs in energy (electricity and heat), and recovers the metals from the bottom ash and recycle/sell them to industry. The rest of the bottom ash is used in road construction and in prefabricated concrete products, reducing material extraction through mining procedures. The import of waste makes Sweden's example unique as far as circular economy management is concerned [24].

Based on this decision, Sweden uses imported wastes so as to fuel district heating networks of cities and villages, covering a significant part of their needs in electricity. From the bottom, ash metals (ferrous and non-ferrous) are recovered and supplied in metals' industries as raw materials, and prefabricated cement parts are constructed, resulting in a very high level of resource utilization from wastes [24]. Thus, Sweden is using wastes, internal and imported, to cover part of the country's energy needs, recovers raw materials for the industry, and creates new products using the by-products from these processes. Wealth creations are more than obvious in multiple ways from a decision that in many cases creates questions, if analyzed superficially.

Discussion

The EU policy tends to favor circular economy (CE) practices. Further research on the other categories of wastes and how they can be transformed to wealth can lead to a CE. This entails identification of the limitations, needs, and requirements of the desired transformations through intensive research. Only then can opportunities and challenges be met to lead to a CE. But the pathways are not that easy to address the circular economy. Though the EU roadmap is very consistent, it covers everything, and most of all, it presents mainly the issues related to the environment and jobs creation, as well as economics for the consumers. The critical part is the clear presentation that wastes can create wealth and well-being if treated as resources, allowing people to adopt and embrace the efforts. Although the climate crisis is at the top reasons that make people worry globally, the circularity approach in the everyday economy is not yet a reality.

Barriers remain toward triggering the full potential of CE (e.g., economic and market-related, technological and information-related, institutional and sociocultural) [27]. In this regard, waste management can promote the CE by highlighting its benefits, sharing waste-related data, and boosting stakeholder cooperation. Moreover, stronger connection between product designers and the waste management sector is needed to support circularity and wealth creation by making recycling/reusing easier (e.g., better material choice and eco-designed products [28]. On top of that, supply chain management and CE should be integrated more sustainably to benefit the waste management system [28].

Recently, several authors have highlighted that waste management strategy should be shifted toward the top of the waste hierarchy (WH) if a real contribution to CE is

Fig. 7 Waste-to-energy plant in Malmö, Sweden [26]

expected [29]. To this end, a high technology readiness level (TRL) is also needed. According to Rybicka et al. [30], four scenarios can be defined in a WH–TRL plane: (i) Desired (i.e., high WH and TRL), (ii) high environmental/innovation potential (i.e., high-WH and low-TRL), (iii) re-thinking needed (i.e., low-WH and high-TRL), (iv) not viable (i.e., opposite to desired). Based on these classifications, the waste-to-wealth contribution to CE, as presented in this paper, can be categorized as Re-thinking needed. The examples described and the waste-related data show a high TRL degree for certain technologies. At the same time, the waste is not yet considered a resource in other cases, leading to a lack of misalignment from CE principles. This has been recently pointed out by other authors within the EU framework when assessing waste management policies and CE goals [31]. Nevertheless, the examples discussed present the approaches that local communities have used to create measurable wealth by providing low-cost heating and cooling feed by wastes while simultaneously creating economies of scale for the cities. This approach allows citizens and large communities to benefit directly from the same action: Transforming waste to usable resources, here is energy, with a direct economic benefit for all involved parties.

Conclusions

Wastes are resources and should be treated as such. They are commodities with significant economic, environmental, and sociological added value. Proper waste treatment is a key indicator for achieving sustainable development and sustainable economic growth. A well-designed waste management plan reduces or even annihilates the wastes in landfills preserving valuable land. The lack of waste dumps and non-controlled landfills without leakage collection is one of the key elements to preserve underground waters. An optimally designed waste management plan transforms wastes to raw materials and reduces the need for new ones. Additionally, jobs are created and innovation is enhanced with novel, advanced waste management technologies. Significant reduction of GHG emissions related to wastes supporting the global efforts to minimize the climate change can also be achieved by the implementation of a proper waste management system.

Recovered paper to be recycled will help in forest preservation. Organic fertilizers will reduce the need for chemicals, and underground waters will be less polluted from agricultural activities. Metals recovery will reduce the need for mining and will preserve remaining quantities, while at the same time a new market will be developed, to cover the industry’s needs. Energy resources will be preserved, as the energy recovery from wastes will lead to reduced consumption of oil, coal and natural gas. Energy security will be increased, and energy goods’ (electricity, heating, fuels) imports will be reduced. All these parameters will lead to wealth creation and increased gross domestic product.

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Declarations

Conflicts of Interest The authors declare no competing interests.

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