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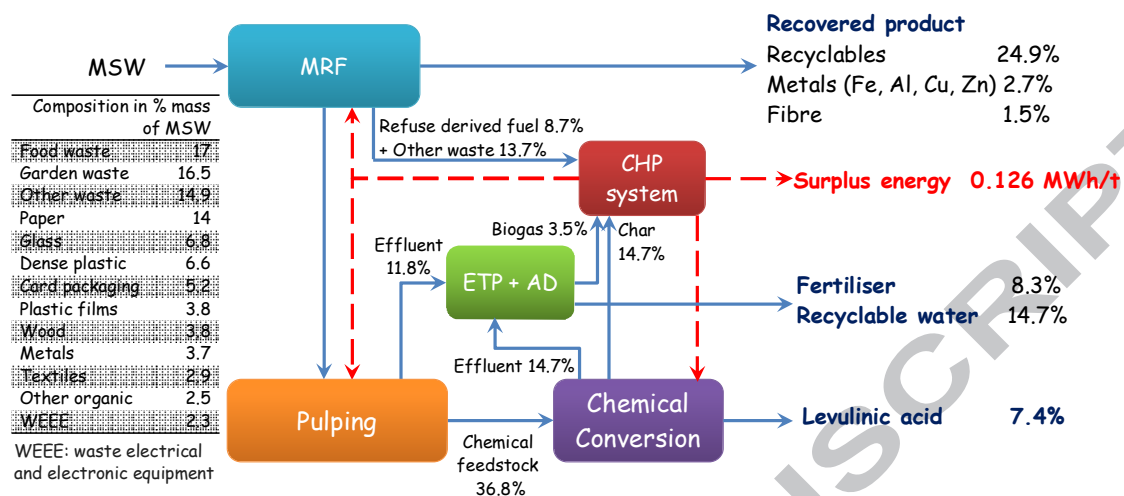
Material Flow and Sustainability Analyses of Biorefining of Municipal Solid Waste**Jhuma Sadhukhan^{*1} and Elias Martinez-Hernandez²**¹Centre for Environmental and Sustainability, University of Surrey, GU2 7XH, UK²Department of Chemical Engineering, University of Bath, Bath, BA2 7AY, UK**Abstract**

This paper presents material flow and sustainability analyses of novel mechanical biological chemical treatment system for complete valorization of municipal solid waste (MSW). It integrates material recovery facility (MRF); pulping, chemical conversion; effluent treatment plant (ETP), anaerobic digestion (AD); and combined heat and power (CHP) systems producing end products: recyclables (24.9% by mass of MSW), metals (2.7%), fibre (1.5%); levulinic acid (7.4%); recyclable water (14.7%), fertiliser (8.3%); and electricity (0.126 MWh/t MSW), respectively. Refuse derived fuel (RDF) and non-recyclable other waste, char and biogas from MRF, chemical conversion and AD systems, respectively, are energy recovered in the CHP system. Levulinic acid gives profitability independent of subsidies; MSW priced at 50 Euro/t gives a margin of 204 Euro/t. Global warming potential savings are 2.4 and 1.3 kg CO₂ equivalent per kg of levulinic acid and fertiliser, and 0.17 kg CO₂ equivalent per MJ of grid electricity offset, respectively.

Keywords: levulinic acid, techno-economic analysis, integrated biorefinery and resource recovery from waste (RRfW), process integration, circular economy, life cycle assessment (LCA)

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Graphical abstract



1. Introduction

The world needs to urgently deploy eco-innovative integrated solutions for resource recovery from urban or municipal solid waste (MSW) in the form of biorefinery for the realization of a circular economy resulting into zero-waste urban systems. According to the European Commission department responsible for EU policy on the environment, in 2010, a total of 2.5 billion tonnes of waste was produced (European Commission, Environment, 2017). Only, 40% were reused or recycled, while some countries sent 80% of the waste to landfill. According to the estimation by the World Bank, at the current pace, MSW generation would exceed 11 million tonnes per day by 2100 (World Bank, 2013). The rate of waste generation would increase from 1.2 to 1.42 kg per person per day in the next fifteen years. Wastes are the main cause of pollution posing threat to health, and the natural, and living environment. The world is faced with resource constraints, and increased waste generation and demands for products. An approach / opportunity to deal with these challenges is using lesser amount of virgin resources, and reusing waste as resources.

Technologies for bulk conversion of MSW are mature, but have disadvantages such as generation of toxic wastes and emissions, requiring disposal via costly routes (Cheng and Hu, 2010). The state-of-the-art treatment technologies of MSW include incineration, and anaerobic digestion (AD) and compost like output (CLO) generation, broadly fall into two categories, thermochemical (Bhaskar and Steele, 2015; Emun et al. 2010) and biochemical (Walker et al., 2009; Peralta-Yahya et al., 2012) processing, respectively. Incineration of MSW, a mean of energy recovery from waste supported by numerous waste legislations (e.g. European Commission, Environment, 2017), produces three main types of residues, bottom ash considered as non-hazardous waste, fly ash contains metals, heavy metals, metal oxides, chlorides and organic compounds, and air pollution control residue contains chlorides (Margallo et al., 2015). Life cycle assessment (LCA) studies have revealed high

environmental impacts due to air pollutant emissions, and fly ash disposal, in addition to high capital and operational costs, and equipment corrosion, etc. as the main bottlenecks of these technologies (Cherubini et al., 2009), for the consideration of policy makers (Finnveden et al., 2005). Some post-combustion or end-of-pipe clean-up technologies exist, however, are not particularly effective in mitigating pollution to the environment or lowering the cost of processing (McKay, 2002; Buekens and Huang, 1998). Thermal degradation of MSW in a progressive manner, e.g. first decomposition of biomass then polymers using enhanced gasification with CO₂ recycling, has been effective in generating a clean fuel gas (Kwon and Castaldi, 2012). Mechanical biological treatment (MBT) is the main alternative to thermochemical processing of MSW. A recent work shows that MBT facilities incorporating composting with AD have a higher waste treatment performance efficiency than the MBT facilities relying on composting (Colón et al., 2017). However, leaching of heavy metals and other elements from the use of CLO as soil amendment has remained as a consistent problem, if not removed before AD, and poses a high risk to the environment (Page et al., 2014).

As waste resources are a heterogeneous mixture of many components, which if unrecovered pose the greatest environmental impacts, recovery of every pollutant as an added value resource is essential for sustainability. It is critical to recover recyclables and metals at the beginning of the processing chain of MSW before fuel production, such as refuse derived fuel (RDF), a coal like fuel, and the facility to achieve so, is coined as material recovery facility (MRF) (Chang et al., 2005). Resource recovery from waste (RRfW) coined by the Natural Environment Research Council (2012) infers by definition, recovery of every potential pollutant to the environment, as added value resources from waste streams and putting the added value resources back into value chains for a zero waste circular economy and better health of the environment (Sadhukhan, 2017). Since the introduction of the concept, process integration between RRfW and biorefinery is being researched (Sadhukhan et al., 2016a and

2016b). Metallurgical, and microbial electrosynthesis are the main secondary mining technologies that can play a key role RRFW (Ng et al., 2016). RRFW can be designed and configured to recover metals, heavy metals, metal oxides, elements, inorganics, etc. prior to valorisation of biodegradable components of MSW, thus mitigating the in-process and end-of-pipe environmental emissions. Furthermore, pollutant-free biodegradable component of MSW opens up a plethora of product choices. Plausible processes, products, and pathways in biorefinery have been investigated in Sadhukhan et al. (2014). The conversion of this organic fraction into value added chemicals has been studied for the production of polyhydroxyalkanoates (Amulya et al., 2015), volatile fatty acids (Bonk et al., 2015; Karthikeyan et al., 2016) and lactic acid (Kwan et al., 2016). A biorefinery combining anaerobic fermentation and hydrothermal liquefaction for production of volatile fatty acids and bio-oil has also been conceptualised (Coma et al., 2017). Other potential pathways for valorisation of the organic biodegradable fraction of MSW have been reviewed elsewhere (Arancon et al., 2013; Bastidas-Oyanedel et al., 2016; Mohan et al., 2016; Chen et al., 2016).

Extraction of C1-C6 molecules from the biodegradable or biomass or lignocellulose or organic components of MSW is the key to determine economic feasibility and sustainability of the system. Presently, there is only one study on valorisation of biodegradable fraction of MSW into the production of levulinic acid (Sadhukhan et al., 2016a). Levulinic acid is a platform or building block chemical precursor to many added value products (Sadhukhan et al., 2014). Ethyl valerate, an ester derived from levulinic acid, is a drop-in biofuel, which can be blended upto 45% by volume and have a demand as high as 22 million barrel a day (GF Biochemicals, 2015). Derivatives of levulinic acid have applications as pharmaceutical, specialty chemical, agricultural, solvent, platform chemical and fuel additive products. Levulinic acid is one of few molecules referred as ‘sleeping giants’ owing to their vast potentials in the emerging bio-based economy due to their key positions in the production of

biomass-derived intermediates and transition from fossil based economy to bio- renewable-based circular economy. GF Biochemicals to date is the main producer of levulinic acid at their plant in Caserta, Italy (GF Biochemicals, 2015). Levulinic acid has emerged as a niche platform chemical in production of pharmaceutical and agrochemical derivatives: δ -aminolevulinic acid, specialty chemical: γ -valerolactone, polymers and resins: diphenolic acid, platform chemical: pyrrolidones, succinic acid and fuel additive: levulinate esters, 2-methyltetrahydrofuran with addressable petrochemical replacement potential of over 25×10^6 t by 2020 (GF Biochemicals, 2015).

As discussed, there is only one comprehensive study on valorisation of biodegradable fraction of MSW into the production of functional chemicals such as levulinic acid (Sadhukhan et al., 2016a). A paradigm shift in MSW processing systems is thus the need of the hour not only to eliminate losses of value-added products to landfills, save virgin resources and increase resource recovery efficiency, but also to close the loop for a circular economy. This paper, thus to fill the gap, presents eco-innovative, efficient, cleanest, and sustainable options for recovering high-grade valuable materials and chemicals that are not currently recovered from MSW. These have been systematically derived using the following tools:

1. Analysis of MSW mass flows into products via Sankey diagrams.
2. Economic value analysis for finding profitable and non-profitable products and integrated biorefinery configurations of MSW for highest economic benefit.
3. Assessment of avoided global warming potential over 100 years (GWP) impact for relative benefits by delivering new products with respect to current use of waste feedstocks, and by replacing one by the other in order to be able to move towards a more circular economy paradigm.

Section 2 discusses the above methods for deriving sustainable biorefinery systems recovering resources from MSW, section 3 results and discussions, and section 4 conclusions.

2. Materials and Methods

MSW consists of paper and cardboard packaging; glass; dense plastic and plastic films (container, plastic packaging); wood, garden and food waste; textiles; WEEE (waste electrical and electronic equipment); metals and unidentified wastes. These streams are split into various lines for recycling. Source segregation of urban waste or MSW is a usual feature of developed economies, which can be adaptable for developing economies. Thereafter, pretreatment, chemical valorisation, AD and CHP generation take place to make the whole system sustainable. The following sub-sections present the analyses of mass flows from MSW to products via Sankey diagrams, economic values and life cycle environmental impacts, respectively.

Mass flow analysis: Figure 1 shows the split of MSW in terms of food waste (17%), garden waste (16.5%), other waste (14.9%), paper (14%), glass (6.8%), dense plastic (6.6%), card packaging (5.2%), plastic films (3.8%), wood (3.8%), metals (3.7%), textiles (2.9%), other organic (2.5%) and WEEE (2.3%), by mass of MSW, respectively (DEFRA, 2015). Amongst these, other waste (1.2%), paper (7.6%), glass (6.8%), dense plastic (1.1%), card packaging (2.8%), plastic films (0.6%), metals (1%), textiles (1.5%) and WEEE (2.3%), by mass of MSW, respectively, are recycled. RDF carries the balance of dense plastic and plastic films. The balance of metals can also be recovered. Food waste (8.5%) and garden waste (13.2%) by mass of MSW and the balances of paper, card packaging, wood and other organic wastes can be used as a feedstock for high value chemical production. The balances of food (8.5%) and garden (3.3%) wastes are routed to AD, other waste (13.7%) as fuel for combined heat and power (CHP) generation, and textile (1.5%) as fibre, respectively. Figure 1 shows the material flow analysis across various process blocks, in the form of a Sankey diagram.

Furthermore, the data for the construction of the Sankey diagram, i.e. mass transfer from one segregated stream to another is summarised in the table within Figure 1.

Figure 1

The proposed system for the total valorisation of MSW, coined as mechanical biological chemical treatment (MBCT) system, has an MRF, a chemical section comprising pulping, chemical conversion, separation and purification of chemical products, an effluent treatment plant (ETP) for recycling water, a biochemical section comprising an AD for fertiliser and biogas production, and a CHP section utilising RDF, char and biogas as fuel.

Mass and energy balances of all processes have been generated using spreadsheet models, with exception to chemical conversion process. The detail design, simulation and analysis of the chemical conversion process has been performed in Aspen Plus®, comprehended in the earlier paper (Sadhukhan et al., 2016a). Yield based correlations have then been developed for incorporation into spreadsheet based software. Thus, an interactive spreadsheet based software for levulinic production system simulation and evaluation has been developed, which is freely available under a Creative Common License (Sadhukhan et al., 2016c). The basis of the input and output mass flowrates across the chemical conversion section is thus supported by detailed process simulation (Sadhukhan et al., 2016a; 2016c). Here, the detailed simulation results are omitted and final mass transfers on MSW have been used to construct the Sankey diagram in Figure 1. According to Sadhukhan et al. (2016c), levulinic acid, char and effluent extracted by chemical conversion of lignocellulose present in MSW are 20%, 40% and 40%, by mass of lignocellulose, respectively. The yields of biogas and fertiliser from AD are obtained from Sadhukhan, (2014): 30% and 70% by mass of AD feedstock, respectively. The following sub-sections discuss the various processes that assemble the MBCT system.

MRF: The mechanical operations of the MBCT system, i.e. *MRF*, comprise an air classifier fitted with a digital camera and a weighing machine to separate between paper and cardboard packaging. The air flowrate is adjusted to separate paper and cardboard packaging that are not recycled according to their images and weights, into two separate compartments and bailed for transporting to milling sites.

MRF also deals with valorisation of plastic waste. The stream containing dense plastic and plastic films (container, plastic packaging) after conveyance is separated by automated sorting system employing various types of sensing systems into three streams: Al cartons with HDPE (high density polyethylene) (according to the numbering of plastic, it is numbered as 2), PET (polyethylene terephthalate, numbered as 1) and mixed plastic waste (MPW, numbered as 3-7). Magnetic and Eddy current separators are used downstream to Al cartons with HDPE stream to first isolate ferrous and non-ferrous streams and then to separate Al cans from the non-ferrous stream. Other streams if manually or automatically detected to be containing Al are also directed to the Eddy current separator. An 'Eddy current' occurs when a conductor is exposed to a changing magnetic field.

RDF, an alternative to fossil fuel, specifically coal, is produced from plastic materials, which are not otherwise possible to recycle, in the *MRF*. To make RDF useful in industrial incineration and energy generating plant, it is important to ensure the quality of RDF, when it comes to heating values, ingredients, and contaminants like metals, stones and chemicals. Therefore, in some plants, induction sorting systems and x-ray sorting systems are installed to detect and remove these components. In induction sorting, material is sent along a conveyor belt with a series of sensors underneath. These sensors locate different types of metal which are then separated by a system of fast air jets which are linked to the sensors. X-rays can be used to distinguish between different types of materials based on their density.

For more advanced and intense valorisation, emerging technologies such as microbial electrosynthesis (MES) alongside state-of-the-art metallurgical operations can be applied for recovery of metals (Sadhukhan et al., 2016b; Ng et al., 2016).

Pulping: The pulping or supercritical water (420°C and 230 bar) extraction process separates the curbside-type recyclables from the lignocellulosic fraction of MSW. The lignocellulosic fraction of MSW goes through a primary wash for ash removal and cellular disruption for yield maximization combined with a sterilization stage – decomposition of this lignocellulosic fraction of MSW is then carried out by the controlled acid hydrolysis process for eventually producing levulinic acid and char in the chemical conversion section.

Chemical conversion section: Biomass pretreatment followed by biochemical degradation allows recovery of targeted molecules (Sindhu et al., 2016). Pretreatment for decomposition of biomass into cellulose, hemicellulose and lignin is needed for lignocellulosic or second generation feedstock, such as lignocelluloses extracted from MSW. The various methods of pretreatment broadly fall into two categories: addition of extraneous agent and application of energy (Sadhukhan et al., 2016d). The former incurs higher cost of chemical and downstream separation and purification and the latter incurs higher cost of energy and capital cost of pretreatment. Hydrolysis (acid or alkali), organosolv (extraction using organic solvent) and ionic liquid extraction use extraneous agents for biomass decomposition (Mathew et al., 2016), while ultrasonication and microwave irradiation technologies make use of energy for biomass decomposition (Singh et al., 2016).

The proposed chemical conversion section is targeted to produce levulinic acid as the main chemical product. For this, the proven system comprises controlled acid hydrolysis in 2 wt% dilute H₂SO₄ catalyst producing levulinic acid, furfural, formic acid, via C₅/C₆ sugar extraction, in a plug flow (210–230°C, 25 bar, 12 seconds) and a continuous stirred tank (195–215°C, 14 bar, 20 minutes) reactors; char separation and levulinic acid extraction and

purification by methyl isobutyl ketone solvent; acid, solvent and by-product recovery sections. The detailed process description, simulation and mass and energy balances are presented by the authors elsewhere (Sadhukhan et al., 2016a; 2016c).

ETP, AD and CHP sections: Effluent generated from pulping and chemical conversion process is treated for water recycling in ETP, followed by AD of organic residues from ETP into biogas and fertiliser. Biogas, char and RDF are fuels to a total site utility system giving net energy generation from the total site.

Economic value analysis: The value analysis methodology (Martinez-Hernandez et al., 2014; Sadhukhan et al., 2014; 2008; 2004; 2003) has been applied to evaluate the economic margins of individual products recovered from MSW. Aggregation of economic margins of all output flows gives the overall economic margin of the system. Thus, maximising positive economic margins of profitable products and minimising or eliminating negative economic margins of non-profitable products and outlet streams can give the highest economic margin of the overall system. Economic margin of a stream i , EM_i is calculated by multiplying the flowrate of the stream, F_i with the difference between its value on processing (VOP) and its cost of production (COP), shown in equation 1. As an example, the unit of F is t/h and that of COP and VOP is \$/t and EM is \$/h.

$$EM_i = F_i \times (VOP_i - COP_i) \quad (1)$$

The VOP of a stream is the prices of products that are ultimately produced from it, subtracted by the costs of auxiliary raw materials, utilities and annualised capital cost of equipment that contribute to its further processing into these final products. Thus, VOP of a feed f to a process unit k is calculated from the known VOP values of the outlet streams p and the total costs of the process unit k , shown in equation 2.

$$VOP_f = [\sum_{p=1}^q VOP_p P_p - \bar{O}_k] / \sum_{f=1}^g F_f \quad (2)$$

where q is the number of products, g is the number of feedstocks considered as main material streams (excluding auxiliary raw materials). P_p and F_f correspond to the mass flowrates of product and feedstock, respectively. Note that VOP corresponds to the market price only if a stream is an end product.

The *COP* of a stream is the summation of all associated cost components, i.e. the costs of feedstocks, auxiliary raw materials, utilities and annualised capital cost that have contributed to the production of the stream. This means that only those fractional costs involved with the stream's production are included in its *COP*. *COP* of a product p from a process unit k is calculated from the known costs of the feed streams f and the total costs of the process unit k , shown in equation 3.

$$COP_p = [\sum_{f=1}^q COP_f P_f + \bar{O}_k] / \sum_{f=1}^g F_f \quad (3)$$

Note that COP corresponds to the market price only if a stream is a feedstock or input flow externally supplied to the system.

Capital cost consists of direct and indirect capital costs. The direct capital cost comprises the costs of equipment, installation, instrumentation and control, piping, electrical systems, building, yard improvements and service facilities.

The delivered cost of equipment can be estimated using cost and size correlation, shown in equation 4, at first, and thereafter updating that cost from reported year to the current year, by applying the Chemical Engineering Plant Cost Index (CEPCI), shown in equation 5.

$$NEW\ COST\ AT\ THE\ BASE\ YEAR = BASE\ COST \times \left(\frac{NEW\ SIZE}{BASE\ SIZE} \right)^{SCALING\ FACTOR} \quad (4)$$

$$NEW\ COST\ AT\ THE\ CURRENT\ YEAR = NEW\ COST\ AT\ THE\ BASE\ YEAR \times \frac{CEPCI\ AT\ THE\ CURRENT\ YEAR}{CEPCI\ AT\ THE\ BASE\ YEAR} \quad (5)$$

The total capital cost, also called capital expenses (CAPEX), is the summation of direct costs, indirect costs and working capital; i.e. the total CAPEX is 5.03 times the delivered cost of

equipment (calculated using equations 4 and 5) for a solid-fluid processing system (Sadhukhan et al. 2014). An annual capital charge of 13% corresponding to a discount rate of 10%, a plant life of 15 years and a start-up period of 2 years (capital expenditures of 25% and 75% on the 1st and 2nd year) for example, can then be applied to the total CAPEX, to estimate the annual capital cost (Sadhukhan et al., 2016a).

The annual capital cost of a unit must be added to its annual operating cost to obtain the total annual cost of the unit. The annual operating cost consists of the fixed and variable (raw materials and utilities) costs. The parameters for estimating fixed operating costs such as maintenance, laboratory, supervision and plant overheads, etc. are given in (Sadhukhan et al. 2014). A brief overview of the correlations to calculate the various operating cost is as follows.

Fixed operating cost items are as follows 1-3.

1. Costs of maintenance, capital charges, insurance, local taxes and royalties = 24% of indirect capital cost
2. Personnel cost = 0.595×10^6 Euro per 100 MW LHV (low heating value)
3. Laboratory, supervision and plant overhead costs = 90% of personnel cost

Direct Production Cost (DPC) is then calculated as the summation of the variable and fixed operating costs: $DPC = \text{Variable operating cost (e.g. raw materials and utilities, etc.)} + \text{Fixed operating cost}$. The DPC is then increased by 30% (or 1.3 times the DPC) to account for miscellaneous items: sales expense, general overheads and research and developments.

Life cycle assessment (LCA): LCA is a holistic and systematic environmental impact assessment tool in a standardised way and format for cradle to grave systems, discussed with practical applications elsewhere (Sadhukhan et al. 2014). The LCA study follows the guidelines of the International Organisation for Standards (ISO) 14040 (1997), 14041 (1998) and 14044 (2006).

To date, there is no LCA study for added benefits from chemical products from MSW. Thus, this work makes a novel contribution in understanding of environmental impact costs and benefits of MSW based biorefinery systems. The system boundary considered includes gate to grave, i.e. from MSW at the system gate carrying no burden, through processing into products to consumption of products. The inlet and outlet mass and energy flowrates of the system are extracted from the process modelling and simulation discussed elsewhere (Sadhukhan et al., 2016a). For each inlet or outlet flow, inventory data are extracted from Ecoinvent 3.0 (2016) and characterised and aggregated for life cycle impact assessments (LCIA) using Impact 2002+ (2016) and CML (2016) methods. GWP has been assessed on an individual product basis. Thus, avoided GWP impacts to examine the relative benefits by the delivering of new products with respect to current use of waste feedstocks, and by replacing one by the other have been estimated. The LCA has been performed in GaBi 6.0 using Ecoinvent 3.0 inventory databases (2016). The LCA approach undertaken is “change oriented” or “consequential”, whereby sustainability of prospective MSW treatment systems has been evaluated. The results obtained are applicable for both synthesis and retrofit design projects.

3. Results and discussions

The forward looking process that integrates RRfW within a biorefinery configuration to deliver environmental-economic-social benefits, superior to bio/renewable process/product developed to date, to replace petroleum is illustrated by a Sankey diagram in Figure 1. Earlier works developed wood based process or process dealing with relatively clean biomass for bio-based products. Impurities pose the greatest obstacle in waste valorisation. Incorporation of RRfW within biorefinery concept has resulted in an MBCT system that is the cleanest, highest resource-efficient and sustainable technology for valorisation of MSW, to date. This resource-efficient process is not selective in terms of compositions, because it

can deal with impurities of MSW by RRfW prior to chemical recovery from organic fraction.

Figure 1 gives the splits of MSW into the main process blocks. Furthermore, the Sankey diagram of mass transfers from sources of MSW to products in Figure 1 shows the mass splits across the chemical conversion block and the ETP + AD block. 36.8% by mass of MSW are routed as the feedstock to chemical conversion, which generates levulinic acid (7.4%), char (14.7%) and effluent to the ETP + AD block (14.7%). The total input to the ETP + AD block is 26.5% of the mass of MSW: effluent (14.7%) + some food and garden waste (11.8%). The outputs from this block are biogas (3.5%) and fertiliser (8.3%) from AD and recyclable water (14.7%) from the ETP, respectively. These mass transfers from MSW at the MBCT system gate to products are used as the bases of economic analysis and LCA. For transferability and adaptation of results, the mass flowrate of MSW is assumed to be 100 t/h, as the basis of all the following calculations.

Energy balance of the MBCT system: RDF (mass fraction of 8.7% of MSW) and non-recyclable other waste (mass fraction of 13.7% of MSW) from MRF, biogas (mass fraction of 3.5% of MSW) from AD and char (mass fraction of 14.7% of MSW) from the chemical conversion section are the fuel to a CHP system comprising a biomass boiler with in-situ boiler feed water (BFW) preheater, steam drum for steam economiser or saturation and steam superheater and back pressure and condensing steam turbines (Wan et al., 2016a; 2016b). The boiler co-combusts the mixed biomass fuel and recovers heat from the resulting exhaust or flue gas to generate superheated steam. The boiler has a rotating disc at the bottom for recovering ash and solid particulates and preventing entrainment with the exhaust gas. Also, activated carbon based adsorbent can be used at the outlet of the exhaust gas to recover particulates and any other combustibles, which can be recirculated to the boiler for complete combustion. Complete combustion in the boiler is essential to meet the regulatory limits on

the pollutants and mitigate emissions such as volatile organic compounds that can cause urban smog. Detailed schematics, models and data for economic performances have been analysed elsewhere (Wan et al., 2016a; 2016b). The calorific values (CVs) of the boiler fuels are used here to estimate the energy generation from the MBCT system. The CV of char is 16.2 MJ/kg or 4.5 MWh/t (Sadhukhan et al. 2016a). The CVs of biogas and RDF + non-recyclable other waste are: 23 and 19.5 MJ/kg or 6.4 and 5.4 MWh/t, respectively (Sadhukhan et al. 2016a). Thus, the following energy input and output calculations for the total site CHP system can be performed:

$$\text{Energy input to biomass boiler} = \frac{(16.2 \times 14700 + 23 \times 3500 + 19.5 \times 22400)}{3600} = 209.5 \text{ MW}$$

$$\text{Steam generation from biomass boiler} = 209.5 \times 0.8 = 167.7 \text{ MW}$$

Hot utility (steam) demand by the pulping and chemical conversion sections (based on 2.65 MW per t/h obtained from heat integration (Sadhukhan et al. 2016a) for a total feedstock mass flowrate of (36.8+11.8) or 48.6 t/h to the pulping section: $2.65 \times 48.6 = 128.7 \text{ MW}$

$$\begin{aligned} \text{Net steam available for electricity generation via steam turbines} &= 167.7 - 128.7 \\ &= 39 \text{ MW} \end{aligned}$$

$$\text{Electricity generation from steam turbines} = 39 \times 0.35 = 13.6 \text{ MW}$$

$$\text{Electricity demand by the site} = 10 \text{ kWh/t MSW}$$

$$\text{Electricity demand by the site} = \frac{10 \times 100}{1000} = 1 \text{ MW}$$

$$\text{Net electricity export} = 13.6 - 1 = 12.6 \text{ MW} = 0.126 \text{ MWh/t MSW}$$

$$\text{Market price of electricity} = 0.118 \text{ Euro/kWh (DECC, 2015)}$$

$$\begin{aligned} \text{Price of net electricity export per unit mass of MSW} &= 0.118 \times 0.126 \times 1000 \\ &= 14.9 \text{ Euro/t MSW} \end{aligned}$$

The net electricity export is thus 0.126 MWh/t MSW. The list of MSW fractions that can be used as fuels for CHP generation is given in Table 1. Their individual representative mass flowrates, CVs and net electricity generations are summarised in Table 1. Their output energy

contributions in the decreasing order are: Other waste (non-recyclable) > Char > RDF > Biogas, respectively, which are due to the combined effects of mass flowrates and CVs, even though in terms of CVs, their ranks are: Biogas > RDF and Non-recyclable other waste > Char, respectively. These data given on mass percentage of MSW can be applied to other case studies.

Table 1

Capital and operating cost analyses of the MBCT system: Table 2 shows the base sizes, base costs, estimated scaling factors, base or reported years and the CEPCI at the base years of the various process units in the MBCT system, and thus, the estimation of the delivered cost of equipment (using equations 4-5), total CAPEX and annual capital cost. The recent most year for cost update is taken 2015, when the CEPCI has been stabilised at 576.73. The delivered cost of equipment calculated by equations 4-5 is then multiplied by 5.03 to obtain the total CAPEX, which is then factored by the annual capital charge (0.13 in this case) to obtain the annual capital cost.

Table 2

As the utilities are supplied by the total site CHP system, there is no energy cost for the MBCT system. The operating cost is primarily due to the fixed operating cost, which has two components, dependent on personnel cost and indirect capital cost. The cost of MSW has been analysed separately. The personnel cost based on a CV of MSW of 18 MJ/kg and a mass flowrate of 100 t/h, is 2.975×10^6 Euro and the fixed operating cost dependent on the personnel cost is 5.65×10^6 Euro or 0.73×10^6 Euro/y when factored by the annual capital charge, respectively. The indirect capital cost dependent fixed operating cost component is 0.3024 times the delivered cost of equipment. This is then factored by the annual capital charge to obtain the indirect capital cost dependent fixed operating cost component per annum basis. Thus, the indirect capital cost dependent fixed operating cost components of

individual process units are estimated, as shown in Table 3. The total operating cost is 1.3 times the total fixed operating cost, as the utility (variable) cost of the site is negligible.

Table 3

The total annual cost is the summation of the annual capital and operating cost, as shown in Table 4. For convenience of value analysis, unit processes are grouped together into a process block with either feedstock in common or product in common or both. Thus, the site can be represented by six main process blocks:

- 1) **MRF** taking certain fractions of MSW as shown in Figure 1 to produce outputs: Recyclables, RDF, Metals and Fibre.
- 2) **Non-recyclable other waste to CHP**
- 3) **RDF to CHP**
- 4) **Pulping** taking some other fractions of MSW as shown in Figure 1 to produce outputs: feedstock to chemical conversion section and an effluent stream routed to ETP.
- 5) **Chemical section with char CHP**
- 6) **ETP + AD + biogas CHP + fertiliser**

Their mass throughputs (on 100 mass units of MSW basis), annual capital, operating and thereby total costs are given in Table 4. The fixed costs related to personnel are allocated to individual process blocks according to their percentage contributions to the total capital cost. The most cost intensive process blocks are chemical conversion with char CHP and ETP + AD + biogas CHP + fertiliser, contributing by 79% and 15%, respectively, of the total annual cost of 83 million.

Table 4

Cost of MSW: An average waste collection fee of 84.5 Euro/t MSW is paid by the MBCT plant owner to the local authority (WRAP, 2016). At the same time, the MBCT plant owner

is eligible to receive a gate fee from the local authority, for treating MSW. This rate is 109.12 Euro/t MSW. Therefore, the *COP* of MSW is estimated to be $(84.5 - 109.1) = -24.6$ Euro/t. This implies that the current business model allows 24.6 Euro/t revenue guaranteed for the MSW treatment plant owner. This is a strong economic incentive for waste valorisation as opposed to landfilling, which costs to the MSW treatment plant owner. Valorisation of organics of MSW into chemicals embraces economic independence of the MSW treatment systems.

Value analyses of the MBCT system: The value analysis methodology is then applied to estimate *COP*, *VOP* and thereby economic margins of individual products from the MBCT system. The cost of the MSW feedstock is -24.6 Euro/t as it enters the MBCT system, because of the revenue from its gate fee. The *COP* of a product is then obtained by adding the *COP* of its feedstock with the unit cost of the process block producing it. This way, a stair case diagram in increasing order of *COP* of various outlet streams from the MBCT system is created starting from the *COP* of MSW at -24.6 Euro/t, as shown in Figure 2. The outlet streams are presented in increasing order of *COP* in Figure 2. *COPs* of the outlet streams (Figure 1) in increasing order are estimated using the following correlation. Annual operating hours are assumed to be 8000.

COP of electricity from non – recyclable other waste (Euro/t)

$$= \frac{-24.6 \times 13.7 + 0.99 \times \frac{10^6}{8000}}{13.7} = -15.6$$

$$\text{COP of recyclables, RDF, metals and fibre (Euro/t)} = \frac{-24.6 \times 37.7 + 2.93 \times \frac{10^6}{8000}}{37.7}$$

$$= -14.9$$

$$\text{COP of electricity from RDF (Euro/t)} = \frac{-14.9 \times 8.7 + 0.62 \times \frac{10^6}{8000}}{8.7} = -5.9$$

$$\begin{aligned} \text{COP of outlet streams from pulping (Euro/t)} &= \frac{-24.6 \times 48.6 + 0.95 \times \frac{10^6}{8000}}{48.6} \\ &= -22.2 \end{aligned}$$

COP of outlet streams from chemical conversion (Euro/t)

$$= \frac{-22.2 \times 36.8 + 65.16 \times \frac{10^6}{8000}}{36.8} = 199.1$$

COP of inlet streams to ETP + AD process block (Euro/t)

$$= \frac{-22.2 \times 11.8 + 199.1 \times 14.7}{26.5} = 100.6$$

COP of recycled water, fertiliser and electricity from biogas (Euro/t)

$$= \frac{100.6 \times 26.5 + 12.01 \times \frac{10^6}{8000}}{26.5} = 157.3$$

Low *COP* of a product is desired, so that it is below the *VOP* or market price of the product, in order to make a positive economic marginal contribution. Thus, with the support of the gate fee scheme, negative *COP* obtained for the electricity generated from non-recyclable other waste and RDF and recyclables, metals and fibre, ensures, positive economic margins from resourcing these from MSW. However, high *COP* of electricity from char and biogas, fertiliser and recycled water implies economic losses from these streams. Chemicals have a high market price, e.g. 3-5 Euro/kg for levulinic acid compared to 0.3-0.5 Euro/kg for bioethanol. Hence, making chemical from waste materials is always a highly economic proposition. These points can be proven by analysing the *VOP* of the streams as follows.

VOP of outlet streams is shown in Table 5 along with their *COP*, mass flowrates and economic margins. *VOP* of an output stream from the MBCT system is its market price (Sadhukhan et al. 2016a), with the exception of recycled water (no price has been considered as the stream is an internal stream within the system) and electricity, for which the market

price (118 Euro/MWh) has been transformed into Euro/t corresponding to each fuel, by multiplying the fuel's net electricity generation in MWh/t (Table 1).

Table 5

The *VOP* of all the output streams from the MBCT system given in Table 5 can be plotted alongside their respective *COP*, as shown in Figure 3. The area bounded between *VOP* and *COP* of a stream in such a plot: $EM = (VOP - COP) \times Flowrate$, gives its economic margin (*EM*). The total of economic margins of individual output streams from the MBCT system is the overall economic margin of the MBCT system. The overall economic margin of the MBCT system is thus equal to 279 Euro/t of MSW.

Figure 3

Clearly, chemical product that contributes by 79% of the total economic margin of the MBCT system can unlock the value of MSW. This is followed by recyclables, metals and fibre (2%) > electricity from non-recyclable other waste (2%) > electricity from RDF (1%) > electricity from biogas (-1%) > fertiliser (-3%) > recycled water (-6%) > electricity from char (-6%), respectively, under the gate fee scheme.

If the gate fee revenue on MSW is not considered, all products become non-profitable with the exception of the chemical product. For example, if the cost of MSW at plant gate is 50 Euro/t, the overall economic margin of the MBCT system is decreased to 204 Euro/t, with the chemical product being the only profitable product. All other products have negative economic margins. Figure 4 shows economic marginal contributions by individual products in the MBCT system, when a cost of MSW of 50 Euro/t is considered. This shows that the MSW treatment plant that not only treats the waste but also generates economic value out of it by chemical production becomes self-sustainable, without relying on policy incentives.

Figure 4

This also shows that in absence of chemical product from the waste treatment sector, making the waste treatment sector a profitable sector is the prime reason for government incentives via the gate fee scheme in the developed economies. There is a knowledge gap between technical researchers in the area of RRfW and biorefinery and policy makers, which is why waste management companies are still enjoying profitable businesses with outdated technologies and are not geared to embrace innovations in the sector.

LCA of the MBCT system: The environmental costs and benefits are analysed for the MBCT system as shown in Figure 5. The environmental benefits are due to displacement of fossil derived equivalent products, while the environmental costs are due to emission resulting from fuel combustion in the CHP system. The net saving is estimated by environmental benefits subtracted by environmental costs estimated over the lifetime of the system. Figure 5 shows the environmental costs and benefits in percentage of the total in each environmental impact category, scaled to 100. The environmental impact categories include selective, important and relevant CML and Impact 2002+ categories. These also give a wider and more comprehensive perspective on environmental feasibility of the MBCT system than that from just the GWP selection. The CML and Impact 2002+ LCIA methodologies give primary level and mid-point impacts, respectively.

Figure 5

Environmental costs are due to the use of fuels resourced from the MSW in the CHP system. The fuels, RDF and non-recyclable other waste from MRF, biogas from AD and char from chemical conversion section are produced internally. However, combusting these in the boiler results in exhaust or flue gas, which after filtering (or adsorption) through an activated carbon filter or sorbent is released to the environment. The adsorption process prevents any uncombusted VOCs and particulates from release to the environment. During the sorbent regeneration process by temperature or pressure swing, the VOCs recovered can be recycled

back to the biomass boiler for their complete combustion. Particulates can be separately handled and accumulated for construction sector or safe release to the land. This scheme ensures that no environmental stressor, other than carbon dioxide and moisture resulting from combustion of hydrocarbons, is released to the atmosphere. The carbon released is primarily embedded biogenic carbon, which is sequestered by the system, hence, the overall performance can be considered carbon neutral. However, in Figure 5, the environmental cost due to combustion of fuels does not take into account of the benefit due to biogenic carbon sequestration and assumes emission inventory data from Ecoinvent 3.0.

The main products that give environmental benefits due to displacements of equivalent petroleum derived products are: chemical (levulinic acid: usage as solvent), fertiliser, excess electricity for export. Production of these offsets fossil resources that would have been used to make products with respective functionalities. GWP benefits thus estimated from displacement per unit mass of levulinic acid (application as a solvent) and fertiliser are 2.4 and 1.3 mass unit CO₂ equivalent, respectively, while GWP saving by per MJ of grid electricity offset is 0.17 kg CO₂ equivalent. Levulinic acid gives the highest benefit if used as a solvent, displacing an equivalent fossil derived solvent. Excess electricity generated can displace grid electricity and thereby offset equivalent amount of fossil needed to generate the same amount of electricity. Fertiliser produced from AD in the system can replace inorganic fertiliser derived from primary fossil resources. Environmental benefits due to recyclables, metals and fibre are relatively smaller than others, hence, have not been included in the analyses in Figure 5. The environmental benefits from replacement of petroleum derived solvent seem to be the highest in all categories with the exceptions of freshwater aquatic ecotoxicity and acidification potentials, where the benefits from replacement of petroleum derived inorganic fertiliser are the highest. Both these benefits are greater than that from displacement of grid electricity. Thus, similar to their economic performances, in the

decreasing order of environmental benefits, the products are chemical used as solvent > fertiliser > electricity, respectively. Once again, this proves the point that high value functional chemicals must be a product alongside fertiliser and energy products from integrated biorefinery system for economic and environmental feasibility. Self-sufficiency by in-process energy recovery and recycling water is also important for sustainability. This proves the point that a biorefinery should be advanced and implemented at the right scale to include all sections for recovery and recycling of all resources including in-process energy and water recoveries.

Sustainability of the MBCT system: From the perspective of sustainability of a biorefinery system, this study shows that chemical product brings the highest benefit, followed by fertiliser and energy products, respectively. Recyclables, metals and fibre must also be recovered by MRF at first not only for additional income generations, but also to eliminate their interference with the (bio)chemical valorisation of lignocelluloses. There are some hypotheses or characteristics inherent that determine the sustainability of the MBCT system; these are:

- (1) Source segregation of MSW (an important feature of developed economy that must be adapted for developing economy) is essential.
- (2) Availability of bioresources or lignocelluloses come from food, garden, paper, cardboard, wood and organic waste that give the main products, chemical, fertiliser and solid and gas fuel, is essential.
- (3) Without bioresources present in MSW, MRF is sufficient to recover recyclables, fibre and metal resources.
- (4) Yield of levulinic acid is 20% by mass of lignocellulose present in MSW (or 7.4% by mass of MSW). This value results from levulinic acid yield by 46% of the mass of cellulose

(Sadhukhan et al., 2016a). Feasibility of MBCT system will thus decrease with decreasing cellulose content in MSW.

(5) Use of levulinic acid as solvent has been assumed to assess environmental benefit from replacement of petroleum derived solvent.

6) Levulinic acid is a versatile chemical. One of the uses of its one of the derivatives, ethyl levulinate, is as fuel additive. This usage can generate a comparable market demand as bioethanol. Levulinic acid is referred as a 'sleeping giant' owing to its vast potentials in the emerging bio-based economy due to its key positions in the production of biomass-derived intermediates that can attain effective transition from fossil based to bio-based economy. For newer biorefinery businesses, targeting such chemicals as bio-based products alongside bioenergy is the safest and low risk option, because demands for such chemicals are expected to increase due to versatility in their applications.

(7) Yield, price and usage of the target product (levulinic acid here) must be updated, if the target product is different. For e.g. bioethanol could be the choice of product using biochemical rather than chemical conversion process utilising lignocelluloses in MSW, given the advantage of its established market. It can be seen that levulinic acid gives a much higher revenue, by 7 times greater, than that from bioethanol. Furthermore, from the capital cost relations between t

4. Conclusions

This study comprises material flow, economic value and LCA analyses for deriving sustainable RRfW integrated biorefinery system, coined as MBCT system, to deliver environmental-economic-social benefits of utilization of MSW. Process integration has been applied to take advantage of the economy at the right scale and configure optimal interconnections between systems, MRF, pulping/chemical conversion, ETP/AD and CHP. The Sankey diagram shows the transfer of MSW components to added value products in the cleanest, highest resource-efficient and sustainable system. This study draws upon a futuristic

scenario of complete reuse-recycling-recovery cycles of source segregated MSW urgently needed for achieving a circular economy.

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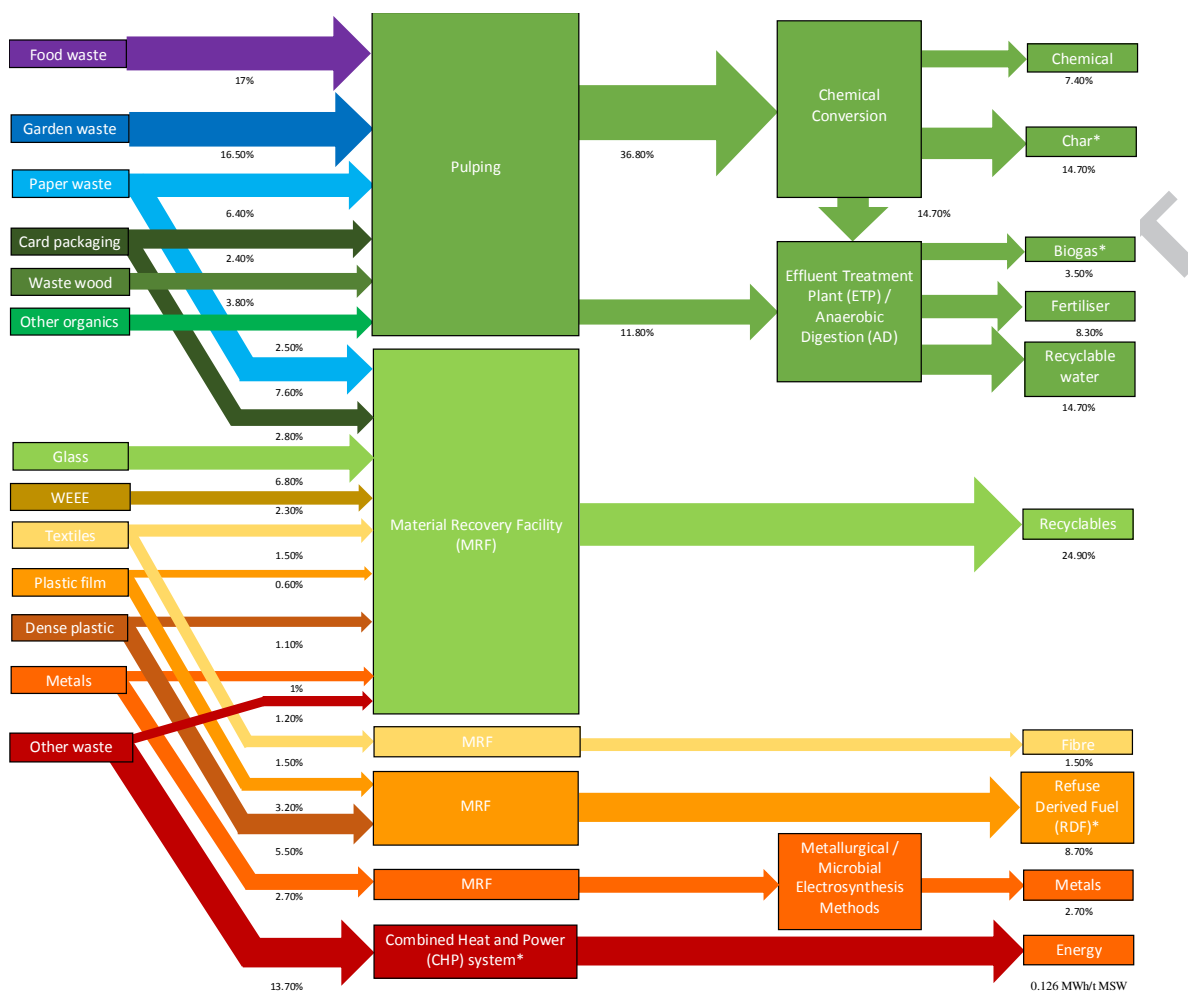
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MSW constituents and mass transfer in % mass of MSW to various production routes.

	Total	Recyclables	RDF	Recovered metal	Chemical feedstock	AD feedstock	Energy feedstock	Fibre
Food waste	17				8.5	8.5		
Garden waste	16.5				13.2	3.3		
Other waste	14.9	1.2					13.7	
Paper	14	7.6			6.4			
Glass	6.8	6.8						
Dense plastic	6.6	1.1	5.5					
Card packaging	5.2	2.8			2.4			

Plastic films	3.8	0.6	3.2					
Wood	3.8				3.8			
Metals	3.7	1.0		2.7				
Textiles	2.9	1.5						1.5
Other organic	2.5				2.5			
WEEE	2.3	2.3						
Total	100	24.9	8.7	2.7	36.8	11.8	13.7	1.5

Figure 1. Sankey diagram of mass transfer from MSW to products in % mass of MSW. * indicates fuel to CHP system. The net electricity export is 0.126 MWh/t MSW.

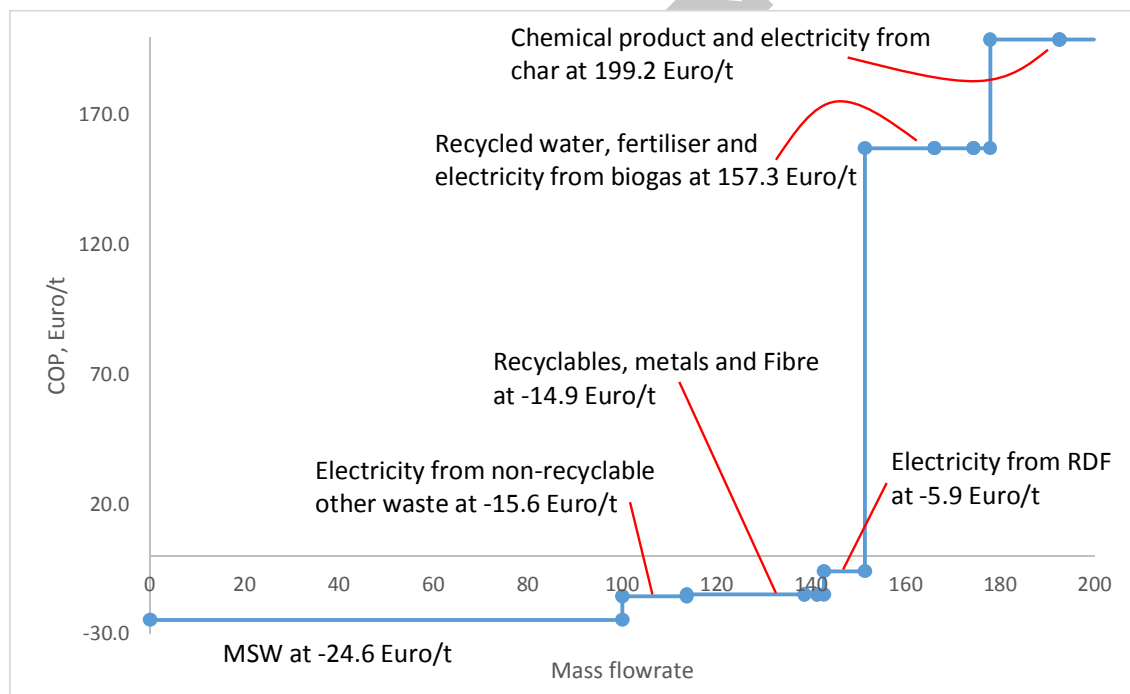


Figure 2. COP of various outlet streams from the MBCT system in increasing order, with respect to the COP of MSW of -24.6 Euro/t.

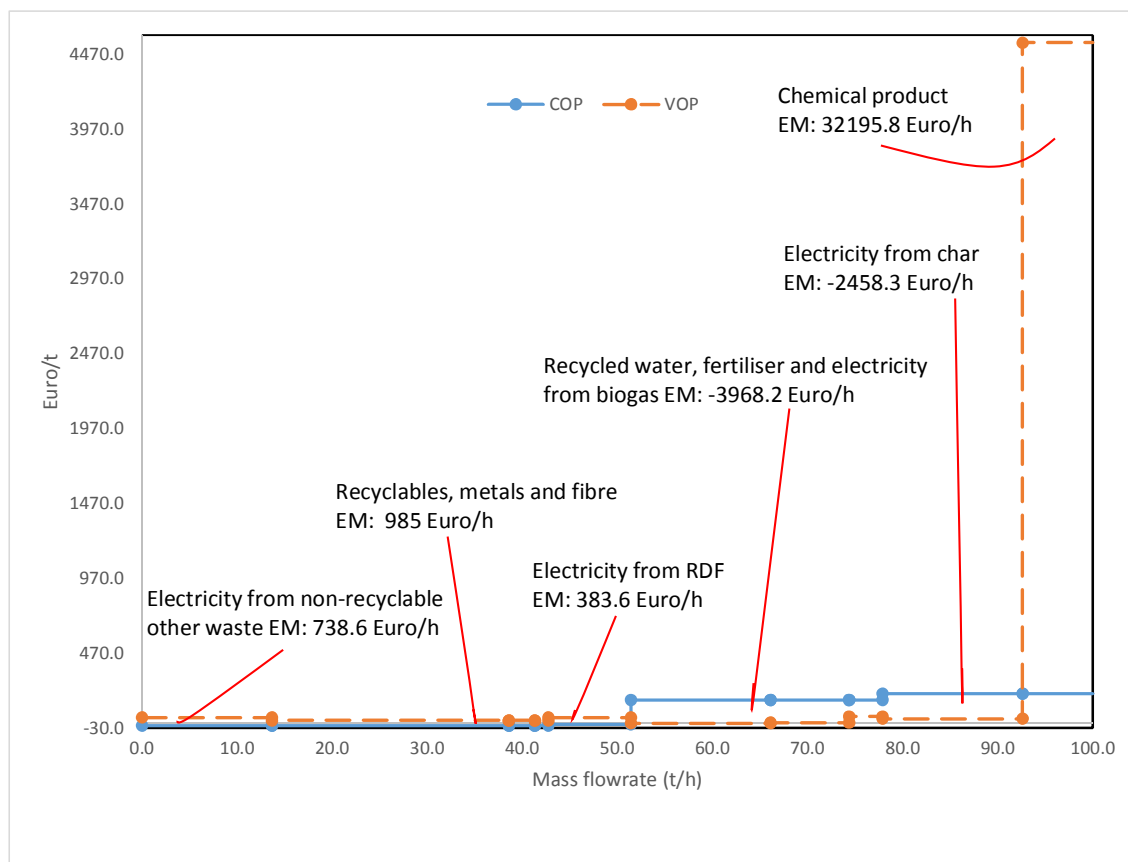


Figure 3. COP and VOP and thus economic margin ($EM = (VOP - COP) \times Flowrate$) of various outlet streams from the MBCT system.

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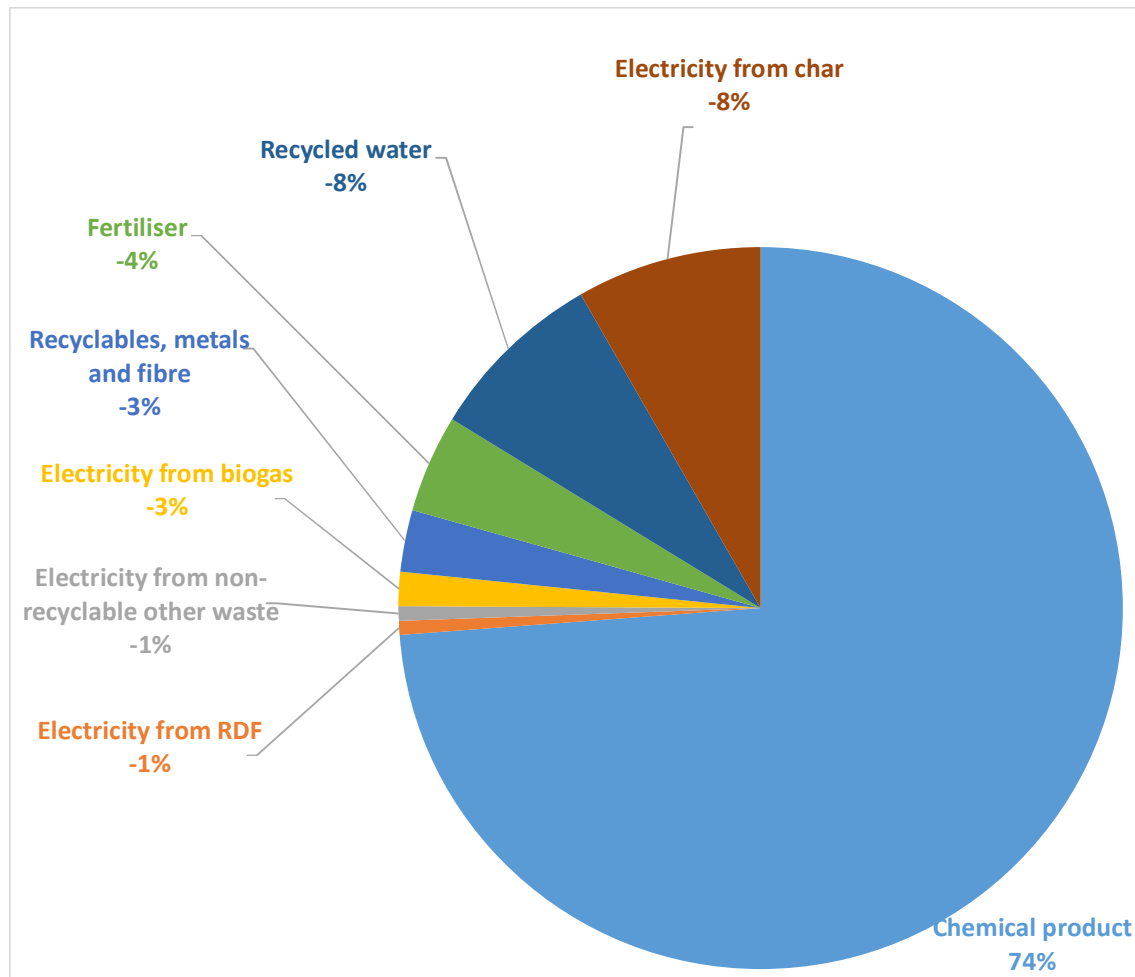


Figure 4. Contributions of individual output streams from the MBCT system to the overall EM of 204 Euro/t MSW for a cost of MSW of 50 Euro/t.

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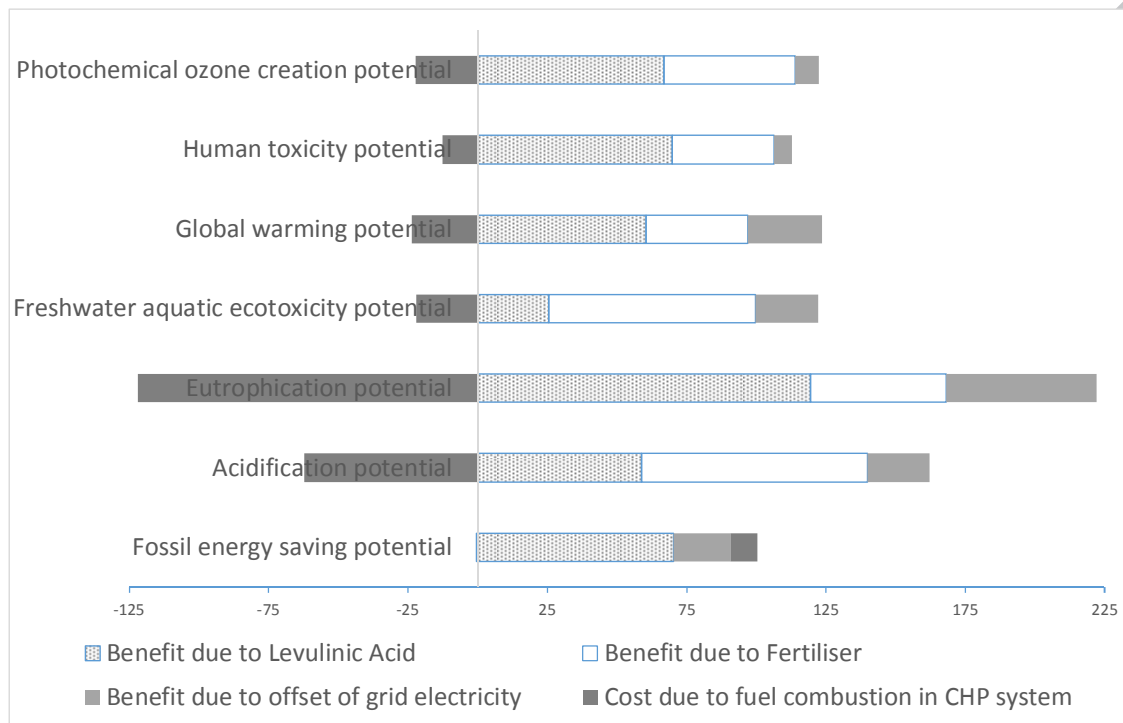


Figure 5. Environmental impact potential benefits and costs and thus net saving of the MBCT system in important Impact 2002+ and CML categories normalised to 100. The actual values are per tonne of MSW are: Fossil energy saving potential (Impact 2002+) = 6.14 GJ; and CML: Acidification potential = 1.17 kg SO₂ equivalent; Eutrophication potential = 0.17 kg phosphate equivalent; Freshwater aquatic ecotoxicity potential = 59.16 kg 1,4-dichlorobenzene (DCB) equivalent; Global warming potential = 294 kg CO₂ equivalent; Human toxicity potential = 251 kg DCB equivalent; Photochemical ozone creation potential = 0.196 kg ethylene equivalent.

Table 1. MSW fractions to CHP for estimation of individual fuel's energy performances: mass flowrate in % of MSW, calorific value and net electricity generation, in various units.

Fuel to CHP	t/h or % by mass of MSW	MWh/t	MW	% MW	Net electricity, MW	Net electricity, MWh/t of fuel
RDF	8.7	5.4	46.79	22.34	2.8	0.33
Other waste	13.7	5.4	73.90	35.27	4.5	0.33
Char	14.7	4.5	66.15	31.58	4.0	0.27
Biogas	3.54	6.4	22.66	10.81	1.4	0.39
Total	40.59		209.50	100	12.6	

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Table 2. Parameters used for estimation of delivered cost of equipment and the estimated delivered cost of equipment, total CAPEX and annual capital cost of each unit in the MBCT system.

Process unit	Base size (t/h)	Base cost ($\times 10^6$ Euro)	Scaling factor	Year	CEPCI of base year	Size (t/h)	Delivered cost of equipment ($\times 10^6$ Euro)	Total CAPEX ($\times 10^6$ Euro)	Annual capital cost ($\times 10^6$ Euro/y)
MRF with CHP									
Shredder	10	0.27	0.60	2014	576.10	37.70	0.60	3.01	0.39
Screen	10	0.16	0.97	2014	576.10	37.70	0.58	2.92	0.38
Magnetic separator	10	0.06	0.58	2014	576.10	37.70	0.13	0.65	0.08
Eddy current separator	10	0.12	0.33	2014	576.10	37.70	0.19	0.94	0.12
Manually sorting cabin	10	0.12	0.19	2014	576.10	37.70	0.15	0.78	0.10
Induction sorting	7	0.28	0.81	2011	585.70	37.70	1.08	5.42	0.71
Near infrared sensors	1.8	0.08	0.94	2011	585.70	37.70	1.37	6.91	0.90
CHP (RDF + non-recyclable other waste)	2.23	0.38	0.61	2002	395.60	22.4	2.26	11.38	1.48
Pulping section									
ETP + AD section with CHP	83.3	1.41	0.78	2003	402.00	48.6	1.33	6.68	0.87
ETP + AD	12.5	1 + 11.62	0.92	2005	468.20	26.5 + 11.8	16.03	80.65	10.48
Biogas CHP	2.2	0.38	0.61	2002	395.60	3.5	0.74	3.70	0.48
Compost post-processing	6	0.05	0.44	2007	525.40	8.3	0.06	0.32	0.04
Chemical section with CHP									
Total	4	11.28	0.78	2003	402.00	36.8	91.37	459.60	59.75
							115.90	380.69	49.49

Table 3. Indirect capital cost dependent fixed operating cost components of individual process units.

Process unit	Fixed costs related to indirect capital cost ($\times 10^6$ Euro/y)
MRF with CHP	
Shredder	0.0236
Screen	0.0228
Magnetic separator	0.0051
Eddy current separator	0.0073
Manually sorting cabin	0.0061
Induction sorting	0.0424
Near infrared sensors	0.0541
CHP (RDF + non-recyclable other waste)	0.0888
Pulping section	0.0522
ETP + AD section with CHP	
ETP + AD	0.6303
Biogas CHP	0.0291
Compost post-processing	0.0025
Chemical section with CHP	3.5913
Total	4.56

Table 4. Mass throughputs (on the basis of 100 mass units of MSW), annual capital, operating and total costs of main process blocks.

Process block / stream	Mass throughput (t/h)	Annual capital cost ($\times 10^6$ Euro/y)	% Total CAPEX	Fixed costs related to indirect capital cost ($\times 10^6$ Euro/y)	Fixed costs related to personnel ($\times 10^6$ Euro/y)	Total operating cost ($\times 10^6$ Euro/y)	Total annual cost ($\times 10^6$ Euro/y)
MRF	37.7	2.68	3.54	0.16	0.03	0.24	2.93
Non-recyclable other waste to CHP	13.7	0.90	1.19	0.05	0.01	0.08	0.99
RDF to CHP	8.7	0.57	0.76	0.03	0.01	0.05	0.62
Pulping	48.6	0.87	1.15	0.05	0.01	0.08	0.95
Chemical section with char CHP	36.8	59.74	78.83	3.59	0.58	5.42	65.16
ETP + AD + biogas CHP + fertiliser	26.5	11.01	14.53	0.66	0.11	1.00	12.01
Total		75.78	100.00	4.56	0.73	6.88	82.65

Table 5. VOP, COP, mass flowrate and economic margin of output streams from the MBCT system.

Output stream from MBCT system	VOP	COP	Flowrate	Profitability
	Euro/t	Euro/t	t/h	Euro/h
Electricity from non-recyclable other waste	38.4	-15.6	13.7	738.6
Electricity from RDF	38.4	-5.9	8.7	383.6
Recyclables	19.0	-14.9	24.9	844.1
Metals (mixed stream without separation)	19.0	-14.9	2.7	91.8
Fibre	19.0	-14.9	1.5	49.2
Biogas electricity	45.5	157.3	3.5	-395.8
Fertiliser	4.7	157.3	8.3	-1260.4
Recycled water	0.0	157.3	14.7	-2312.1
Chemical product	4550.0	199.2	7.4	32195.8
Char electricity	32.0	199.2	14.7	-2458.3
Total			100.0	27876.4

Highlights

- MRF and biorefinery integration for resource recovery from waste (RRfW)
- Integrated system produces levulinic acid, fertiliser and electricity
- 7.4% mass yield of levulinic acid produced from MSW gives 204 Euro/t net margin
- Global warming potential (GWP) saving is 2.4 kg CO₂-eq per kg levulinic acid
- Process integration, essential for achieving the estimated benefits from MSW

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