Financial and environmental assessment of four advanced European MBT facilities

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Abstract

The aim of this paper is to assess the efficiency of Mechanical Biological Treatment (MBT) facilities that operate in Europe, and to evaluate the impact on the local public sector, the private party operating the plant, and the local community. In 2017-18, the authors visited four advanced Mechanical Biological Treatment (MBT) facilities in Cyprus, Greece, and Spain. These plants, of different capacities and output products, were studied with respect to their feedstock composition, operating conditions, capital expenditure, financial viability and environmental impacts. Different treatment processes yield different results both in terms of economics and environmental impact. It can be concluded that an MBT plant should be built upon a thorough sorting and recyclables recovery line, to achieve both the negative emissions but also the reduced gate fee required to achieve an IRR of 12%. For the material that cannot be recovered, there should be an RDF stream, to further reduce emissions, but also adding to the revenue stream. The compost product of all cases examined did not comply with the agricultural standards, and therefore, in the best case, it was used as daily cover in landfills. However, the plant in Barcelona uses the RDF and the organic fraction as a fuel in the adjacent waste to energy plant, a solution that is more costly in the short term as compared to the other cases, but it provides a sustainable solution for the city. Finally, only the by-products of the processes should be landfilled, given the high emissions in the landfilling scenario, and the fact that the net present value for this scenario is the lowest of all three.

Keywords: MBT, recycling, composting, gate fee, integrated waste management systems, circular economy

1. Introduction

The waste hierarchy is the cornerstone of policy and legislation on waste and a key to the transition to the circular economy. Its primary purpose is to establish an order of priority that minimizes adverse environmental effects and optimizes resource efficiency in waste prevention and management. In this context the gradual diversion of waste from landfill should go hand-in-hand with the creation of greater recycling capacity combined with energy recovery (EU Directive 2018).

The challenge with recycling is that three ingredients are needed to make it successful:

1. Communities with efficient collection systems, e.g. dry and wet waste,

2. Citizens that source separate materials and are aware of the environmental and economic benefits of recycling

3. Markets able to make profit out of these materials.

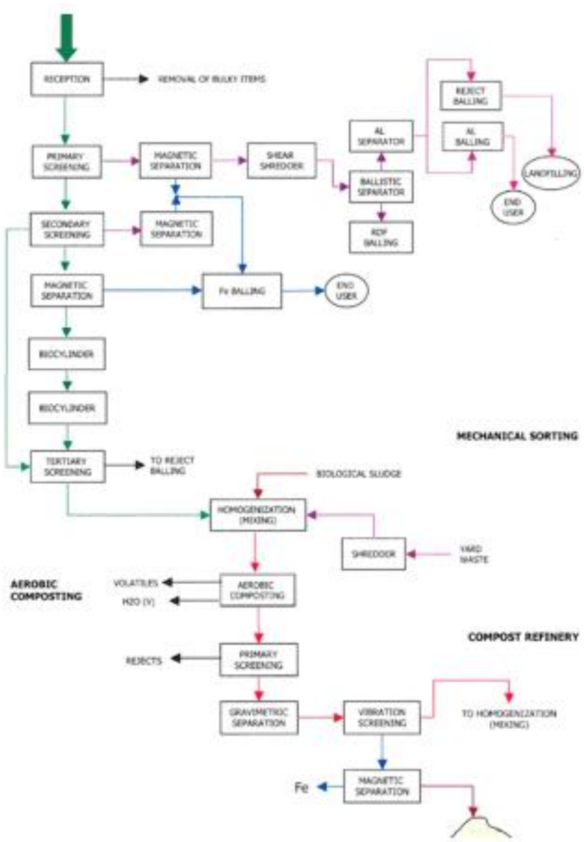

Figure 1: Typical MBT Process

Municipalities have generally been characterized as external facilitators of recycling, encouraging consumer behavior through the provision of incentives, promotion and education and investments in recycling infrastructure (Lakhan, 2014, Lakhan, 2015a, Lakhan, 2015b, Elia et al., 2015, Jurczak et al., 2006, Simmons and Widmar, 1990, Reams and Ray, 1993, Tucker, 1999, Mee et al., 2004). An important requirement for successful recycling is the advocacy through state or federal legislations. For example, the European waste framework directive established recycling targets for a number of waste streams (EU, 2018). In the U.S., California have set a 75% diversion target for 2020 (Calrecycle, 2015), while cities such as San Francisco, Oakland, and Seattle have set “zero waste” goals with the intent of eliminating landfill disposal (Calrecycle, 2015). In addition to increased waste diversion, the environmental benefits of recycling include the avoided use of virgin resources and energy savings (Merrild et al., 2012).

The recovery of recyclables typically occurs in Materials Recovery Facilities (MRF) or Mechanical Biological Treatment (MBT) plants. The latter is a combination of a sorting facility with a form of biological treatment such as composting or anaerobic digestion. The configuration and layout of MRF-related separation equipment depends critically on the input stream to the facility. MRFs can be designed to accept all recyclables in a single-stream, recyclables mixed with non-recyclables (mixed waste), recyclables separated into two streams (dual stream), or pre-sorted recyclables. As a result, the waste stream type accepted by the MRF determines the required separation equipment, which in turn determines recovery efficiencies and energy requirements to run the equipment within the facility. Only limited work has been done to characterize Materials Recovery Facilities (MRF) operations and the resulting emissions. Fitzgerald et al. (2012) quantified greenhouse gas emissions of three MRFs to compare the impact of dual versus single-stream facilities. However, the study did not consider system costs and it was not clear whether the purity of recovered materials was considered, as the presence of residual materials was higher than expected. Franchetti (2009) modeled MRF economics but did not consider energy requirements or environmental emissions. Chester et al. (2008) examined the total system energy requirement and greenhouse gas emissions from implementing recycling strategies but did not model MRFs in detail. Themelis and Todd (2004) investigated recycling systems used in New York City, but did not quantify environmental impacts. Nishtala (1995) developed a model that quantified MRF costs and emissions, but it is now outdated because modern MRFs include several pieces of automated separation equipment that were not in use 20 years ago.

Few studies associate with the effect of MRF in the waste management system with a specific reference to the costs (Cimpan et al., 2016b), environmental impacts by Life cycle assessment (LCA) (Bueno et al., 2015, Cherubini et al., 2009) and technical features (Feil et al., 2016, The Dougherty Group, 2006). In general, industry surveys and the use of primary data for MRFs are rare and the data on process efficiency are largely missing (Cimpan et al., 2016a, The Dougherty Group, 2006). Few studies (Barlaz et al., 2015, Beylot et al., 2015, Damgaard, 2015) investigated in depth how the analysis of these facilities should be carried out, in order to obtain a reliable assessment of the environmental performances, independently of the specific configuration. In particular, they highlight the necessity to take into account, with high quality data, some specific aspects such as mixed waste composition, impurities, sorting technology, purity targets, equipment performance, properties of final recovered material, residual contaminants, direct emissions, fuel and energy consumptions. In addition, there are not any studies that assess ways of treating waste both in financial and environmental terms, and in terms of the subsequent costs to the municipality (gate fee).

The study presented here is designed to fill in this gap. The authors used primary/industrial data to compare the environmental and financial flows of four advanced Mechanical Biological Treatment (MBT) facilities that operate in Europe. The objective of the study was to provide a better understanding on the MBT processes by focusing both on the actual MBT process, and on hypothetical alternatives to the uses of the recovered products.

2. Materials and Methods

2.1. Scenarios examined

Data were obtained by personal contacts and visits of the authors to the plants. Operational data were confirmed from the operators of the plants that were located in Spain, Greece, and Cyprus.

Plants of different sizes were examined in order to provide a holistic approach on the financial and environmental benefits MBT technologies. Three distinct cases that represent the actual status of the MBT plants are studied: the case in which recyclable materials are recovered from the stream and the residue is landfilled, the case in which only RDF is produced and sold to the local cement industry, and finally the case in which all material is landfilled. For each scenario, the CAPEX and OPEX data used represent the actual construction and operation of the plants, respectively, whereas for each plant one scenario is the actual and the other two are hypothetical.

2.2. Description of the plants examined.

The authors visited and collected information from four advanced MBT plants in Europe, as described below. Figure 1 presents a typical MBT plant. The input and output materials of the examined processes are presented in Tables 1 and 2, respectively.

Table 1: Input Compositions

Incoming Fraction	Chania MSW	Chania Pre-Sorted	Larnaca	Liosia	Barcelona
Organic	38%	2%	42%	32%	49%
Carton	6%	41%	3%	11%	
Paper (Mixed)	17%	28%	15%	21%	21%
Mixed Film	6%	10%	6%	3%	
Mixed Plastics	14%	3%	8%	16%	12%
Ferrous	2%	2%	2%	1%	4%
Non-Ferrous	1%	1%	2%	1%	
Tetrapack		1%			
Glass	2%	3%	3%	3%	8%
Various	8%	6%	10%	10%	6%
Inert	6%	3%	9%	2%	
Total	100%	100%	100%	100%	100%

- Chania, Greece: The plant operates in two modes, where either ~38,500 tons of mixed MSW per year or ~ 14,500 tons per year of pre-sorted MSW at the city of Chania are processed. Time splitting between the two types of materials is decided by the plant manager according to the requirement of the market. The process involves size separation with the aid of trommels that sort the materials to <25 cm. The oversized items are hand sorted, and the material that is <25 cm is processed in a secondary rotary screen. The material is separated into two fractions: 7 to 25 cm that undergoes manual sorting.
    - Materials which are < 7 cm are mostly the organic fraction of MSM. This fraction is mostly biodegradable and is transferred to the composting facility. A magnetic separator is used to remove any metals remained in the material, and therefore, advance the quality of the compost product. The organic fraction is mixed with branches and leaves, which arrive by special garbage trucks to the plant. This mixing increases the porosity of the material and facilitates the airing and the degradation of the organic substances. The mixture is then transferred to the compost facility that the organic material is being wetted, aerated and mixed for 6-7 weeks. After maturation compost enters into the forth building for refining. Refining is achieved by the use of screens and tables which separate the compost from small plastic, inert and metallic materials. The clean compost is ready for sale, at approximately 50 Euros per ton. It is used as improver for the soil of ornamental plants. However, it is not permitted to be used as

fertilizer to edible plants. The residue of the waste (currently about 80% of the incoming waste) is not useful and therefore goes to the landfill.

- Materials which are in the 7-25 cm fraction will be processed by optical and mechanical units, each one of which sorts a specific material from the belt. Two parallel NIR units sort mixed plastics out of the stream. The remaining stream goes through two parallel NIRs that sort mixed paper out of the stream. The mixed plastics stream goes through a 2D/3D separating staged, performed by means of two parallel ballistic separators. The 2D streams, which are mainly comprised of plastic film go through two parallel NIR units recovering PE/PP film from the stream. The 3D streams, which are mainly comprised of rigid plastics merge and go through 3 NIR units. The first unit recovers rigid PE plastics from the stream, the second NIR unit recovers rigid PP plastics from the stream, and the third unit recovers rigid PET from the stream. The recovered materials coming out of each NIR unit are then quality controlled.

- Larnaca, Cyprus: On a total yearly capacity of 160,000 tons of Municipal Solid Waste (MSW) fed to the plant, the following quantities of recyclable materials and other byproducts are separated: 5,500 tons of plastic foil, 1,700 tons of PET bottles, 2,500 tons of polyethylene-polypropylene packaging, 20,000 tons of mixed paper, 25,500 tons of RDF, 29,000 tons of compost, 30,000 tons of moisture and volatile compounds, 2,100 tons of ferrous materials, 1,200 tons of aluminum materials, 800 tons of glass, and 41,700 tons of residual materials to be landfilled. The process mainly consists of bag opening, screening, and separation of the organic fraction of the wastes, which further undergoes aerobic stabilization (composting). The stabilized organic fraction can then be used as covering material in the landfill nearby, as a filling material for the restoring quarries, or in other ways. Source separated organic material collected in the city can be composted, and after refinement, sacked to be used as fertilizer, in the composting line of the plant. The organic free fraction material undergoes a sequence of separations in order for recyclable materials to be separated. These materials are ferrous, aluminum, plastic foil, PET bottles, polyethylene-polypropylene packaging, mixed paper, solid fuel (refuse derived fuel, RDF). The residual materials are transferred to a sanitary landfill. The separations are performed by ballistic, magnetic, eddy current, and near infrared spectra optical separators in order for the recovery and the purity of the recyclable materials to be maximized and for hand picking to be minimized or avoided.

Table 2: Output Compositions

Recovered Fraction	Chania MSW	Chania Pre-Sorted	Larnaca	Liosia	Barcelona
Carton		27%		1%	
Mixed Paper	16%		12%		1%
Film PE	3%	5%	3%	1%	1%
Rigid PE	3%	1%		1%	1%
Rigid PP	2%	2%	2%	1%	1%
Rigid PET	2%	1%	1%	1%	1%
Non-Ferrous	1%	1%	1%	1%	1%
Ferrous	2%	1%	1%	1%	1%
Process Losses	30%	22%		13%	16%
Residue	18%	20%	26%	20%	15%
CLO	23%	20%		15%	
Organic Fraction			37%		
Digest Dewatered					3%
RDF/WtE			16%	46%	59%
Glass			1%		1%
Total	100%	100%	100%	100%	100%

- Liosia, Greece: The plant processes 186,500 tons of waste per year, with around 1/3 of the input material being organic. The recovery of recyclables is less than 4%, and the plant mainly produces RDF and compost. The plant generates around ~22% of residue. The waste undergoes size reduction and mechanical separation through screening. Ferrous and non-ferrous materials are removed by the use of a magnet and an eddy-current, respectively. The organic fraction undergoes aerobic degradation. It remains in the specially designed channels for several weeks until it is stabilized. The stabilized organic material is then refined (materials such as glass or hard plastics are removed).
- Barcelona, Spain: The MBT processes ~265,650 tons per annum. A detailed analysis of the input stream was not available. The only available breakdown was between total MSW and rest material. The recovery of recyclables in this plant is less than 7 wt.%. A total of 60 wt.% of the output material is fuel to be utilized in WTE plants and the residue generated is ~14 wt.%. The incoming < 200 mm MSW is processed in the MBT facility, which is in operation about 250 days/year (16 h/day; 2 shifts) and has 2 lines of 30 t/hour capacity. The process involves hand sorting of oversized items, bag openers, hand sorting of paper, plastics and glass materials and trommels. This process separates the MSW to the following size fractions:
    - 70 to 200 mm: this is mostly 'dry' stream to be processed for the recovery of recyclable products by means of magnetic and eddy current separators and ballistic separators that sort out light plastics, paper, stones and glass. The 70 to 200 mm fraction corresponds to about 35 to 40 wt.% of the MSW stream to the MBT plant.
    - < 70 mm: this fraction consists of mostly 'wet' materials that are divided into two streams, one that goes to the anaerobic digesters, to recover biogas (50% CH4) and the other to biostabilization. The organic material corresponds to about 40 wt.% of the feedstock to the MBT plant.
    - The metals contained in the 70 to 200 mm are separated with magnetic and eddy current separators. Ballistic separation is used to separate the recyclable materials (paper, plastics, glass, and heavy materials (stones etc.) This stream is conveyed past optical sensors and separators for the extraction of paper fiber, marketable plastics, and glass. The process is adjustable, according to the prevailing prices of the different commodities.
    - The remaining fraction of the 70 to 200 mm fraction is then introduced to the pulping stage of the BTA® Processes that consists of two steps: the BTA® hydromechanical pre-treatment and the subsequent anaerobic digestion of the cleaned organic suspension. The cleared organic suspension is temporarily stored in a suspension tank. The organic fraction is digested in the anaerobic digestion stage, under mesophilic conditions, between 35 - 38°C. There are two horizontal digesters in series, each of 3,000 m^3 capacity (dimensions: 120 m long x 26 m wide x 3 m high). The biogas production is about 4.2 million Nm^3/year (estimated 1t about 1,300 tons CH4 annually) and fuels two biogas engines of generating capacity of 800 kW each. About 15% of the MSW to the MBT

Table 3: Investment Assumptions

Life Cycle (years)	20
Equity (%)	30.0
Equity Period (years)	10
Equity Cost (%)	6.0
Debt (%)	70.0
Tax Rate (%)	30.0
Debt Cost (%)	5.0
Discount Rate (%)	9.0
Rate of Increase (%)	1.0

plant (about 34,000 tonnes) is digested for the production of energy (biomethanisation process) able to recover 0.15 MWh/ ton of MSW, i.e. a total of 4,801 MWh. The compost product of the AD process is mixed with the other residues of the MBT plant and are sent to the adjacent WTE plant.

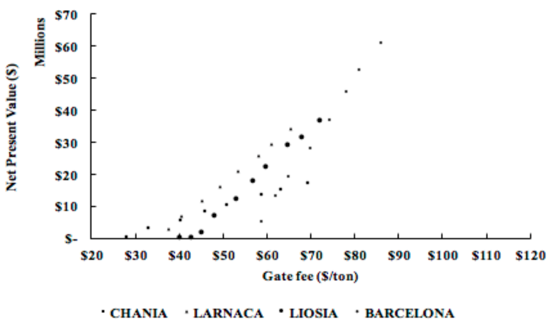

Figure 2: NPV & IRR vs. Gate Fee for the case of Recyclables

2.3. Financial analysis

The financial analysis involved three factors. The first is the gate fee, which practically assesses the burden of a plant, on the local municipality. In short, it determines how much the municipality will be required to pay per truck entering the facility in order for the company owning the plant to achieve an internal rate of return equal to 12%. The second factor is the net present value of the plant. This factor determines the viability of the investment, depending on the mode of operation of the plant, for the investor. Finally, the third factor in play is the environmental impact of the plant according to its mode of operation.

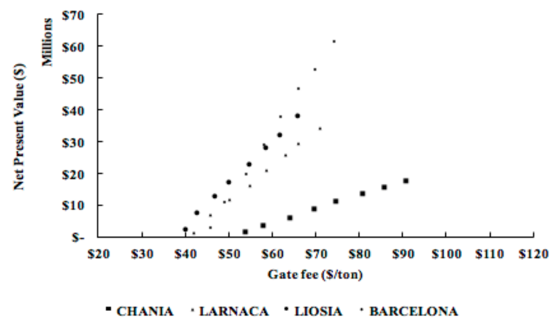

Figure 3: NPV & IRR vs. Gate Fee for the case of RDF

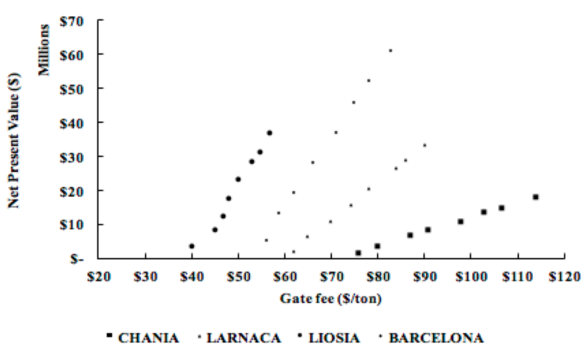

Figure 4: NPV & IRR vs. Gate Fee for the case of Landfilling

The purpose of this analysis is to relate the gate fee, the independent variable, to the net present value (NPV), and consequently to the internal rate of return (IRR), i.e. the dependent variable. The financial viability of the plants was assessed, by considering the capital and operating expenditures, the revenue streams, the loan and equity payments and the life cycle of the project. The project debt, equity, depreciation, as well as profit and loss analysis and cash flow are calculated for each of the 20-years of the plant's lifetime. The cash flows and profit/tables were used for the calculation of the NPV and IRR values of each scenario.

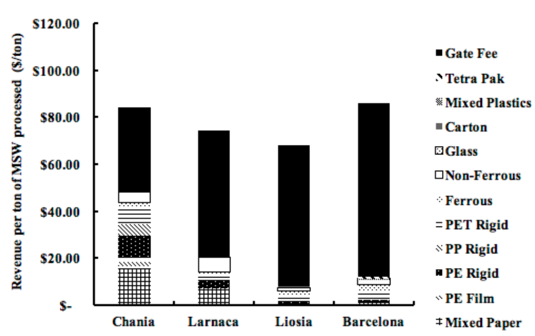

Figure 5: Revenue per Ton for the case of Recyclables

The assumptions regarding the investment structure are presented in Table 3. Interest rates were assumed to be 5% over a 15-year period and the tax rate was set to 30%. The capital and operational expenses of the plants were normalized on a per ton of material processed basis, and the results are presented in Tables 4, and 5.

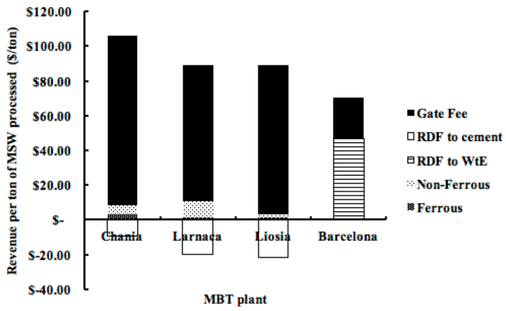

Figure 6: Revenue per Ton for the case of RDF

The effect of varying gate fee on the NPV and IRR values was examined. The gate fee was varied to provide IRRs of 0%, 3%, 6%, 9%, 12%, 15%, 17%, and 20%, and the NPVs were calculated. The breakdown of the revenues from the recyclables and the RDF, as these were reported by the operators of the plants, and the calculated gate fee for an IRR=12% is presented in detail. It should be noted, that for the case of Chania two fractions are processed: mixed MSW and pre-sorted. The weighted average of the revenue was used, based on the share of operating time the plant runs in each mode.

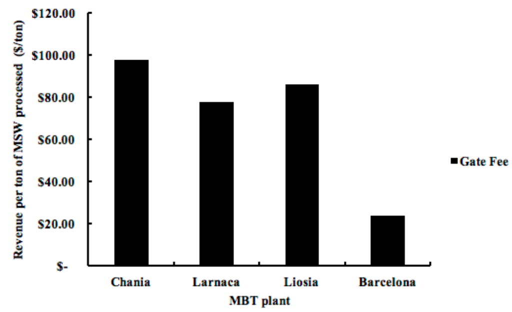

Figure 7: Revenue per Ton for the case of Landfilling

2.4. Environmental analysis

In total, three sources of emissions are considered: collection of MSW, transport and waste treatment processes (including landfilling, combustion, and recovery) and plant operations.

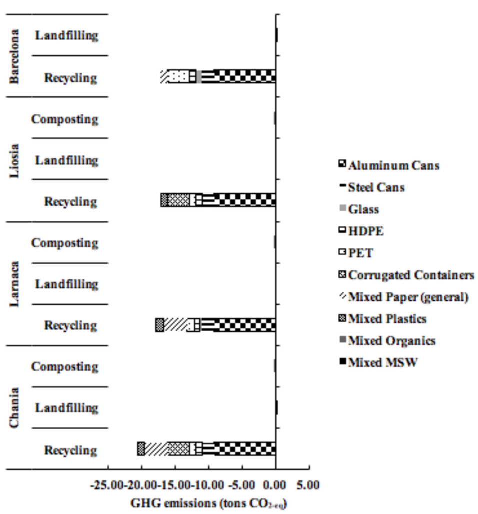

Figure 8: GHG Emissions for the case of Recyclables

The environmental impact of each plant is estimated according to a comparative spreadsheet provided by the US Environmental Protection Agency. The methodology considers the input waste composition and quantity, and the output products regarding the final disposition. In our case, the output was the recyclables stream, RDF stream, or landfilled materials. Two assumptions were made: a. the marginal electricity grid emission for landfilling and combustion is assumed to be the same as the U.S. national average, and b. emissions associated with transport from and to the plant are based on the transportation distances of 20 miles (Fitzgerald et. al., 2012). According to G.C. Fitzgerald et. al., the average emissions for dual stream (DS) recycling is 0.059 $MTCO_2E/MT$ of collection, while for single stream (SS) recycling is 0.038 $MTCO_2E/MT$ of collection; and these factors were used to calculate the associated emissions from the collection

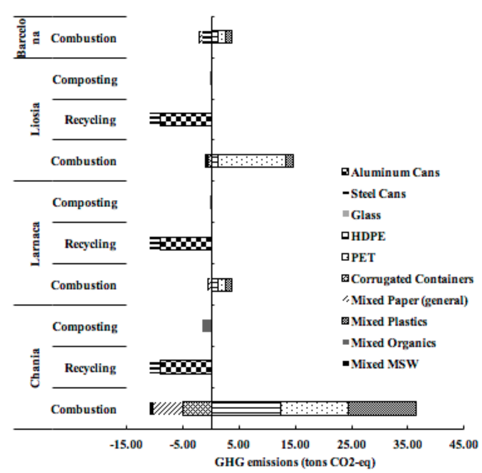

Figure 9: GHG Emissions for the case of RDF

of the waste. The total emissions from all the scenarios were calculated, by assuming a 10% of humidity losses during processing.

3. Results and Discussion

3.1. Financial analysis

The lowest capital expenditure on a per ton basis was observed at the plant in Chania, where mixed MSW is processed.

The plants that receive mixed waste materials had an average CAPEX of $379.8/ton of waste, and a standard deviation of $15.1/ton. This number excludes the outliner that is the Chania plant when operates in a 'source separation' mode that indicates the highest CAPEX of $2,189.7/ton, associated with the limited availability of the input material (Cruz et al., 2012; Marques et al. 2014; Lavee, 2007, Pingsha, 2004).

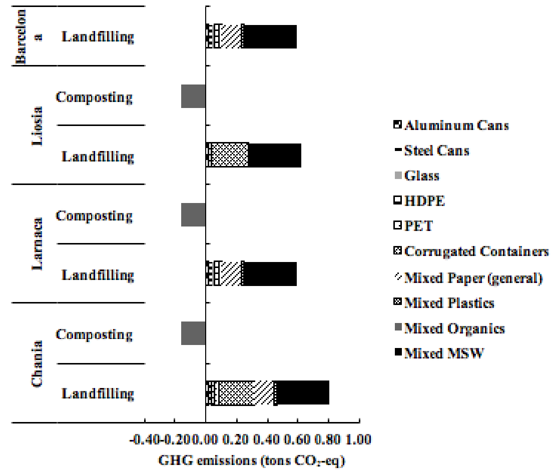

Figure 10: GHG Emissions for the case of Landfilling

The reported and calculated OPEX of the scenarios examined are presented in Tables 5 and 6. For the scenario that only recyclables are recovered and the scenario that RDF is recovered, the average OPEX of the plants was $35.1/ton of mixed MSW, and a standard deviation of $7.2/ton. The Chania plant when processes source separated materials reported OPEX of $66.4/ton, for the same reasons that explained the significant difference of the CAPEX. For the case that the material is landfilled, the average OPEX is $17.9/ton of MSW with a standard deviation of $2.6/ton, whereas the Chania plant on a 'source separated' mode has an OPEX of ~$25.7/ton.

Table 4: Capex per Ton of Material Treated

CAPEX COMPONENTS		Chania MSW	Chania Pre-Sorted	Larnaca	Liosia	Barcelona
1. CIVIL WORKS	1.1 CIVIL WORKS	$59.55	$357.30	$66.99	$71.47	$65.60
	1.2 EXCAVATIONS	$38.11	$228.67	$40.06	$40.43	$39.30
	1.3 LANDFILL	$11.91	$71.46	$13.33	$11.50	$12.51
2. MECHANICAL WORKS	2.1 MECHANICAL EQUIPMENT	$35.73	$214.38	$41.80	$34.49	$39.23
	2.2 CONVEYORS	$45.26	$271.55	$49.58	$43.12	$49.06
	2.3 DEDUSTING	$5.33	$31.99	$5.96	$5.75	$19.62
	2.4 DEODORIZATION	$6.07	$36.44	$6.70	$5.75	$6.88
	2.5 COMPRESSED AIR	$1.97	$11.79	$2.18	$1.98	$1.89
	2.6 AUTOMATION	$3.81	$22.87	$4.25	$3.27	$4.47
3.BIOLOGICAL TREATMENT		$92.90	$557.39	$88.43	$84.30	$74.68
4. WWTP		$11.91	$71.46	$13.40	$11.50	$13.22
5.CONVENTIONAL		$23.82	$142.92	$33.43	$25.87	$24.87
6. MOBILE EQUIPMENT		$28.58	$171.50	$32.49	$31.04	$33.64
GRAND TOTAL		**$364.95**	**$2,189.72**	**$398.61**	**$370.48**	**$384.96**

Figures 2 to 4 present the relation between the gate fee (x-axis) and the NPV (y-axis) for the several IRR assumed, and for the different scenarios examined. The detailed calculations for the NPV, IRR and gate fee values are presented in the Tables of the Appendix. It is observed that the NPV of the Chania plant is affected most with varying gate fee for all the scenarios examined. This is associated with the economies of scale, and the fact that the Chania plant is the smallest in terms of capacity, from all the plants examined. The highest NPV was obtained from the Barcelona plant, for all the scenarios examined, associated with the highest capacity of the plant. The scenario that that all the materials are landfilled will require the highest gate fee for all the plants examined, as compared to the other scenarios. This relates to the significant investment required for the construction of the plants, and the losses in the revenues. It should be noted, however, that many facilities in the EU have reported this status. The scenario that all the materials will be recycled, has the lowest required gate fee, which relates to the high value of few products in the market, such as ferrous and non-ferrous metals, as it is explained in the following sections. The case that the plants will recover fuel that will be sold to the cement industry, indicate required gate fee values close to the recycling scenario. However, it has been assumed that the Chania, Larnaca, and Liosia plants will pay the cement operators, whereas the Barcelona plant will be paid, which are the actual cases. If the cement operators are keen to pay for the produced fuel, then the NPVs are favorable for the recovery of fuel, rather than recycling, as it is obvious by the Barcelona plant in Figures 2 and 3. It should be noted that the situation at the Chania, Larnaca, and Liosia facilities is not common since typically the cement operators are paying about $20 to 25 /per ton of RDF that replaces a significant amount of coal or other fossil fuels used in these energy intense operations. However, the operators of the MBT plants should secure long contracts with the cement operators, in order to minimize the risk of the investment. The results for the NPV are therefore relatively intuitive, and it seems that in order to decide between RDF production and recyclables recovery, environmental impact and gate fee would be the tiebreakers.

Table 5: Opex per Ton of Material Treated

OPEX Components	Chania pre-sorted MSW ($/ton)	Chania mixed MSW ($/ton)	Larnaca ($/ton)	Liosia ($/ton)	Barcelona ($/ton)
1. MBT Costs	**$23.79**	**$45.21**	**$18.77**	**$17.47**	**$32.01**
1.1 Maintenance	$3.81	$7.50	$2.08	$1.90	$5.72
1.2 Fuels	$2.50	$5.36	$2.55	$2.30	$3.22
1.3 Electricity	$4.53	$4.82	$4.82	$4.60	$4.82
1.4 Consumables	$2.14	$4.29	$1.84	$1.67	$2.79
1.5 Composting	$0.09	$0.01	$0.11	$0.11	$0.11
1.6 Staff	$10.72	$23.22	$7.37	$6.90	$15.36
2. WWTP	**$2.32**	**$7.86**	**$2.04**	**$1.84**	**$3.43**
3. Anaerobic Digestion	**$3.45**	**$8.58**	**$2.68**	**$3.48**	**$2.89**
4. Landfill	**$3.57**	**$4.75**	**$3.68**	**$3.45**	**$4.11**
5. CLO Utilization	**$3.10**	**$-**	**$3.01**	**$2.85**	**$2.36**
TOTAL	**$36.24**	**$66.40**	**$30.19**	**$29.08**	**$44.81**

Table 6: Opex Required for Landfilling

OPEX Components	Chania MSW ($/ton)	Chania Pre-Sorted ($/ton)	Larnaca ($/ton)	Liosia ($/ton)	Barcelona ($/ton)
1. MBT Costs	**$4.74**	**$9.04**	**$3.75**	**$3.49**	**$6.49**
1.1 Maintenance	$0.76	$1.50	$0.42	$0.38	$1.14
1.2 Fuels	$0.50	$1.07	$0.51	$0.46	$0.64
1.3 Electricity	$0.91	$0.96	$0.96	$0.92	$0.96
1.4 Consumables	$0.43	$0.86	$0.37	$0.33	$0.56
1.5 Composting	$-	$-	$0.02	$0.02	$0.11
1.6 Staff	$2.14	$4.64	$1.47	$1.38	$3.07
2. WWTP	**$0.46**	**$-**	**$-**	**$-**	**$0.69**
3. Aerobic Digestion	**$-**	**$-**	**$-**	**$-**	**$-**
4. Landfill	**$12.51**	**$16.63**	**$12.90**	**$12.07**	**$14.38**
5. CLO Utilization	**$-**	**$-**	**$-**	**$-**	**$-**
TOTAL	**$17.71**	**$25.67**	**$16.65**	**$15.57**	**$21.56**

Figures 5 to 6 present the revenue streams as these were reported by the operators of the plants, and the required gate fee to obtain an IRR of 12%. For the recovery of recyclables scenario at an IRR of 12%, the Chania plant will require a gate fee of $51/ton of mixed MSW, the Larnaca plant a gate fee of $54/ton of MSW, the Liosia plant $60/ton of MSW, and the Barcelona plant \$60/ton of MSW. The NPV were \$10,578,280, \$20,891,919, \$21,797,502, and \$37,125,846, respectively. For the RDF scenario, the combustible recyclables, i.e. the paper and plastics, will be included in the RDF in order to increase its calorific value. The distribution of the RDF to the cement plants costs ~ \$38/ton. Therefore, in the absence of revenue streams from recyclables, we would need to increase the gate fee to \$86/ton in order to maintain the same levels of IRR, for the case of Larnaca. For the Chania plant a gate fee of \$104/ton of mixed MSW is required to achieve an IRR of 12%, and a NPV of \$10,383,373. The Larnaca plant requires \$86/ton of MSW for NPV of \$21,423,143, and the Liosia plant \$89/ton for NPV of \$22,739,056. The Barcelona plant will require \$7/ton of material for an NPV of \$37,093,051. For the landfilling scenario the Chania plant requires a \$75/ton for an NPV of \$10,580,674. The Larnaca plant \$59/ton for \$20,967,075, and the Liosia plant \$55/ton for \$20,424,380. The Barcelona plant needs \$62/ton for an NPV of \$37,473,902.

In order to achieve an IRR of 12%, it ought to be the highest when the plant operates in an RDF production mode for the plants in Chania, Larnaca and Liosia, given that RDF production is not their main mode of operation. However, this is not the case for the Barcelona plant, which is designed to produce RDF. In the case of Barcelona, the gate fee yielding an IRR of 12% for RDF production mode, is about equal to that of the mode of operation in which recyclables are recovered. It is evident that for the Chania and Larnaca plants, which are the most similar ones in terms of both throughput capacity and operation, the gate fee is the lowest for recyclables recovery, it is higher for the landfilling scenario, and the highest of all for the production for RDF scenario. As explained earlier, the plants in Chania, Larnaca, and Liosia pay the local cement industry to provide them with their fuel, associated with the high gate fee costs required to achieve an IRR of 12%. In Barcelona, where the opposite happens, the gate fee is lower relative to the recyclable's recovery scenario. It should be noted that the recyclables recovery scenario gate fee is high because this is not the main operation mode of the plant. It should also be noted that there is no apparent trend between gate fee and throughput capacity. The main revenues of the plants when recycling takes place, are contributed by the mixed paper, the PE rigid, and ferrous and non-ferrous metals.

Table 7: Collection & Operational Emissions

Energy Type	Annual emissions MTCO2E Mode 1 (DS)- Chania	Annual emissions MTCO2E Mode 2 (SS)- Chania	Annual emissions MTCO2E Mode 2 (SS)- Larnaca	Annual emissions MTCO2E Mode 2 (SS)- Liosia	Annual emissions MTCO2E Mode 2 (SS)- Barcelona
Electricity	93.45	668.7	1,188.8	1385.5	1973.8
Natural Gas	35.4	129.6	230.4	268.5	382.5
On-site diesel	32.4	170.1	302.4	352.4	502.1
Fleet fuel	6.0	27	48	55.9	79.7
Total	167.25	995.4	1,769.6	2062.4	2938.1

3.2. Environmental analysis

Figures 8 to 10 present the results of the environmental analysis, in tons of CO_{2-eq}/ton of MSW processed. The emissions associated with the operation and the transportation of the materials to the plant, are the same for all the scenarios examined, independent of the final disposition. The weighted emissions associated with the collection of the materials and the operation of the plants are presented in Table 7. In the following section the total values are reported, provided the

For the case that only recyclables are recovered, the total emissions of the Chania plant were -43,545 tons CO_{2-eq} per year (1.1 ton/ton of waste), the emissions of the plant in Larnaca were -76,148 tons CO_{2-eq} per year (~0.48 tons/ton of waste), the emissions of the plant in Liosia 37,805.1

tons $CO_{2\text{-eq}}$ per year (~0.2 tons/ton of waste), and the calculated emissions of the plant in Barcelona were 43,964.9 tons $CO_{2\text{-eq}}$ per year (~0.17 tons/ton of waste).

For the recycling scenario, the Barcelona plant landfills a significant fraction of mixed MSW that associates with the emission of about 68,000 tons of $CO_{2\text{-eq}}$ (~0.26 tons/ ton of waste) whereas the recovery of mixed paper saves about 17,000 tons of $CO_{2\text{-eq}}$ (~0.06 tons/ton of waste) and the recovery of aluminium and steel cans saves about 6,900 tons (0.026 tons/ton of waste) and 6,800 tons of $CO_{2\text{-eq}}$ per year (0.026 tons/ton of waste), respectively. For the Chania plant the recovery of mixed paper saves a total of about 36,000 tons of $CO_{2\text{-eq}}$ per year (0.93 tons/ton of waste), while in Larnaca the savings from the recovery of paper and aluminium are about 69,000 (0.43 tons/ton of waste) and 11,000 tons of $CO_{2\text{-eq}}$ per year (0.07 tons/ton of waste), accordingly. The plant in Liosia does not recover paper, and this relates to the relatively higher emissions, as compared to the other scenarios.

For the case that RDF is recovered, the Chania plant indicated 149 tons CO 2-eq per year (practically negligible on a per ton basis), the Larnaca plant - 6,723 tons CO 2-eq per year (0.04 tons/ton of waste), the Liosia plant - 7,491.9 tons CO 2-eq per year (~0.04 tons/ton of waste), and the Barcelona plant -923.63 tons CO 2-eq per year. For the case that the material is landfilled, the Chania plant will emit 9,931 tons CO 2-eq per year (0.26 tons/ton of waste), the Larnaca plant 19,042 tons CO 2-eq per year (~0.12 tons/ton of waste), the Liosia plant 50,921.01 tons CO 2-eq per year (0.27 tons/ton of waste), and the Barcelona plant 81,843.3 tons CO 2-eq per year (~0.31 tons/ton of waste).

Table 8: Summary of Results

Scenario	Gate Fee (needed to achieve IRR=12%)	Revenue/ $ p.a.	Total Greenhouse Gas Emissions / $MTCO_2E$ p.a.
CHANIA			
Recyclables Recovery	51	6,448,764	-43,545
RDF Production	104	6,418,262	149
Landfilling	75	5,0112,75	9,931
LARNACA			
Recyclables Recovery	54	12,419,954	-76,148
RDF Production	86	12,503,087	-6,723
Landfilling	59	10,110,933	19,042
LIOSIA			
Recyclables Recovery	60	13,527,162	37,805
RDF Production	89	13,674,511	-7,492
Landfilling	55	10,925,846	50,921
BARCELONA			
Recyclables Recovery	74	2,409,070	43,965
RDF Production	71	27,403,938	-924
Landfilling	62	19,992,071	81,843

The highest emissions of all four cases are obtained in the scenario of landfilling. Nevertheless, large variations are observed in the scenarios of recovery of recyclables and RDF production. For the plants in Chania and Larnaca, there is significant negative overall impact in the scenario of recyclables recovery and small positive impact in the scenario of RDF production, whereas in the plants of Liosia and Barcelona, there is large impact in the former scenario and slight negative impact in the latter. This difference can be attributed to the thorough sorting process taking place in the first two plants, as is evident in their respective output compositions. On the other hand, the fact that the Liosia plant does not incorporate a thorough sorting line, and the fact that sorting and recyclables recovery does not constitute the primary function of the Barcelona plant, yield positive environmental impact in the scenario of recovery.

4. Conclusions

The impact of four advanced EU MBT facilities on the local public sector, the private party operating the plant, and the local community was assessed. The paper is also destined to provide primary data of the processes operating in Europe, and therefore, provide stakeholders and academics with the data required to consider the introduction of such technologies in their communities, and the advancement of these processes.

A summary of the results is presented in Table 8. It can be concluded, that the optimal solution for the municipalities should be built upon a thorough sorting and recyclables recovery line, to achieve both the negative emissions that the Chania and Larnaca plants have achieved, and to reduce the gate fee needed to achieve an IRR of 12%, given that recyclables constitute a considerable revenue stream. For the high calorific value materials that cannot be recovered or do not have a value in the market, there should be an RDF stream produced, to further reduce emissions, that would have been caused in the case of landfilling, but also adding to the revenue stream (this considers that the plant is not build in the area of southeastern Europe, where the plants actually pay the cement industry to provide them with fuel). In the case of Barcelona that represents an integrated solution, the mixed RDF and organic fraction are combusted for the production of energy. This was found to be an efficient way that provided a complete solution for the city, associated also with the low quality of compost product that is being produced in all cases examined. The compost material cannot be used in agriculture, and it is therefore used, in the best case, as daily cover in landfills. Finally, only the by-products of the processes should be landfilled, given the high emissions in the landfilling scenario, and the fact that the net present value for this scenario is the lowest of all three.

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