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CASE REPORT: MUNICIPAL SOLID WASTE TREATMENT AND ENERGY RECOVERY FOR ALTERNATIVE FUEL PURPOSE IN GERMANY

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ABSTRACT

This present case report aimed to analyze the waste sector in Germany regarding the pre-processed municipal solid waste (MSW) application for alternative fuel purposes, whose monitoring and specification of performance parameters are aligned with environmental and regulatory requirements, in order to obey emission limits and ensure the quality standards. Therefore, unlike other studies in the literature, it was made the correct differentiation about the denomination of alternative fuels in terms of their final quality, since this is directly related to the type of equipment and technology to be applied. It was observed that the lighter fractions (< 25 mm) of pre-processed waste are the most desirable for the high grade SRF (Solid Recovered Fuel) purposes in cement kilns, because they have less potential for contamination and can achieve higher calorific value and also. While the heavier fractions (< 80-100mm) are used as RDF (Refuse Derived Fuel) to denote the alternative fuel with lower burning performance. Besides, it was found that this successful performance in Germany was achieved in a long-term evolutionary process based on technological development, stricter legislation, educational actions, and cooperation between industries and society.

1. INTRODUCTION

Germany is known worldwide as a technological reference in the waste sector, however, this good performance was built on a progressive process of implementing safety measures over the years, since the late 1980s, such as the prohibition of waste disposal in landfills without treatment, the reinforcement of mechanical-biological treatment, and stricted emission limits. In addition, the proper functioning of the entire waste chain happens because of the alignment of the roles played by each sub-sector, which act in synergy and cooperation, from the consumer to the industries. Thus, the concept of circular economy, by the introduction of a more sustainable proposal of conscious consumption of energy and natural resources to the society, as well as the attribution to producers of the responsibility for products from their manufacture to their disposal by the polluter-pays principle.

This study presents an extensive overview over the most successful practices of municipal solid waste treatment and energy recovery in Germany. It is based on a qualitative approach, whose primary data was obtained by an operator survey that was carried out for the main facilities in the country, while secondary data was obtained from literature sources and official data. In terms of methodology, a survey was first carried out regarding the main official data on the subject, and it was added secondary data from scientific articles. In addition, in order to provide new relevant information to the research, technical visits were made to six large facilities known in Germany for their excellence in quality, which technical data was provided by operators.

2. WASTE POLICY IN GERMANY

By the end of the 1980s, waste management in Germany was facing the following problems:

- Strong increasing of waste volumes;
- Large number of uncontrolled landfills with risk of contamination;
- Lack of available volume for disposal in sanitary landfills;
- Low standards for emissions avoidance (landfill gas and ground water pollution);
- Low capacities for recycling and municipal waste incineration.

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Therefore, it was urgently recognized the need of safety measures (such as emission limits for incineration activity), followed by the implementation of an efficient management that would lead to waste reduction and recovery, and therefore producers will become responsible according to the polluter-pays principle from production to waste disposal (BMUV, 2023).

Figure 1 shows the main measures adopted in Germany from 1991 to 2012, which contributed to the implementation of the circular economy concept in the country. Thus, the Packaging Ordinance was established in 1991 in order to assign the packaging return obligation to the producer, which was extended in 1996 by the 'Closed Substance Cycle and Waste Management Act' and replaced in 2012 by the Circular Economy Act. Another important milestone in the sector was the encouragement of mechanical-biological treatment and also incineration with the ending of untreated waste disposal in 2005, which was arranged by the Waste Disposal Ordinance in 2001 and was later incorporated into the Landfill Ordinance in 2009.

The Circular Economy Law is another important milestone in waste valorization, aiming to extend the life cycle of products and avoid waste generation, in order to keep materials inside the chain by recycling (European Parliament, 2023). Thus, while in the traditional linear model the products become obsolete and are replaced more quickly, the concept of circular economy introduces a more sustainable proposal regarding a conscious consumption of energy and natural resources, and consequently, lower emissions. Circular economy strategies are based on three aspects: eliminating waste, recirculating materials, and regenerating ecosystems; and can be used to combat climate change by transforming recycling solid waste into circulating materials and also, reducing waste disposal and eliminating greenhouse gas emissions with the increasing of the entire product life cycle and resulting in long-term sustainability benefits, such as the efficient use of natural resources, smaller carbon footprint and food waste reduction (Yang et al., 2023).

New plans have been adopted by the European Parliament through the implementation of compulsory goals and strict rules in order to accelerate the transition to a low-carbon economy, such as measures related to waste generation reduction, packaging reuse and biodegradable raw materials.

The European Waste Framework Directive 2006/12/EC (EC, 2006) of the European Parliament and the Council of the European Union, which was updated in 2008 by the Directive 2008/98/EC (EC, 2008), establishes the waste reuse and recovery through the concept of hierarchy concept, which follows the order of prevention, reuse, recycling, energy recovery and disposal, and also, aims to prevent from negative impacts on the environment by establishing the obligation of waste treatment.

In Germany, the prohibition of the final disposal of waste without prior treatment in landfills in 2005 led to an increase in plants for mechanical biological treatment (MBT) and MSW incineration, as well as a growth in recycling and selective collection efforts. It is necessary to mention that such results were achieved in Germany from the awareness of companies and the population through the adoption of educational measures, both regulatory and enforcement, as well as the application of strict fines in case of noncompliance with the laws, which have been implemented and improved during the years. It is also important to understand that the successful performance of the waste sector in Germany was built from a progressive process over the years and the entire system works because of the alignment of each sector roles, which have been acting in synergy in a cooperation chain from the consumers to the industries. The municipal solid waste (MSW) separation is a successful practice that is initially done at the generating source, i.e., in the households themselves, through segregated waste bins by four types: recyclables (such as metal, plastic and packaging), paper and cardboard, compostable/biodegradable organic waste, and residual materials.According to the Global Waste Index (Sensoneo, 2022), Germany recycles 47.8% of the total waste produced and is in third place in terms of waste management regarding recycling (302kg per capita), incineration (204kg per capita), landfill (5 kg per capita) and waste production (632 kg per capita), after South Korea (1st place) and Denmark (2nd place).

Organics represents 30-40% of the municipal waste volume in Germany and have been collected separately since 2015 through the 'Biotonne', playing an important role in the circular economy by aligning recycling with the segregation of green (yard trimmings) and food wastes for composting and/or energy production by fermentation (BMUV, 2020). Although the separation of organics is mandatory and established by legislation, exceptionally in some municipalities this still does not happen. Regarding the electronic waste, batteries, textiles, lamps and glass, as well as for construction and demolition waste, there are special collection systems (collection and/or delivery) under the responsibility of the municipality.

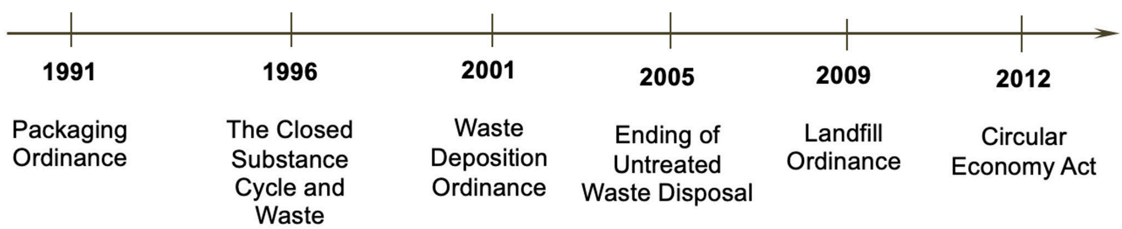

FIGURE 1: Main measures implemented in Germany's waste sector from 1991 to 2012. Source: Elaborated from information available on BMUV (2023).

TABLE 1: Waste balance in Germany in 2020. Source: Destatis, 2022.

Waste Type	Waste Generation (1,000 tons)	Disposal Operations (1,000 tons)			Recovery Operations (1,000 tons)		Recovery Rate (%)
		Landfilling	Incineration	Treatment for Disposal	Energy Recovery	Recycling	
Municipal Solid Waste (MSW)	50,993	209	365	521	15,518	34,379	98

The mandatory deposit collection system for cans and bottles was first introduced in Germany through the Packaging Ordinance in 1991 for disposable packaging, and was later adapted and implemented in 2003 with the aim of increasing the recycling rate in the country. The regulation involved much resistance from large beverage producers due to the high cost of investment in reverse logistics machinery, as well as, it was also met with annoyance by consumers due to the absence of a uniformly regulated return system (Tagesschau, 2015). The return system for beverage packaging involves the payment of a deposit (from German, 'Pfand') whose value can vary from 8 to 25 euro cents, depending on the type of use (single and/or reusable), which is later returned to the consumer when the material is returned, in which, in general, the deposit value for glass bottles equivalent to 8 cents, PET bottles equivalent to 25 cents, while single-use containers (used only once before recycling) equivalent to 25 cents (Ruíz & Cwienk, 2021).

Each consumer is responsible for his own waste, and therefore, such initiatives of separating materials in bins and collection points, although seem to play a small role, are extremely relevant to the functioning of the entire system by reinforcing the recycling activity and preserving the circular economy.

3. BRIEF OVERVIEW OF MUNICIPAL SOLID WASTE TREATMENT AND MANAGEMENT IN GERMANY

According to the German Federal Statistical Office (Destatis, 2022), it was generated an amount of 50 million tons of Municipal Solid Waste in 2020, as shown in Table 1, and regarding the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV, 2023), there are 15,000 waste treatment facilities in Germany and an estimated turnover of 80 billion euros in the waste management sector.

Mechanical-biological treatment is one of the principles of waste management in Germany (UBA, 2015b), in which organics, recyclables and high-calorific fraction from household and commercial origins are separated, recycled and co-incinerated (in case of no recycling potential) in coal-fired power plants or thermal production industries such as lime, cement and WtE (Waste-to-Energy) plants. The waste transformation into alternative fuel is shown in Figure 2. Table 2 lists the number of facilities for the main waste treatments in Germany in 2021.

Germany's thermal treatment facilities follow the standards of the European Directive 2010/75/EC (EC, 2010), whose incineration and co-incineration activities were first regulated for small and medium combustion units by the Federal Emission Control Act (BGBl, 2010), which was updated in 2019, and subsequently, extended to all facilities from the Ordinance on the Incineration and Co-incineration of Waste (BGBl, 2013). The contribution of energy from waste in Germany represents approximately 3.7% of final energy consumption, with most of the energy supply from waste is provided by incineration plants, along with RDF power plants (WEBER et al., 2020). According to Statista (2024), Germany had the greatest installed capacity of energy from municipal waste in Europe in 2023, of approximately 1,023MW, followed by the United Kingdom (773 MW), France (625MW) and Italy (396MW).

According to The Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Pro-

TABLE 2: Main waste treatment facilities in Germany. Source: Adapted from Destatis, 2021.

Facility Type	Number of Facilities	Waste Input (1.000 tons)
Thermal Waste Treatment Facility	155	25.493,6
Combustion Facility with Energy Recovery	481	22.088,9
Physical-Chemical Treatment Facility	390	7.711,6
Biological Treatment Facility	1.190	16.132,0
Mechanical-Biological Treatment Facility	50	3.591,2
Sorting Facility	957	24.973,6
Total	4,222	139,747.3

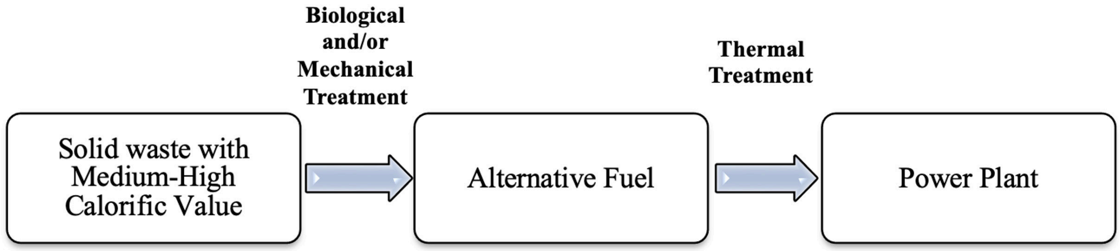

FIGURE 2: Simple scheme of solid waste transformation of medium to high calorific residues into alternative fuel.

tection (BMUV), waste is incinerated in 155 facilities in Germany, whose total incinerated waste in 2020 was 25 million tons. In these facilities the generation of heat and electricity (combined heat and power generation (CHP) or at least only electricity is mandatory. After the separation of metals (circa 10%) and impurities (inert and unburnt materials) about 95% of the remaining bottom ashes (slags) are reused as a raw material in further processes, in particular in the road construction area. The residues from flue gas cleaning are recycled or deposited in special landfills for hazardous waste. Grate fired incineration is the most commonly technology in Germany, although fluidized bed combustion is also available, while hazardous waste incineration is carried out exclusively in special licensed plants (BMUV, 2021).

According to the German Federal Environmental Agency (UBA, 2015a), there are 29 facilities in operation and 2 others in construction, as shown in Table 3, with an annual capacity of 4.7 million tons from medium to high calorific waste.

According to the CEN/TS 15359 specification from the European Standardization Commission (CEN, 2006), non-hazardous waste can be pre-processed and used as alternative fuels for energy recovery purposes in incinerators, lime and cement industries. In the past, five classes tried to classify, according to the parameters of net calorific value (NCV), chlorine content (Cl) and mercury content (Hg), as shown in Table 4.

This classification doesn't allow to re-declare waste as a product and define it for the authorities. In reality, each alternative fuel must be adapted to the respective production needs and is subject to the waste legislation and air pollution control measures equal to waste incineration plants – including power plant and cement industry.

With regard to the specification, both emission-relevant parameters (volatile until non-volatile dust bound heavy metals) and performance parameters such as calorific value, residual moisture, chlorine, ash, portion of biomass, etc. must be agreed prior and monitored during conditioning and use.

4. RESULTS AND DISCUSSION

For the purpose of this case report, visits of the main facilities in Germany have been made in order to identify the main technological practices of waste treatment and energy recovery:

- ALBA (located in Berlin) – pre-processing of waste with physical-mechanical stabilization;
- ALBA (located in Braunschweig) – waste sorting and recycling;
- KAVG in Pohlsche Heide (located in the district of Minden-Lübbecke) – mechanical biological treatment of waste and biodrying;

TABLE 3: Power plants in Germany. Source: UBA, 2015a.

Name	Location	Capacity [Mg a-1]
Power Plants in Operation		
EBS-KW	Bernburg	500,000
EBS-KW	Eisenhüttenstadt	340,000
EBS-KW	Hürth-Knapsack	300,000
KW	Glückstadt	270,000
MHKW	Heringen	270,000
HKW	Witzenhausen	270,000
HKW	Schwedt	250,000
EBS-KW	Großräschen	240,000
HKW	Rostock	230,000
IKW	Rüdersdorf	226,000
MKK	Bremen	226,000
EVE	Premnitz	150,000
TEV	Neumünster	150,000
DZ	Weener	140,000
IHKW	Andernach	114,000
TRB	Bitterfeld	110,000
IKW	Premnitz	100,000
HKW	Stavenhagen	90,000
HKW	Hagenow	80,000
IHKW	Korbach	70,000
HKW	Gersthofen	70,000
HKW	Bremen-Blumenthal	66,000
TVA	Schwarza	60,000
IKW	Amsdorf	60,000
IKW	Amsdorf	60,000
HKW	Meuselwitz	50,000
HKW	Minden	40,000
EVA	Essen	26,000
TREA	Gießen	25,000
Power Plants in Construction		
EBS-KW	Frankfurt Hoe	675,000
HKW	Brunsbüttel	165,000

TABLE 4: Classification of Alternative Fuels from waste. Source: CEN, 2006.

Parameters	Statistical Measures	Classes				
		1	2	3	4	5
Net Calorific Value	Median	≥25	≥20	≥15	≥10	≥3
Chlorine Content	Median	≤0,2	≤0,6	≤1,0	≤1,5	≤3
Mercury Content	Median	≤0,02	≤0,03	≤0,08	≤0,15	≤0,05
	80 Percentile	≤0,04	≤0,06	≤0,16	≤0,30	≤1,00

- A.R.T. (located in the village of Mertesdorf) – mechanical biological treatment of waste with biodrying;
- MBA ECOWEST (located in Ennigerloh) – pre-processing of waste to customized alternative fuels with biodrying and natural gas drying;
- HOLCIM Cement Plant (located in Beckum) – applies customized SRF via kiln end burner – one example of co-processing in the cement industry.

It must be emphasized that the financing is covered by the polluter pays principle, which was introduced for three reasons: 1) to force the polluter to pay for his large amounts of waste through high disposal fees, and 2) to make the entire chain from collection to disposal more sustainable and harmless, 3) an important factor in economy.

It is necessary to emphasize that the operations in the waste treatment and energy recovery facilities involve extremely high costs, which are financially viable due to the payment made by the municipalities from the fees paid by taxpayers (population) and waste generators (such as commerce and industry). Thus, the execution of such activities would not be feasible if these operations were paid unilaterally by these facilities.

4.1 Mechanical – Physical Stabilization – operated by ALBA, located in Reinickendorf

The facility in Reinickendorf (located in Berlin, operated by ALBA) has an annual production capacity of 180,000 tons from two Mechanical-Physical Stabilization (MPS) systems, in which municipal solid waste is transformed into an alternative fuel to replace fossil fuels in power plants and industrial facilities (BSR, 2023). The treatment process involves shredding, sorting (by material type and particle size) and drying, as can be seen in Figure 3.

In the end, the waste is transformed into alternative fuel with a particle size of less than 30 mm and the majority part is applied as a fuel in the cement industry while the other part is used for incineration at the Jänschwalde Coal-Fired Power Plant (located in Brandenburg).

4.2 Waste Sorting – operated by ALBA, located in Braunschweig

The sorting and waste recovery facility of the company ALBA in the city of Braunschweig receives only yellow bin's waste from household and commercial sources, with the capacity to recycle up to 50% of all received material, while the remaining 50% are materials with no recycling potential, which are destined for incineration. The recyclables (segregated in the yellow bins) are driven by the producer industry, especially with regard to packaging, and have a different system than commercial materials and household waste, since they are still separated at source by consumers, collected and sent to sorting units - supported by the private sector.

The unit has 72 employees and receives about 120,000 tons/year, whose sorting capacity corresponds to 60,000 tons/year. The operations are distributed over two kilometers of belts, involving the waste sorting (by type and size), with a view to separating the recyclable from the non-recyclable.

Once the waste is placed in the facility's moving floor, the packages are opened with a grinder equipment, and then the recyclables are mechanically sorted by granulometry (respectively from the largest to the smallest: greater than 300 mm, 300-150 mm, 50-150 mm, 1-50 mm) and by composition.

Among the recyclables, it is also done the separation of metals and tetra pak (with presence of aluminum and without aluminum). The ballistic separator is responsible for the segregation of the lighter residues from the heavy ones, whose mechanism operates with screening paddles that move in opposite positions and in an inclined way, allowing a more optimized classification of the material fractions. Next, such materials are reallocated to two different belts, one for receiving materials destined for recycling, while the other for disposal in incineration. The sequence of such operations is shown in Figure 4.

Additionally, it is done the manual sorting of non-reusable materials, in order to recover eventual waste with recycling potential and to dispose of only rejects to incineration.

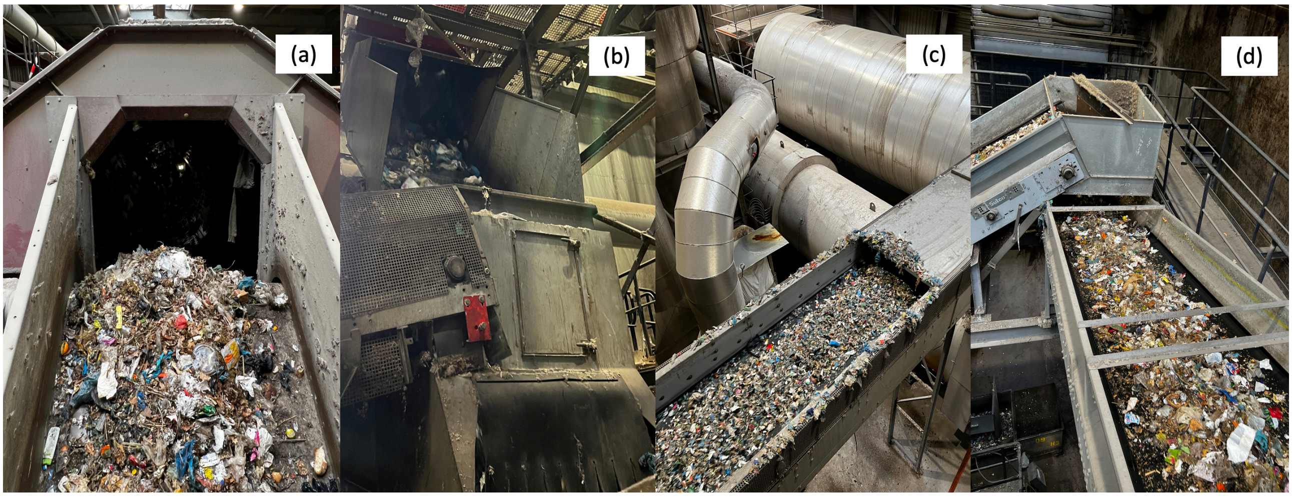

FIGURE 3: (a) material sorting by granulometry; (b) metal separation; (c) crushing; (d) drying. Source: Author's personal collection, 2023.

FIGURE 4: Operation flow: (a) waste separation by ballistic separator; (b) reallocation of light and heavy materials on two different belts; (c) separation of reusable materials for recycling and non-recyclable materials for incineration. Source: Author's personal collection, 2023.

Although it has been observed an increase in the recycled material rate from 30% to 50% since the beginning of the activities due to the optimization of the operations, it is still very difficult to reduce the significant number of non-recyclables, possibly due to the inadequate material separation in the source, causing high costs of rejects' incinerating, which price range is from 50 to 60 euros per ton, according to ALBA's Braunschweig. In addition, it is estimated that 6 to 7% of all incoming material is equivalent to organic fraction, which is also sent to incineration. At the end of all the operation flow, the recyclable waste is baled for transport according to the type of composition, as: (a) high density polymer; (b) low density polymer; (c) paper; (d) metal; (e) tetra pak.

One of the problems in the facility is the risk of explosion resulting from Lithium batteries, causing a temporary interruption of operations from three to six times a day. Therefore, real-time monitoring is made by heat detection sensors in order to prevent fire.

4.3 Mechanical Biological Treatment – operated by KAVG, in Pohlsche Heide

Pohlsche Heide is a waste management center operated by the public company KAVG, responsible for receiving residual materials from black bins (residual materials) from eleven cities and municipalities in the Minden-Lübbecke district. The facility has about 130 employees and includes a landfill, two recycling centers, a composting plant for organic and greens, a biological treatment plant, and a mechanical biological treatment plant segregated into two processing lines, being one for household waste, while the other for commercial waste (KAVG, 2023).

The plant has the capacity to process 300,000 tons of waste per year, whose treatment steps involve shredding, size separation and sorting. Magnetic separation is also performed, distinguishing ferrous and non-ferrous materials, which are destined for a smelting plant. Waste with a higher calorific value is used as an alternative fuel (HCF – High Calorific Fraction) for thermal energy purposes in KAVG's cogeneration Energos plant in Minden, thereby partially replacing fossil fuels (such as gas or coal).

The organic waste is treated in the anaerobic digestion unit to produce biogas, which is converted into heat and electricity in the thermal power station and reused for power generation at the Pohlsche Heide facility itself. The output of this unit is together with the treated non-recyclable waste disposed of in the landfill.

The facility has the capacity to receive 100,000 tons of household and commercial waste per year. After receiving the material, the waste must follow strictly distinct routes, one for household and another for commercial, since they involve different fee systems. Thus, in case of losses in the commercial waste line, for example, it does not cause impacts on the household waste line. Although the maximum capacity of the facility for the commercial waste route is 40,000 t/year, the unit has been receiving only 14,000 t/year because of the low price (disposal fee) paid to the incinerators. For the unit that treats commercial waste the ideal would be to receive approximately 135 euros per ton of waste, however, it has been paid to the incinerators from 80-90 euros per metric ton of waste. On the other hand, new investments have been made in the commercial waste treatment line in order to adapt the techniques and equipment to comply with the standards established in regulations. All the operation costs are financed by disposal fees (polluter-pay principal), which are proportional to the number of residents in a household, and also by the industries.

The mechanical biological treatment unit is responsible for pre-processing the waste higher than 60 mm through the stages of sorting, grinding, drying, magnetic separation and ballistic separation, which are destined for incineration in order to produce steam for the pharmaceutical industry. The pre-processed residues with a final particle size of 60-120 mm and a calorific value of 12,000 J (about 2,866 Kcal) are destined for incineration, of which 35,000 t/year are destined for a local incinerator in Minden (in a distance of

15 km) and about 15,000 t/year for an external incinerator. Approximately 3-5% of the total amount of waste received are metals, which are separated by magnets into ferrous and non-ferrous by eddy-current separator, and sold to the market.

In the aerobic biological treatment process, the waste below 60 mm is stabilized by bacterias in boxes under a controlled environment to be later disposed of in the landfill. While in the anaerobic treatment process, fermentation and biogas production of the smaller fractions of waste is performed, which is treated and distributed to the gas network.

The inadequate separation of materials by the population causes some problems to the facility, such as the high concentration of plastics due to the packaging of organics in inappropriate bags and also, the risk of explosion during the waste shredding process, due to the presence of lithium batteries, which can motivate from two to three weekly stops in the operations, even if eventually.

It has been a long history until Germany becomes a world reference in the waste sector, coming from overloaded landfills to presenting treatment and energy recovery facilities. Despite successful recycling activities, landfills are still needed for the disposal of materials without thermal and recycling potential according to the disposal criteria of the Landfill Ordinance. One of the future goals is to enable recovery alternatives for such materials without reuse, so that the numbers of sanitary landfills can be reduced furtherly. However, there is a consensus about the value of such materials and, therefore, the will to return them, somehow, to the reverse logistics cycle. Even though there is the practice of waste avoidance and separation in the source (households), most of such materials are still destined for incineration, because the infrastructure is still insufficient for more advanced recycling capacities or because the quality is still poor and costs for reuse are still too expensive and thus it becomes cheaper to use new ("virgin") materials than recycled ones. In a way, many materials even containing recyclable components are still going to incineration.

Thus, there is still a long way to go in the country before it is possible to extend the life cycle of products and comply with circular economy principles. Some industry conversations involve discussions about how producers can in the future bring such materials back into the circular economy circle from their material components - such as chemical recycling - without the energy recovery process, for example.

4.4 Waste Stabilization by Biodrying – operated by A.R.T., located in Mertesdorf

The A.R.T.'s facility in the locality of Mertesdorf is one of the plants with biodrying technology in Germany. The unity has 300 employees and receives daily 450 tons of residual materials from a district corresponding to 530,000 inhabitants and is responsible for the sorting of waste from black bins (non-recyclables) on 75 hectares (750,000 m^2). Besides the landfill, there are also units for the mechanical biological treatment and biowaste composting, a waste collection point and an energy recovery unit.

First, the truck is weighed on the scale and according to the measure it is identified the gate to be unloaded, and the waste is then relocated for the shredding procedure.

Afterwards, the drying process is started through biological stabilization boxes (Figure 5), which lasts from 9 to 12 days, whose technology allows the removal of 30 to 35% of the residues' humidity for the purposes of calorific value increasing and mass reduction and consequently, lower transportation costs to the incinerators.

Finally, is conducted the sorting of materials, such as organics (later disposed of in landfills) and metals - which are separated into ferrous and non-ferrous, and then sold to a company, enabling the generation of revenues.

One of the problems faced by the facility is the risk of self-combustion of batteries, which are found due to the incorrect waste segregation still at the source (households). Thus, in order to prevent fire, a real-time monitoring is performed by heat sensors located both in the biological drying area (to detect the risk of temperature rise) and in the mechanical part (to detect eventual batteries).

4.5 Waste Pre-Processing – operated by MBA ECOWEST, located in Ennigerloh

The MBA ECOWEST facility in Ennigerloh receives about 150,000 tons per year of waste, of which 60,000 t/year is presorted commercial waste and 90,000 t/year household waste. Because of the different compositions, the flow of operations is planned for two process routes

FIGURE 5: Biological drying stabilization. Source: Author's personal collection, 2023.

on separate feeding belts, and therefore, it is possible to ensure the most appropriate treatment for the type of incoming material and consequently achieve better quality for the alternative fuel production.

At the beginning of the process, the waste is unloaded at the facility's moving floor and then relocated to two different types of the shredders on separate routes, for household and commercial wastes. During the passage of the waste, a magnetic separation is also mandatory here (Figure 6), whereby attention was paid to a sensible positioning. The orientation, which is important for the extraction performance and the quality of the iron, was in the conveying direction, which means that the magnetic field captures the ferromagnetic particles more cleanly in their point of weightlessness and without being covered by impurities.

The facility has replaced the useless compost screens against three large flat screens followed by proper wind shifters that are responsible for receiving two different waste streams on three lines. From each, lighter materials are separated at the top as the high-calorific fractions and which are used in the downstream pre-processing, while the unsuitable heavier materials at the bottom will be send to waste incineration in the cities of Hamm and Bielefeld.

Next, the ferrous materials (corresponding to 2-3% of the total input stream) are removed by the magnets, and at the end, the non-ferrous materials are also removed by an eddy-current separator. In accordance to the local cement industry, which does not operate precalciners and the local fossil-fired power plants, RDF cannot be produced or even used, here. So, the fuels have to be cleaned of heavy materials, which is done by sufficient air classifier. If necessary, the SRF is dried in a drum dryer using natural gas.

The use of appropriate equipment for conditioning will be monitored by sampling which enables a more accurate and representative knowledge in relation to the quality of the pre-processed waste, since the collection is performed randomly by the machine, instead of manual selection by an operator. This procedure is very important to ensure that the limits pre-determined by law are achieved, in accordance to the permission of the customers, and thus obtain a calorific value appropriate to the technology to which it will be applied.

FIGURE 6: Magnetic in the same direction as the belt is conveying. Source: Author's personal collection, 2023.

Therefore, the collection of samples in the MBT, as shown in Figure 7, takes place regularly and combined into a daily mixed sample. It will be analyzed in the laboratory in order to compare them with the qualities in the final product agreed with the customer to be supplied. This MBT is the one of the plants that has been awarded the RAL quality mark 724, which means that the heavy metal content in the SRF corresponds to the permissible emission limit values of co-processing and can directly supply without any blending prior to delivery.

The lighter fractions of pre-processed waste are the most desirable for the high grade SRF purposes in cement kilns, because they have less potential for contamination and can achieve higher calorific value, allowing a better burning performance in suspension after leaving the kiln

FIGURE 7: Sample collecting for quality standardization purposes. Source: Author's personal collection, 2023.

end burner or vessel burners. While the heavier fractions are used as RDF with lower burning performance, eventually becoming ash.

It is very important to have the correct differentiation about the denomination of alternative fuels in terms of their final quality, since this is directly related to the type of equipment and technology to be applied. Therefore, the term "alternative fuel" is usually more broadly used within the German technical area, while the following specific ones are considered:

- SRF (Solid Recovered Fuel), as shown in Figure 8, for the alternative fuel composed of fine fractions free of 3-dimensional heavy particles (< 25 mm) and primary quality, similar to lignite with application in the sinter zone burner in the cement industry and the vessel burners in coal fired power plants;
- RDF (Refuse Derived Fuel) to denote the alternative fuel composed of larger fractions (< 80-100mm) and of poorer quality, with application in the calciner in the cement industry or Fluidized Bed Combustion.

In the cement industry, the alternative fuel composed of finer particles and primary quality (SRF) is used in the main burner, while the alternative fuel of larger particles and poor quality (RDF) is used in the calciner, while very large particle (HCF-High Calorific Fraction) are fed to the pre-combustion chamber or processed to RDF, as it is shown in Figure 9.

4.6 Waste Energy Recovery – operated by HOLCIM Cement Plant, located in Beckum

The cement plant in Beckum-Kollenbach (Figure 10) was founded in 1911 and has been part of the Holcim Group since January 2015. Around 14 tons per hour of SRF through the kiln end burner. A thermal substitution rate (TSR) is equivalent to 80% is achieved, due to the use of customized alternative fuel and animal meal (biomass).

In general, the cement manufacturing process starts first with the raw materials (limestone, sand as silicon

FIGURE 8: SRF, alternative fuel composed of light fractions. Source: Author's personal collection, 2023.

donator, iron ore and aluminum oxide containing clay) are mixed and milled, and then preheated respectively precalcined. Then the decomposed raw meal will be burned in a rotary clinker kiln at 1,450°C (Holcim, 2023). In the main burner, coal, alternative fuel (SRF) and animal mill are added, while in the calciner the secondary alternative fuel (RDF) is used. After burning, the clinker is immediately cooled and ground. It should also be noted that the ash is also chemically integrated as a component in the clinker burning process, which is why it is also referred to as "co-processing".

The decarbonization process in cement works, in which CO_2 is removed from the lime-based raw material, takes place at high temperatures (from 800 to 850°C) and is responsible for one part of the CO_2 emissions. The other part is caused by the combustion of the fuels, which is why seeking for alternatives as to the use of limestone (calcium carbonate) and its calcination through the use of alternative fuels (including biomass) is very important worldwide.

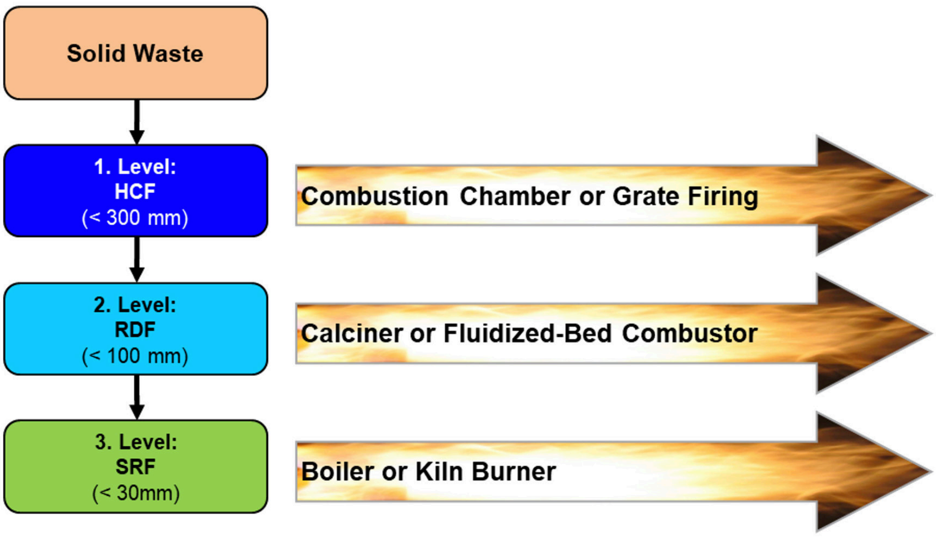

FIGURE 9: Application of alternative fuel according to quality. Source: WLTP, 2012.

FIGURE 10: Holcim Cement Plant in Beckum, Germany. Source: Author's personal collection, 2023.

The clinker burning process requires a lot of energy, which is why it is a constant search for cost-effective alternatives. The plant requires around 3,600 tons of raw material and 600 tons of fuel per day to produce around 2,800 tons of clinker. Lignite dust is stored in four silos, two smaller storages are used for the continuous substitution of the coal dust with alternative fuels. The kiln is of normal length but without a pre-calciner. Via the kiln inlet there is the possibility of giving up small quantities of lower quality (but with a high gate-fee). At the kiln end, the long flame of the sinter zone burner (of almost 20 meters) generates the required high clinkerization temperature which can reach 2,000-2,500°C gas temperature (the clinker formation temperature applies approx. at 1,400°C), which requires a SRF quality similar to lignite.

The bypass technology, which will become necessary, when the suppliers are not willed or in the position to control and reduce that process disturbing chlorine entrance during preprocessing. Cold air is used to rapidly cool the gases just leaving the kiln (at a temperature of 1,100-1,200°C), where chlorine is condensed and removed by combination with alkaline elements. The installation of such a quenching system and the cooling with additional air costs a lot of energy and money, respectively, which has to be compensated by the gate fee to be paid by the supplier in case of delivery of insufficient AF qualities.

The emission limits in Germany are adapted from the municipal waste incinerators and extremely strict and are directly related to the facility's operating permit. Combustion-relevant data are tracked in real time by the authorities. Therefore, the measurements are made for fourteen different chemical elements every 30 minutes (half-hour average of emissions), currently per moment average) and per day (daily average). It is mandatory by law to measure once a year such as dioxin and furane which cannot be detected constantly and elaborate a report. In the case of any irregularities the facility is notified by the authorities to stop its operation in order to correct any deviations. It is also possible to be fined and/or lose the permission in case of non-compliance with the law and failure in presenting an appropriate justification to the environmental inspection agency. The adequacy of technologies in cement plants in the country occurs aligned with the updated legislation, especially in the implementation of new emission limits in 2013.

One of the biggest problems faced by cement plants is the large amount of CO_2 emissions related to the calcination of raw material to produce clinker, whose process aims to reduce CaO content in the clinker. Much has been discussed in the sector regarding new strategies to reduce emissions through the optimization and/or adoption of new technologies, such as the application of hydrogen in the clinker formation process, oxy-fuel combustion and the use of calcined clay to replace clinker. Such adaptations in the chemical composition of lime are complex and require caution, since any change in this process, however small, implies major impacts on the burner, the clinker mineralization and also on the fuels. For this reason, chlorides are a major challenge in the industry, since they present several combination/fixation mechanisms for the salts' formation, whose stability can be influenced by the presence of acid aggregates or mineral additions, causing a decrease in pH and consequently, a reduction in the cement resistance (Saciloto, 2005).

Another future possibility to mitigate CO_2 emissions in the sector, although it is in early studies, is a solution called 'End-of-Pipe Technology', whose carbon capture happens from the removal of CO_2 at the end of the process. Although the cement manufacturing process has existed for many years and has been constantly optimized and new technologies developed to maximize energy efficiency, such as pre-calciner, calciner expansion, low-NOx burners, SNCR, energy recovery by modern clinker cooler technology, waste heat recovery, etc., it is at the edge of a new technology, for example, hydrogen utilization and CO_2 capture and use (CCSU). Ultimately, infrastructure measures (such as roads, schools, hospitals, streets, sewers, etc.) must remain affordable.

Finally, it was observed that the main barrier to the use of pre-processed waste as an alternative fuel in cement plants is to be able to adjust it in the production of clinker within the limits required for the final quality, in order to maintain control of the entire process, and also to ensure the best price per ton of clinker in harmony with all costs and risks from the sector. The cement market is very dynamic and has a constant volatilization, such as price oscillations in the carbon market, the recent authorization regarding the biomass use (saw dust, animal meal etc.) and the mandatory emissions trade certificate for incinerators, which is expected to be effective in 2024, referring to payment for each CO_2 ton that has been emitted - estimated at 35 euros per ton of waste-derived fuel. Thus, it is extremely important to align the industry to such updates, especially the regulatory ones.

5. CONCLUSIONS

This present case report aimed to analyze the waste sector in Germany in order to study the main measures that led to the good performance of the entire chain, as well as to identify the best waste treatment and energy recovery practices in the country. It was found that this successful performance was achieved in a long-term evolutionary process based on technological development, stricter legislation, educational actions, and cooperation between industries and society. The prohibition of untreated waste disposal in landfills, the implementation of the circular economy concept, the establishment of the polluter-pay principle, the consolidation of mechanical-biological treatment and the thermal treatment, recycling activities, as well as, household waste separation and selective collection, all played an important role that led to a successful management.

It was also possible to observe the pre-processed waste application for alternative fuel purposes, whose monitoring and specification of performance parameters are aligned with environmental and regulatory requirements, in order to obey emission limits and ensure the quality standards.

Thus, it was shown that is very important to have the correct differentiation about the denomination of alternative fuels in terms of their final quality, since this is directly related to the type of equipment and technology to be applied. The lighter fractions of pre-processed waste are the most desirable for the high grade SRF purposes in cement kilns, because they have less potential for contamination and can achieve higher calorific value, allowing a better burning performance in suspension after leaving the kiln end burner or vessel burners. While the heavier fractions are used as RDF with lower burning performance, eventually becoming ash.

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For those who believe in science.

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