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Assessment of Energy Recovery from Municipal Waste Management Systems Using Circular Economy Quality Indicators

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Abstract: A complex method developed to assess quality within a proposed framework and at a certain scope of measurement for circular economy (CE) quality indicators is presented. This was used to compare three different scenarios for municipal waste management systems: 1—incineration; 2—recycling and reuse of separated municipal waste and the transformation of the organic fraction into biodiesel and bio-coal; and 3—an upgraded Scenario 2 including decreased recycling of waste streams and the bioprocessing of paper/cardboard and processing the non-recycled fraction into bio-diesel, bio-coal, and second-generation biofuel. For the evaluation of the CE quality indicator, a set of technical, environmental, economic, and social elements was selected by a panel of experts, who also assigned them a qualitative assessment and weighting on the basis of the factors identified. The calculated Relative Increase in the CE indicator for the scenarios analyzed showed that Scenarios 3 and 2 are much more beneficial than Scenario 1 in technical, environmental, economic and social terms.

Keywords: municipal solid waste; incineration; hydrothermal processing; bio fermentation; biofuel; circular economy indicator; qualitative assessment

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1. Introduction

The world's population produces 2010 million t/y of municipal solid waste (MSW) and 240 million t/y of MSW arises in Europe. Worldwide, waste produced per capita averages 0.74 kg/d, ranging significantly, from 0.11 to 4.54 kg/d. The most developed countries, accounting for only 16% the inhabitants of the world, produce 34% (683 million t/y) of the world's waste. Global waste will probably increase to 3400 million t/y of MSW, a rate even greater than that projected for global population increase, by 2050. The amount of waste produced per person in developed countries will increases by 19% by 2050, and in low- and moderate-developed countries by $\leq$40% [1].

EU waste management policies are evolving towards minimization of MSW generation and the support of recycling, reuse and energy recovery instead landfilling. This has resulted in hundreds of mechanical–biological treatment plants (MBT) being installed in EU countries [2,3]. Their main task is to separate the MSW by processing it into its selected streams. The organic fraction of municipal solid waste (OFMSW) and recyclable materials are recovered, and the remaining waste stream (the rejected part) is typically landfilled [4,5].

Incineration has been carried out successfully in countries in which the number of landfills is decreasing and landfilling costs are increasing due to land scarcity and strong environmental regulation. Japan, where 80% of MSW was incinerated in 2015, has the largest number of MSW combustion plants in the world, with over 1900 objects. Around the world, >11% of MSW is incinerated. Factors that have influence the increase in MSW combustion include better pollution and emissions controls, legally binding regulations mandating energy production from renewable sources, goals for reduction in GHG emissions, and qualifying for carbon credits and other financial and tax encouragements [6,7]. According to the circular economy (CE), combustion for energy recovery is a useful option, while landfilling is the ultimate solution [8].

Lignocellulosic biomass is a feedstock in the manufacturing of biofuels, and biomaterials for the sustainable development of bio-refineries with the aim of achieving commercial implementation of the production of highly valuable products and second-generation bio fuels. Hydrothermal pretreatment makes it possible to improve enzymatic cellulose saccharification [9]. Processing of different lignocellulose and lipid raw materials into biodiesel using standing and developed methods indicates that the quality of biodiesel is mostly the result of the raw materials and processing purification methods used [10].

MSW has a calorific value, which enables combustion with energy recovery, but, using current strategies, combustion needs to be realized using recyclable materials, i.e., the recovered fraction from MBT known as refuse-derived fuel (RDF). The advantages of the combustion of RDF over incineration of MSW as fuel include improved efficiency of energy recovery and a better quality of flue gas due to the considerable reduction in the heavy metal content in the fly ash [11,12].

A key CE principle is the optimization of resource efficiency by using materials for the longest possible time in technical and biological cycles. This should be accompanied by the reclamation of natural systems as a result of the rethinking and redesigning of activities to ensure the implementation of a sustainable CE [13]. This allows the product value chain and lifecycle to maintain the highest possible value and quality for as long as feasible, and is as energy efficient as possible [8].

The CE has three scales of implementation: micro, meso, and macro. The CE is predicated on the circularity of substrates at all levels, existing all along the value chain and throughout the product life cycle [14].

Some problems with respect to the CE are related to the measuring and monitoring of its growth. Most metrics are micro-level indicators that concentrate on resource and recovery activities. A second notable group test results in the implementation of new environmental and economic solutions. Social impacts are rarely mentioned. The indicators analyzed apply specifically to resource recycling and do not assess the sustainability performance of circular systems [15]. Life Cycle Thinking (LCT) is also central to the strategy for pollution prevention and waste recycling, sustainable use of natural resources, and cleaner production [16]. Some indicators have been proposed based on the LCA's assessment [17], confirming that LCA is an important method for evaluating CE options and identifying the best strategies for the future.

Ref. [18] reviewed 30 CE indicators at the micro level. Most of them concentrated on recycling, regeneration, and end-of-life stewardship, while a few evaluated dismantling, lifetime elongation, waste management, resource use or reuse. There is no generally recognized method for the measurement of entire CE as well as at the micro level. Due to the circular economy often being described in terms of sustainable development, the degree of compliance of the three SD dimensions and the reviewed indicators is compared, suggesting that most indicators concentrate on economic features, with environmental and particularly social features only being applied to a minor extent. While accepting that comparatively quite-developed collections of indicators have already been worked out to obtain environmental and resource perspectives, it has also been stated that a broader indicator package is necessary to obtain connections with SD and to specific policy purposes, public consciousness of the total results of EU economic and consumption, industrial solutions, and water use and reuse [16].

Indicators measuring quality consider characteristics affected by the consumer or markets, or economic value [19], and the quality figure is longevity [20], using estimation of lifespan from statistical records and experts' approximations. Methods for evaluating the influence of the respective stages of process design have also been proposed [21].

Pieroni et al. presented the developed Circular Economy Business Modeling Expert System for use in production firms [22]. The expert method was presented to benefit firms by taking inspiration from best practices in CE-based business modeling, containing a determined structure for creating assumptions, and a logical framework that influences decision making and reduces uncertainty.

This study compares two municipal waste management systems. The first one consists of the classic method of municipal waste incineration used in many countries [23–25], while the second concerns an innovative smart chain process, currently implemented in Belgium, based on the comprehensive use of various physicochemical methods for MSW treatment in low-temperature processes.

In many countries, incineration is nowadays the most widely used MSW processing method, but due to of the possibility of noxious substances being emitted into the air and their negative impact on human health, MSW incineration meets with strong opposition within society, and therefore, the use of cleaner technologies is required. Additionally, problems regarding the energy consumption and energy recovery efficiency of MSW combustion units are analyzed and discussed. The quantities of incineration bottom ash (IBA) produced from combusted waste indicated a downward tendency due to the increase in the operational effectiveness of MSW combustion units.

The Renasci Smart Chain Process (SCP) was developed and implemented to realize the development of new and cleaner processes, and is scalable and easy implementable, allowing the continuous treatment of different MSW fractions. SCP connects several proven consecutive processes: high-class selective segregation and selection, plastics to chemicals, hydrothermal carbonization, and catalysis. The implementation of this method enables the production of high-in-class materials along with energy recovery. The MSW input materials are used completely, and no waste is produced. Innovative methods have a minimum environmental footprint and are self sufficient with respect to energy use [26,27].

In this study, the primary constituents of CE used in industry on a micro level were applied, focusing on the implementation of new constituents, circumstances, patterns, drafts, effects, and factors for the successful development of the CE system [8,28].

The novelty of this study is highlighted on the basis of a review of most existing methods and techniques used in specific fields, along with an explanation of the drawbacks of these methods, with respect to aspects such as accuracy. The Renasci SCP process described is innovative, and the proposed solution might be fundamentally different from what people are already familiar with. The purpose of this research was to perform an analysis of the industrial implementation of the primary constituents of a CE methodology on a micro level. The use of the most important CE activities was assessed, enabling easier development of the CE system. This study considers and elucidates the proposed activities in light of the development of circular economy methods in industrial models to determine their realization, propose other solutions, identify new problems, and evaluate the elements in new proposals that are necessary to achieve their realization on the basis of adequate methodologies, constituting an important aspect of studies performed with respect to industrial practice. These methodologies combine resources and advances achieved in different sectors and knowledge branches (technical, ecological, economic, and social), and advantages are determined using both quantitative and qualitative approaches [29,30].

Future work will be performed in support of the development of CE eco-innovation activities in the field of MSW management with respect to resource productivity and socio-economic effects. This always includes the recovery of biomaterials and the optimization of resource effectiveness by recycling materials, being highly advantageous for biological cycles. The environmental effects of the CE on a micro scale include decreased hazard to eco-systems, particularly with respect to the emission of pollutants. The key elements should be establishing a policy allowing the universal development of CE standards and systems, not only by means of eco-friendly technical innovation, sustainable development, eco-efficient methods for individual companies, and waste minimization, but also with respect to organizational and community perspectives.

This paper proposes a newly developed methodological framework for measurement on the basis of CE quality indicators for the assessment of production systems in the CE at the micro level. This method can be used to evaluate the influence of different phases of production projects and to compare systems on the basis of qualitative characterization. In terms of indicators measuring CE at the micro scale, a combination of different types of qualitative information is proposed for the assessment of CE indicators by calculating values for the production management options being developed and implemented. One of the new features regarding the categorization of proposed options into four categories and seven subcategories. Four categories—technological/technical, environmental, economic/business and social behavior—were considered in the analysis for the purposes of calculating a total quality value for the CE indicator. The weighting of individual options was performed on the basis of factors determined by a panel of experts. The effects also show how this evaluation method can offer practical results even with a decrease in the level of detail of the input information. The proposed method for calculating the values of CE quality indicators in complex technical products at the micro level takes into consideration the basic quality indicators for the appropriate selection of the most advantageous from among the options being compared [31–33].

The purpose of this research was to compare municipal solid waste management systems. To assess their quality, a complex method was applied using CE quality indicators. The technical, ecological, economic, and social options were considered in the calculation of the value of the CE complex quality indicator. Three different scenarios were compared, as follows: 1—incineration of MSW; 2—Renasci Smart Chain Processing, consisting of the recycling and reuse of separated municipal waste and the processing of the non-recycled parts of selected MSW into biofuels and bio-coal; and 3—an upgraded Scenario 2 including decreased recycling of MSW streams and the processing of paper/cardboard and the non-recycled parts of selected municipal waste into bio-coal pellets and second-generation biofuel.

2. Materials and Methods

2.1. A System Definition for the Qualitative Assessment of the CE at the Micro Level

The methodology presented here can be used to perform a comparative evaluation of MSW management models using a complex assessment method to qualitatively characterize the systems being compared. The evaluation of the quality and completeness of equipment resources was presented with the use of a complex method in [31]. In order to determine the complication question and amend the assessment results, the analyzed data were decomposed into a number of options. Simultaneously, a qualitative assessment method for complex equipment guarantee resources using Grey theory was suggested. Additionally, the Grey correlation calculation was used to perform a general assessment of the resources. The degree of adequacy demonstrated enables the appropriate staff to have a detailed understanding of the general state of the guarantee resources and the significance of each part.

The comprehensive quality assessment of a substance (as well as a technology) includes "n" quality characteristics, where "n" can be any number. Each resultant value can be defined as a unit identified by numerous quality characters [32–34]. For this reason, complex quality can be a function of the changeable quality property [35], such that:

$$\mathrm{Q} = \mathrm{f(Wi)} = \mathrm{f(W1, W2, \ldots Wn)} \tag{1}$$

where Q is the complex quality value, and $W_1 \ldots W_n$ are changeable characters of quality.

In the case of non-measurable features, other methods of assessment should be used, among which scoring is the most useful. Unfortunately, not all indicators or figures are strictly measurable, and must necessarily be based on the subjective opinion of a group of experts. When performing scoring for the purposes of qualitive assessment, a certain number of points is suitable as a basis on which to describe the function of a product. These points describe the relative overall quality of the product under consideration.

Usually, the complex quality value is obtained as a sum:

$$Q = W1 + W2 + \ldots + Wn = \sum_{i=1}^{n} W_i \quad (2)$$

In cases where functions do not interact, the additive pattern may be preferable. The scale of the assessments can be differentiated, because it also depends only on the subjective opinion of the experts setting the scope of grades. A figure for the degree of validity is also established by the following vector:

$$[a_i] = [a_1, a_2, \ldots, a_n] \quad (3)$$

where a_i—the degree of validity of the coefficient of the i feature.

The quality functions described will take the form of:

$$Q = \sum_{i=1}^{n} a_i \cdot W_i \quad (4)$$

The following function was adopted for the final evaluation of the analyzed solutions:

$$Q = (a_1 \cdot W1 + a_2 \cdot W2 + a_3 \cdot W_3 + a_4 \cdot W4) \quad (5)$$

where Q—the final value of the complex quality, a_1; W_1—the degree of validity and technical value of the estimation of technical options, a_2; W_2—the degree of validity and the value of the evaluation of environmental options, a_3; W_3—the degree of validity and the value of the estimation of economic options, a_4; W_4—the degree of validity and the value of the estimation of social behavior options.

Quality assessment of the production of individual products can be implemented through the evaluation of production quality using key performance indicators, which can be divided into two groups. Specifically, these are indicators regarding the quality of the product and the production process [36]. The representation of all of the quality indicators added in a single form is called the quality index, which makes it easy to obtain the composite influence of all of the quality parameters in that system and helps to compare the general quality of the aggregate with a unit value. The quality of the aggregates is determined using the weighted arithmetic index method [37].

In order to assess the complex quality of the analyzed MSW systems using the CE micro-level indicator CEI, a function was applied as shown in Equation (6):

$$CEI = CE_T + CE_{En} + CE_{Ec} + CE_{Sb} \quad (6)$$

where CEI = Q—calculated CE indicator of the analyzed system; CE partial indicators: CE_T = a_1; W_1—technological/technical options quality indicator, CE_{En} = a_2; W_2—environmental options quality indicator CE_{Ec} = a_3; W_3—economic options quality indicator, CE_{Sb} = a_4; W_4—societal behavior options quality indicator.

The assessment of the quality of the CE indicators initially requires the selection of options to characterize the evaluated production systems. Four core sets of options selected for the assessment of CE partial micro-level indicators are proposed:

- *Technological/technical (T)*

These options, based on Cleaner Production (CP), take into consideration key strategies in the CE, including the use of cleaner technologies, reuse and recycling of materials, reduction of emissions and release of waste, prevention of pollution and decreased use of hazardous input substances [28]. CP allows the realization of activities that make it possible to change the relationship between business and the natural environment [38]. The technological options selected are mainly based on the best available techniques (BATs), i.e., the techniques that have the lowest impact on the environment [16,39]. BAT evaluation is usually carried out by expert judgement. One example is the comparative assessment of two different preparations used for the chemical dissolution of boiler scale using the Best Available Technique Not Entailing Excessive Cost (BATNEEC) method [40]. The methodology described in [41] permits expert judgement to be used in a straightforward and transparent way using scores given with respect to technical feasibility.

- *Environmental (En)*

CE actions based on CE strategic information [38,42] are chosen. The proposed methods include recycling and reuse, industrial symbiosis, and projects related to remanufacturing, energy recovery, and product life extension. We distinguish between two types of main rules: those applying to the R structures and the systems approach. The most recently proposed 9R framework [43] was selected, consisting of nine dimensions (refuse, rethink, reduce, reuse, repair, refurbish, remanufactur, repurpose, recycle, recover). To estimate environmental benefits or damages, as well as the probable environmental influence of waste combustion, a life cycle perspective is needed to collect information to implement the life cycle inventory [39].

- *Economic/Business (Ec)*

These options constitute key aspects of the CE, including the management of waste, increasing the stability of wares to keep them within production systems for as long as possible, process costs, investment effectiveness and costs. CE strategic activities [38,42] provide implementation options related to resource efficiency and economic effects. Examples include the efficient use of resources, efficient design strategies, product service, maintaining resource and product value, and removable and modifiable production.

- *Societal behavior (Sb)*

Key strategies regarding CE social options include maintaining the high value of materials and wares, job creation, shift in consumption patterns, and the positive influence of high-quality production on human health.

Specific criteria are used to assess the single option score and the options under assessment were subjected to evaluate by five experts. The range of scores was 0–10 points for each of the individual options. The arithmetic mean of the assigned points is a single score value S.

The method additionally considers the degree of options validity a_j for the assessment of partial CE indicators. The degree of validity a_j of the four option groups are as follows: technical, T—a_j = 1; environmental, En—a_j = 4; economic, Ec—a_j = 3; social, Sb—a_j = 2. These are also proposed by a team of experts.

The single options score $S{*}a_j$, which describes the degree of validity, is calculated using Equation (7).

$$S * a_j = S{\cdot}a_j \tag{7}$$

where $S{*}a_j$—single score of S options considering the degree of validity; S—single options score (0–10 points); a_j—degree of validity for the individual options.

The system for calculating the degree of validity for single options a_j proposed by the team of experts is presented below. Additionally, it is assumed that each of the options included in the four main groups assessed may also be related to the others. Hence, the degree of validity established by the experts takes the form defined in Equations (8)–(11). The degrees of validity of the single options a_j of partial indicators are calculated using Equations (8)–(11):

$$Ta_j = 1 + (a_2 + a_3 + a_4)/3 \tag{8}$$

$$Ena_j = 4 + (a_1 + a_3 + a_2)/3 \tag{9}$$

$$Eca_j = 3 + (a_1 + a_2 + a_4)/3 \tag{10}$$

$$\mathrm{Sba_j} = 2 + (a_1 + a_3 + a_4)/3 \tag{11}$$

where $a_1 = 1$, $a_2 = 2$, $a_3 = 3$, $a_4 = 4$

Finally, Equation (6), considering Equations (7)–(11), takes the form presented in Equation (12).

$$\mathrm{CEI} = \sum S_T \cdot \mathrm{Ta_j} + \sum S_{En} \cdot \mathrm{Ena_j} + \sum S_{Ec} \cdot \mathrm{Eca_j} + \sum S_{Sb} \cdot \mathrm{Sba_j} \tag{12}$$

where

$\sum S_T \cdot \mathrm{Ta_j}$—Technological/technical CE_T partial indicator;
$\sum S_{En} \cdot \mathrm{Ena_j}$—environmental CE_{En} partial indicator;
$\sum S_{Ec} \cdot \mathrm{Eca_j}$—economic/business CE_{Ec} partial indicator;
$\sum S_{Sb} \cdot \mathrm{Sba_j}$—societal behavior CE_{Sb} partial indicator;

A schematic diagram of the measurements of the qualitative CE indicator shows Figure 1.

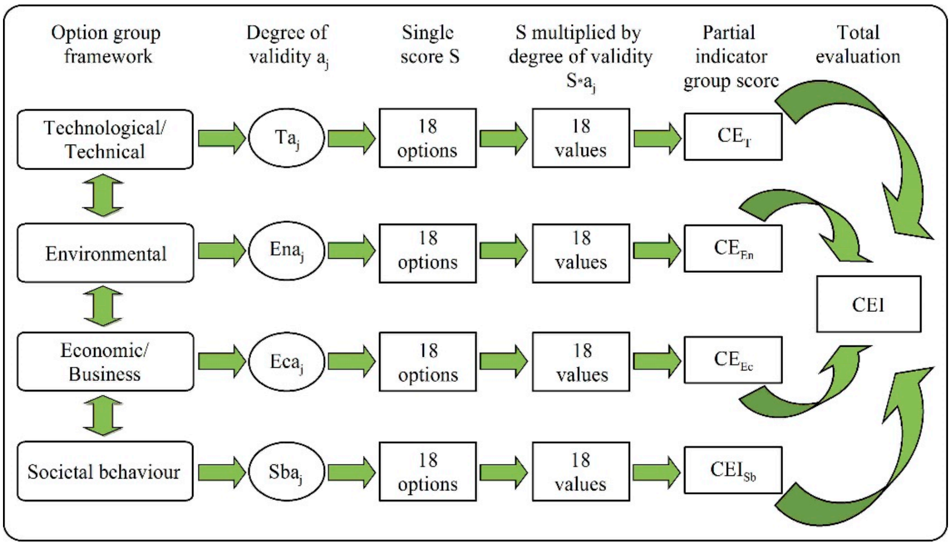

Figure 1. Diagram used to assess the qualitative CE indicator. $\mathrm{Ta_j} = 1 + (a_2 + a_3 + a_4)/3$; $\mathrm{Ena_j} = 4 + (a_1 + a_3 + a_2)/3$; $\mathrm{Eca_j} = 3 + (a_1 + a_2 + a_4)/3$; $\mathrm{Sba_j} = 2 + (a_1 + a_3 + a_4)/3$, where $a_1 = 1$, $a_2 = 2$, $a_3 = 3$, $a_4 = 4$.

In turn, the sum of the technological/technical, environmental, economic/business and social behavior values makes it possible to obtain a value for complex quality CE indicator. By comparing the new CEI_N and the old CNI_O production systems, the Relative Increase in CEI (RI_{CEI}) can be calculated using Equation (13).

$$RI_{CEI} = (CEIN_N - CNI_o)/CNI_o \cdot 100\% \tag{13}$$

2.2. Comparison of MSW Management Systems

2.2.1. Scenario 1—Incineration of Municipal Solid Waste

In Cracow, the MSW stream sent to the Cracow Incineration Plant (220,000 t/y) consists of unsorted municipal waste [44,45]. A flowchart of the MSW incineration method used at the Cracow Incineration Plant, which enables heat to be used and waste processing to be undertaken, is presented in Figure 2.

In the initial stage, the MSW temperature is increased to 250 °C, which causes the volatile constituents to be released. In the next stage, the waste is completely combusted in order to reach 900 °C. During gasification, the volatile parts of flue gases are oxidized by oxygen from the air at 1000 °C in the top zone of the boiler. The post-incineration zone minimizes the amount of unburned CO in the flue gases. Secondary air is supplied to this zone in order to achieve complete combustion. The flue gas stays in this zone for at least 2 sec at ≥850 °C.

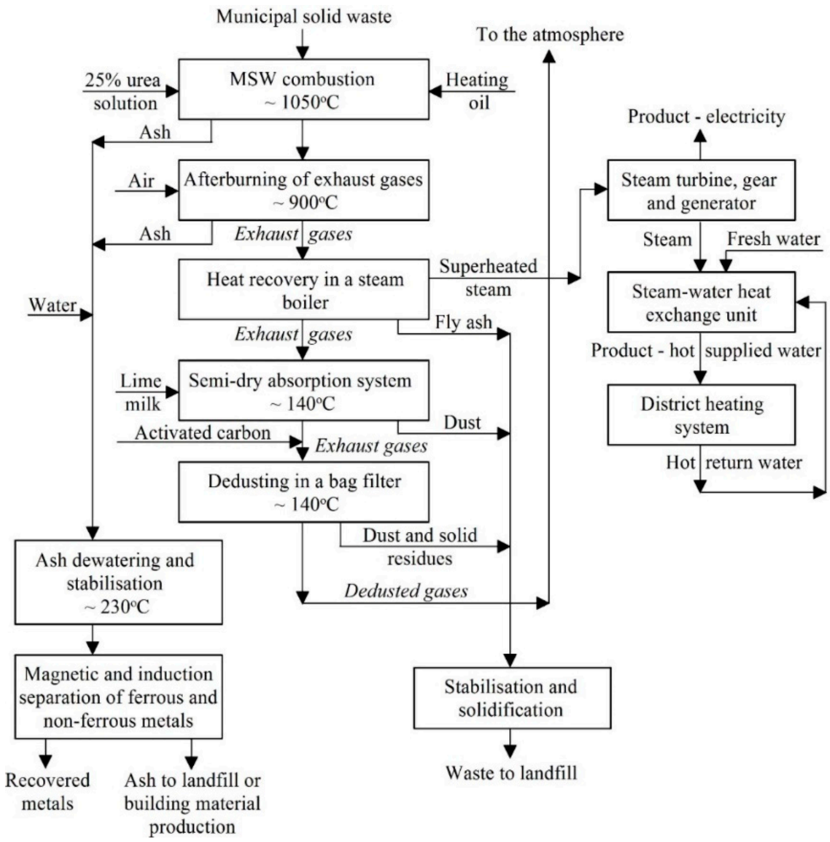

Figure 2. Flowchart of municipal waste combustion at the Cracow Incineration Plant.

The main device in the energy recovery system is a steam boiler with a natural circulation of exhaust gases, in which heat exchange takes place. After giving up the heat, the flue gas cools to 180 °C, and the recovered heat allows the conversion of the water flowing through the boiler into superheated steam. This steam, at a pressure of 40 bar and a temperature of 415 °C, is directed to the steam turbine operating in cogeneration mode, producing both electricity and heat. District heating water heated in the steam/water heat exchangers, is supplied to the heating network at temperatures 135 °C and 70 °C in winter and summer, respectively. The technology used ensures a thermal efficiency of 85% in the steam boiler system, achieving effective energy recovery.

The exhaust gas cleaning process begins in the combustion chamber, in which NO_x concentrations are decreased during the process in order to achieve the selective, non-catalytic reduction of nitrogen oxides (SNCR). This is achieved by the injection of a 25% urea solution into hot flue gases. Next, this gas is introduced into the top of the semi-dry reactor, where the flue gas is treated with lime milk spraying devices. Due to intensive contact with the drops of lime milk, pollutants such as HCl, HF and SO_2 are absorbed, and additionally, the flue gas is cooled to 140 °C.

After the absorber, the gases are directed through a channel into which a dose of activated carbon is placed in order to capture heavy metals as well as dioxins and furans (PCDD/F). Next, the flue gases flow into the bag's filter dedusting station, where the absorption of the remaining SO_2 takes place, and the contents of heavy metals and PCDD/F are reduced. The dust from the bags forms the "filter cake", containing the reaction products, unreacted absorbents, activated carbon, and fly ash. Then, the flue gases are directed through the chimney into the air at a temperature of 140 °C.

The waste materials produced by the incineration process include slag, bottom ash, fly dust and ash, and solid sediments from flue gas dedusting. The slag mainly consists of water-insoluble silicates, aluminum, and iron oxides. These are converted into valuable products in a warehouse inside the building, which serves to dewater and stabilize it. After two weeks, slag fractions of appropriate size and ferrous and non-ferrous metals are separated using magnetic and induction separators and directed to the slag seasoning unit. The capacity of this unit is 70,000 t/y. The slag may be used as a building material after obtaining the appropriate technical approval. Dust fly ash and solid residues from bag filters are stabilized in order to transform this waste from hazardous into inert waste. This is achieved by mixing it with additives and hydraulic binders (e.g., cement). The stabilization and solidification process are aimed at reducing the solubility of the components and preventing the leaching of soluble heavy metal compounds. The parameters of the stabilized and solidified wastes meet the regulations, allowing them to be deposited in landfill.

An analysis of the input and output of the waste and substrates of the MSW combustion process, as well as of the energy generated, is presented in Table 1.

Table 1. Cracow MSW Incineration Plant. Material and energy input/output analysis.

Installation Operation Time **Mass of MSW Incinerated**		**27.4 t/h**	**8000 h/y** **659 t/d**	**333 d/y** **219,569 t/y**
Material balance				
Specification	kg/t	t/h	t/d	t/y
Input				
Wastes from mechanical treatment of MSW	504	13.8	332	110,653
Unsorted (mixed) municipal waste	496	13.6	327	108,916
Incinerated MSW—total	1000	27.4	659	219,569
Heating oil	12.5	0.34	8.2	2748
Output				
Waste after incineration of MSW—total	274.4	7.53	180.86	60,254
Including				
Solid wastes from the treatment of exhaust gases	27.6	0.76	18.16	6052
Bottom ash and slag	216.2	5.93	142.38	47,461
Fly ash containing harmful materials	10.1	0.28	6.63	2211
Stabilized waste	0.3	0.01	0.17	55
Ferrous scrap removed from bottom ash	0.8	0.02	0.55	183
Ferrous metals	18.7	0.51	12.31	4102
Non-ferrous metals	0.9	0.02	0.57	190
Industrial sewage released	10.6	0.29	7.01	2336
CO_2 emissions	1000.7	27.46	659.15	219,715
Output Energy (MWh)				
Energy produced	1.228	33.69	808.57	269,522
Amount of energy used by the incinerator for its own needs	0.137	3.75	90.07	30,023
Electricity produced	0.418	11.47	275.26	91,752
The amount of electricity used by the incinerator itself	0.122	3.35	80.34	26,781
The amount of electricity produced from bio-degradable MSW fraction	0.193	5.29	127.04	42,348

Own calculation based on [44,45].

The Cracow Incineration Plant combusts 219,569 t/y of unsegregated MSW possessing a low calorific value of 9 GJ/t and producing 970,279 GJ/y of energy (of which 30,023 GJ/y are used for the plant's own needs). This results in a rather low efficiency for energy recovery of 49.1%. The CO_2 emissions are very high, amounting to 212,715 t/y. The amount of waste generated by the plant is 27.4% of the amount of MSW incinerated. Of these, 4185 t/y of metals and 190 t/y of non-metals are recovered, accounting for 7.1% and 0.3% of the total weight of the waste, respectively. Generally, it is a typical high temperature MSW treatment unit, having a significant impact on the natural environment. The income comes mainly from fees for processing unsegregated, low-calorie MSW.

2.2.2. Scenario 2—Renasci Smart Chain Processing of MSW

The implemented Renasci Smart Chain Processing (SCP) methods provides selective separation of RDF components into products and materials and renewable–reusable components, combining waste treatment with chain processing for the manufacture of products and energy. The Renasci unit in Ostend (Belgium) processes 102,000 t/y of refuse-derived fuels (RDF) and 18,000 t/y of mixed plastics [26,46].

The RDF obtained at mechanical–biological treatment plants consists of 67% *v*/*v* of the processed MSW. The calorific value of MSW is 10.16 MJ/kg, and that of RDF is 18.28 MJ/kg; therefore, the use of RDF as fuel is more profitable. RDF contains on average (% of dry mass): organic—18; paper/cardboard—28; plastics—32; glass—2; ferrous—1; non-ferrous—0.5; textiles—9; wood—2; remainder—7.5 [47].

The flowchart of the Renasci SCP is shown in Figure 3. The first stage of the process is the segregation of waste into the following fractions: organic compounds, paper/cardboard, plastics, textiles, ferrous and non-ferrous compounds, and inert substances. The ferrous/non-ferrous metals are selected from the waste and sold as valuable materials.

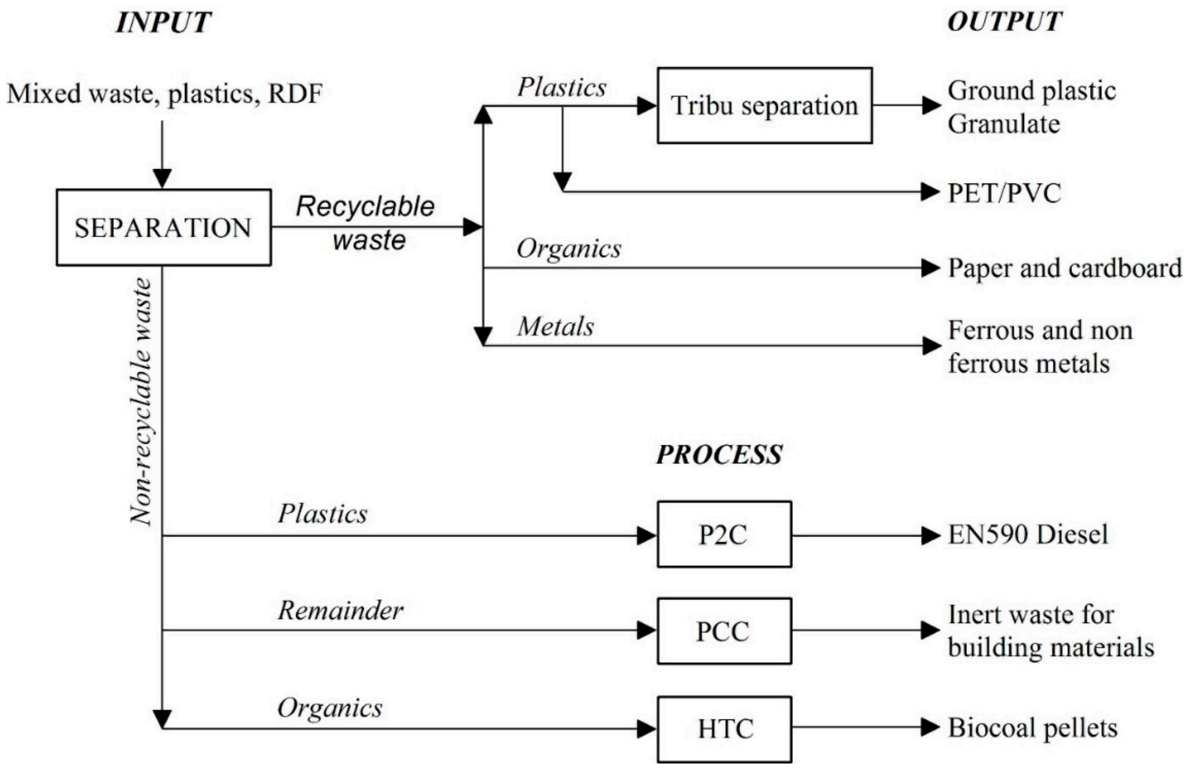

Figure 3. Flowchart of Renasci Smart Chain Processing in Ostend [26].

High-end segregation equipment is used to sort the recyclable and non-recyclable plastics. The non-recyclable plastics are transformed into hydrocarbons using Renasci's Plastic to Chemicals P2C technology [27,48]. P2C allows plastics to be processed using pyrolysis (non-catalytic), and the produced vapors are condensed to obtain heavy oil and light oils. Non-condensable gases are combusted, and the heat produced is recycled into the pyrolysis process. Heavy Pyoil consists of 93% alkenes and 7% cyclic compounds [26]. The current installation, operating since September 2020, operates at a maximum capacity of 35 t/d producing EN590 diesel, which is sold to the market and is rendered commercially viable at this scale.

Recycled paper and cardboard are salable. The organic fraction of MSW is treated by hydrothermal conversion (HTC) into bio-coal char [49,50]. The carbonization of biomass is carried out in water at 200 °C at 18 bar for 6–8 h in an inverted flow reactor (exothermic). After filtration, solid phase (bio-char) is obtained, in addition to the aqueous hydrothermal carbonization liquid (AHL). Bio-coal pellets from HTC production consist of 58% C, with a calorific content >23 MJ/kg. The by-product, non-concentrated AHL, is alkaline (pH 9.2) and has an N content of 1.99 g/L. Sulfur is the macronutrient with the highest concentration in the AHL (0.200 g/L), followed by Ca (0.190 g/L), P (0.100 g/L), and Mg (0.061 g/L). The micronutrient content (B, Cu, Fe, Mn, Mo, Zn) is 22 mg/L. After concentration, this liquid can be used as a soil conditioner. The bio-coal pellets with high calorific value (> 23 MJ/kg) are sold as biofuel.

The remaining fraction is processed by means of physicochemical and catalytic conversion (PCC). It is dosed into the reactor, where the water is evaporated, and the inorganic particles are converted into dry and clean inert ingredients. The heat produced is used to produce electricity, which is used in the facility.

The conversion of the residue from the separation process and the residue from the P2C and HTC processes into an inert fraction (inorganic components) and energy-rich flue gases (H_2, CO_2, CO) is realized in a continuous fluidized-bed reactor (sand) at 450–540 °C. The hot flue gas is burned at 850 °C/2 s, producing a gas stream that is cleaned using cyclone and ceramic filters. Heat recovery increases energy efficiency.

2.2.3. Scenario 3—The BioRen-Renasci Process

The upgraded BioRen-Renasci SCP process only provides recycling for sale in the markets of recyclable plastics, and ferrous and non-ferrous metals. Paper and cardboard, as well as organic waste, is completely processed into second-generation fuels by bio-fermentation, whereas the digested biomass is used to produce bio-pellets using the HTC method. The flowchart of the BioRen-Renasci process is presented in Figure 4.

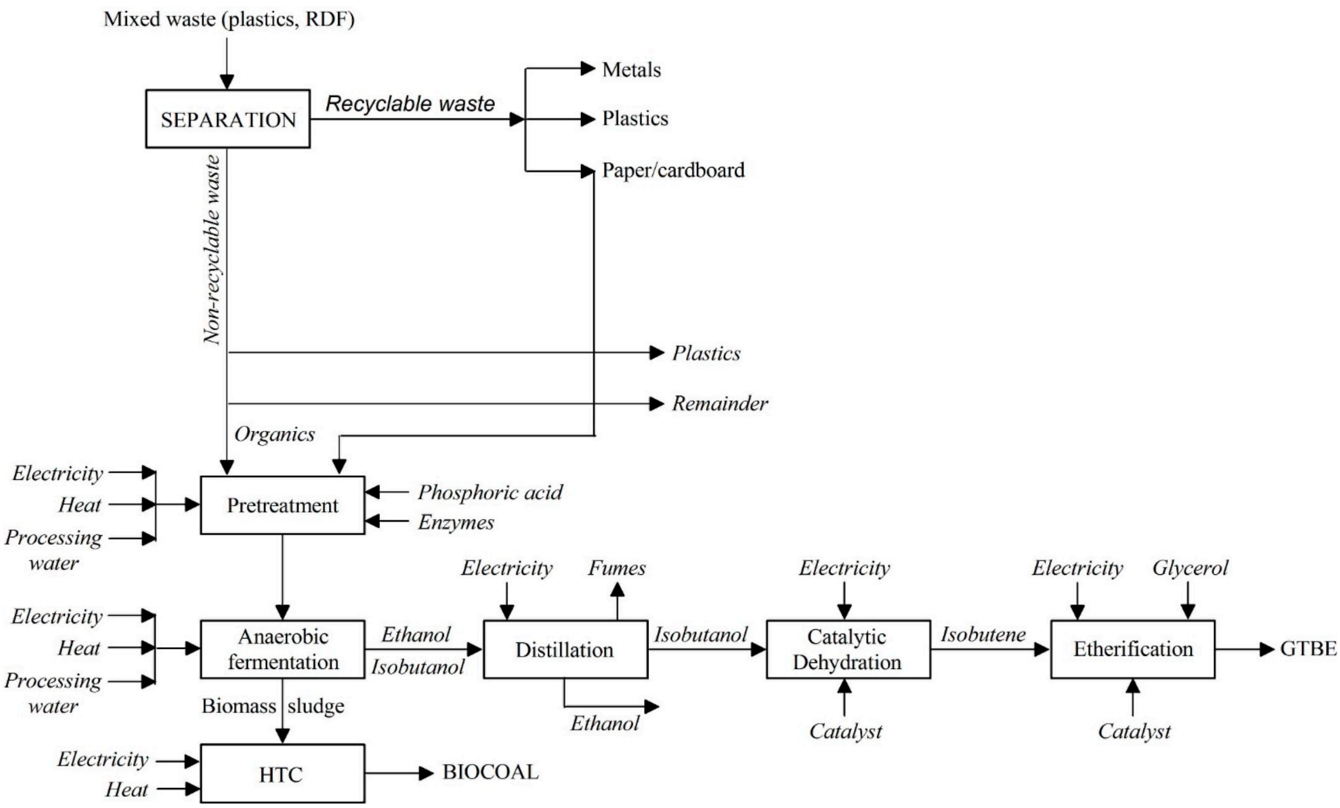

Figure 4. Flowchart of the integration of BioRen into the Renasci concept.

The organic fraction of the processed waste usually consists of 35–40% organic compounds. Paper/cardboard waste (WPC) and textiles could also be used as feedstock for the production of second-generation biofuels. These should be pre-treated with mild acid, which considerably reduces ash content to <4%, before starting the bio-fermentation process [51]. The next stage is to set up the saccharification/fermentation process (SSF) for isobutanol manufacturing.

Pre-treated paper and cardboard are hydrolyzed, through the hydrolysis of cellulose and hemicellulose using chemicals or enzymes in a tank reactor (CSTR) with a stirrer, to produce a sugar solution, which is subsequently fermented into isobutanol.

The soup containing yeast and urea is dosed into the reactor to obtain a urea concentration of 2 g/kg in the treated cardboard slurry. The pH and temperature are at values appropriate for obtaining optimal enzyme action (pH = 4.75–5.25, T = 50–55 °C). Renasci developed an enzymatic hydrolysis process using OFMSW fractions. This allows the manufacturing of 2G sugar (85% glucose) that can serve as a feedstock for the bio-production of fuel. The obtained sugar has no inhibitors, making it particularly suited to being a raw material for fermentation [46]. The glucan and xylan observed in the pre-treated slurry (65–70%) are well modifiable by enzymatic saccharification in preparation for further fermentation with industrial xylose-fermenting yeast to obtain bioethanol. CBHI-I has been recognized as an extremally limiting cellulose enzyme when performing simultaneous saccharification and co-fermentation (SSCF) of the WPC slurry. In order to decrease the enzyme dose and increase the SSCF speed, the expression of the CBH-I gene from *Talaromyce emersonii* in the commercial xylose-fermenting yeast BMD was modified [26]. Under the SSCF parameters, these strains made it possible to obtain a high ethanol concentration of 6.22% (v/v) with a yield of 93.3% [51].

In final fermentation phase, a decanter centrifuge is used to separate the post-fermentation solids from the fermentation pulp, which are then converted into bio-coal pellets using the HTC method [49]. The bio-fermentation of isobutanol is still difficult due to isobutanol inhibiting the development of microorganisms at concentrations of 1–2% w/w. In situ Product Recovery (ISPR) needs to be developed to resolve this problem [52]. An isobutanol content of 20.0 g/L was obtained following a fermentation time of 57 h. With 1 t of glucose, 411 kg of isobutanol can be produced. With 1 ton of biomass (25% water), 246 kg of isobutanol can be produced, with yield of 80%. The residual 200 kg is processed using the HTC method.

Finally, glyceryl tertiary butyl ether (GTBE) is manufactured, with is a promising biofuel admixture that can act as a substitute for fossil fuels. It can also be used in diesel and gasoline engines, improving engine efficiency and decreasing hazardous exhaust emissions. In GTBE production, crude glycerol is also obtained, which can be used in the manufacturing of biodiesel [26]. GTBE is produced through the following reaction (Figure 5):

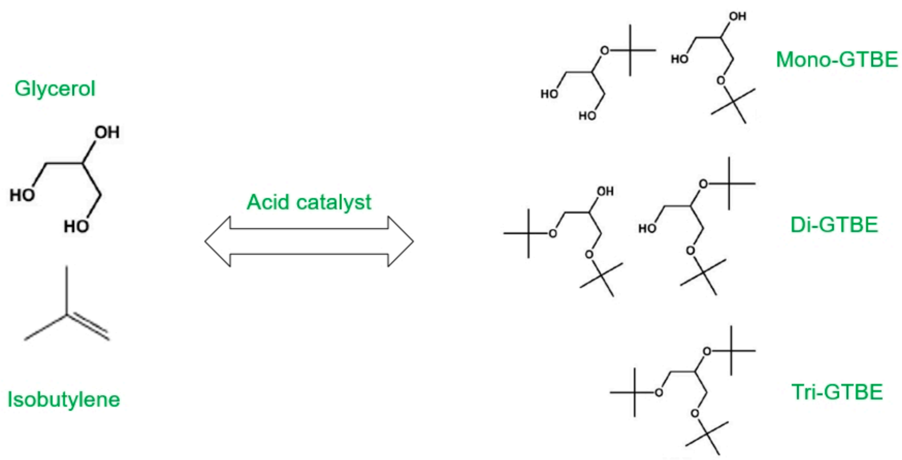

Figure 5. GTBE manufacturing reaction.

The material balances of Renasci SCP and BioRen-Renasci processing to produce GTBE are presented in Table 2.

Table 2. Material balance—input/output analysis per ton of MSW using Renasci Smart Chain Processing and the BioRen-Renasci method.

Installation Operation Time			**8000 h/y**	**333 d/y**
Mass of MSW Processed		**15.00 t/h**	**360.00 t/d**	**120,000 t/y**
Mass of GTBE Produced		**1.5 t/h**	**36.0 t/d**	**12,000 t/y**
Material balance of Renasci Smart Chain Processing				
Specification	kg/t	kg/h	t/d	t/y
I. Separation				
Input				
1. Mixed plastics	150	2250	54	18,000
2. RDF	850	12,750	306	102,000
Total	1000	15,000	360	120,000
Output				
1. Recyclable waste	278	4177	100	33,414
2.Non-recyclable waste	722	10,823	260	86,586
Total	1000	15,000	360	120,000
II. Recyclable waste separation				
Input				
Recyclable waste	272	4077	98	32,613
Output				
1. Recyclable plastics for *Tribu* separation	75	1128	27	9021
2. PET/PVC—product	12	175	4	1402
3. Paper and cardboard—product	162	2428	58	19,421
4. Metals (ferrous and nonferrous)—product	30	446	11	3570
Total	278	4177	100	33,414
III. Recyclable plastics Tribu separation				
Input				
1. Recyclable plastics from II	75	1128	27	9021
Output				
1. Ground plastic—product	75	1128	27	9021
IV. Non-recyclable waste from I				
Input				
1. Plastics for P2C process	337	5052	121	40,417
2. Remainder for PCC process	64	956	23	7650
3. Organics and non-recyclable cardboard for HTC	210	3157	76	25,259
4. Wood, textiles, tetra for HTC	111	1658	40	13,260
Total	722	10,823	260	86,586
Output	0	0	0	
1. EN590 Diesel from P2C process—product	279	4188	101	33,506
2. Inert materials for building materials from PCC process—product	32	478	11	3825
3. Biocoal pellets from HTC process—product	201	3009	72	2,4074
Material balance for BioRen-Renasci processing into GTBE				
V. Pre-treatment				
Input				
1. Organics and paper/cardboard from IV; paper/cardboard from II	372	5585	134	44,680
2. Phosphoric acid	1	15	0.36	120
3. Enzymes	2	30	0.72	240
4. Processing water	124,800	1,872,000	44,928	14,976,000
Total	125,175	1,877,625	45,063	15,021,000
Output				
1. Pre-treated waste	11,071	166,065	3986	1,328,520
2. Water from process	124,104	1,861,560	44,677	1,4892,480
Total	125,175	1,877,625	45,063	15,021,000

Table 2. *Cont.*

Installation Operation Time Mass of MSW Processed Mass of GTBE Produced		15.00 t/h 1.5 t/h	8000 h/y 360.00 t/d 36.0 t/d	333 d/y 120,000 t/y 12,000 t/y
VI. Anaerobic fermentation				
Input				
1. Pre-treated waste	1071	16,065	386	128,520
2. Yeast	63	945	23	7560
3. Nitric acid	340	5100	122	40,800
4. Processing water	104,200	1,563,000	37,512	12,504,000
Total	105,674	1,585,110	38,043	12,680,880
Output				
1. Biomass sludge	14,300	214,500	5148	1,716,000
2. Isobutanol (in water solution)	283.7	4256	102	34,044
3. Ethanol (in water solution)	34.9	524	13	4188
4. Water in isobutanol, ethanol solution	91,055.4	1,365,831	32,780	10,926,648
Total	105,674	1,585,110	38,043	12,680,880
VII. HTC production				
Input				
1. Biomass sludge from VI	14,300	214,500	5148	1,716,000
Output				
1. Biocoal pellets from HTC process- product	370	5550	133	44,400
2. Separated inert materials—product	1023	15,345	5148	122,760
3. Remaining water	4949	74,235	102	593,880
4. Evaporated water (vapour)	4613	69,195	13	553,560
5. Oil	7.6	114	32,780	912
6. Emissions	109	1635	38,043	13,080
NOX	0			
CO2	107			
CO	1.5			
SO2	0			
PM	0.5			
Total 1–6	11,071.6	166,074	3986	1,328,592
VIII. Distillation				
Input				
1. Ethanol in water solution from VI	34.9	524	13	4188
2. Isobutanol in water solution from VI	283.7	4256	102	34,044
3. Water in ethanol, isobutanol solution from VI	91,055.4	1,365,831	32,780	10,926,648
Total	105,674	1,585,110	38,043	12,680,880
Output			0	0
1. Isobutanol	283.7	4256	102	34,044
2. Ethanol	34.9	524	13	4188
3. Water vapour	91,055.4	1,365,831	32,780	10,926,648
Total	105,674	1,585,110	38,043	12,680,880
IX. Catalytic dehydration				
Input				
1. Isobutanol from VIII	283.7	4256	102	34,044
2. Catalyst	0.01	0.15	0.0036	120
Total	283.7	4256	102	283.7
Output				
1. Isobutene	154.6	2319	56	18,552
2. Water	49.7	746	18	5964
Total	204.3	3065	74	24,516

Table 2. *Cont.*

Installation Operation Time **Mass of MSW Processed** **Mass of GTBE Produced**		**15.00 t/h** **1.5 t/h**	**8000 h/y** **360.00 t/d** **36.0 t/d**	**333 d/y** **120,000 t/y** **12,000 t/y**
X. Etherification				
Input				
Glycerol	63.5	953	23	7620
Isobutene from IX	154.6	2319	56	18,552
Catalyst (sulphuric acid)	1	15	0.36	120
Total	219.1	3287	79.36	26,292
Output				
GTBE—product	100.0	1500	36	12,000

The described Renasci and BioRen-Renasci smart chain processes containing a series of low-temperature, zero-waste, physicochemical processes is innovative, and the proposed solution is fundamentally different from typical MSW incineration methods. Renasci and BioRen-Renasci SCP allow the production of valuable products such as bio-coal pellets, Renasci bio-diesel, inert materials used as filler in construction materials, and second-generation biofuel GTBE. Other products returned to the market include recycled PET/PVC, and reground plastics and metals (ferrous and nonferrous). Regarding energy, 78% is recovered from waste.

3. Results and Discussion

The assessment of CE micro-level quality indicators first requires the selection of options used in order to characterize the production systems being evaluated. These are selected by a panel of experts and divided into four types: technological/technical, T; environmental, En; economic/business, Ec; and societal behavior, Sb. These are presented in Table 3.

Table 3. Options for the assessment of CE micro-level indicators.

Options Group Framework	Option Symbol	Option Groups for Micro CE Systems
Technological and technical (T)	T1	Availability of technology. Degree of difficulty of technology and production
	T2	Degree of the novelty of technology and project when compared to BAT
	T3	Process simplification and/or easier conducting and control of production. Reducing the quantity of operation and unitary processes
	T4	Reducing/shortening transport routes
	T5	Reducing energy consumption, e.g., decrease in cumulative energy consumption index
	T6	Reducing in consumption of materials, e.g., decrease in cumulative material consumption index and material toxicity
	T7	Use of renewable energy and/or bioenergy
	T8	Prioritization of renewable resources in order to use recyclable and reusable materials and energy in an efficient way
	T9	Improving product quality and stability
	T10	Design for the future in order to adopt appropriate materials for the adequate prolongation of future consumption and lifetime
	T11	Ecologically designed for repair, refurbishment, recycling and remanufacturing, production, consumption, and use
	T12	Consistency with the objectives of sustainable development and cleaner technology
	T13	Improved efficiency in order to use a smaller amount natural resources in ware production or consumption. Lowering resource demands and increasing resource security
	T14	Combustion of materials with energy recovery
	T15	Risk of implementation and probability of success. Degree of difficulty and time required for implementation.
	T16	Using a discarded product or its elements in a new product with a different function
	T17	Recycling and processing materials to achieve appropriate quality
	T18	Incorporating digital techniques to look after and optimize resource use and enhancing the connection between supply chain firms using digital platforms and technologies

Table 3. *Cont.*

Options Group Framework	Option Symbol	Option Groups for Micro CE Systems
Environmental (En)	En1	Lowering pressure on the environment, both domestic and international. Reducing the release of waste and preventing the emission of pollution
	En2	Evaluating the quantity and quality of emissions, e.g., coefficients of cumulative hazard to determine the release of waste
	En3	Waste reduction at the source
	En4	In-process recycling of materials
	En5	On-site recycling of materials
	En6	Off-site recycling of materials
	En7	In-process recycling of energy
	En8	On-site recycling of energy
	En9	Off-site recycling of energy
	En10	Incentivization of high-quality recycling. Use the life cycle of the material to characterize the sourced materials
	En11	Increasing remanufacturing, reuse and refurbishment of wres and raw materials
	En12	Solutions that produce the optimum collection of waste
	En13	Take-back systems for remanufacturing. Selecting waste streams and delivering the waste to remanufacturing and recycling units
	En14	Reducing the degree of toxicity of waste and formation of secondary waste
	En15	Measuring the environmental effects (burdens/benefits) of technical cycles in consideration of reusability/recyclability/recoverability (RRR)
	En16	Measuring the effects of technical cycles using the RRR indicator in terms of mass rate of recycling, recovery, and reuse of materials and energy
	En17	Sustainability and preservation of what already exists by maintaining, repairing and upgrading resources in use in order to maximize their lifetime using take-back strategies
	En18	Using waste as a raw material through the use of waste streams as a secondary resources and recovering waste for reuse and recycling
Economic/ Business (Ec)	Ec1	Managing waste and by-products
	Ec2	Increasing the stability of wares to keep them being produced and consumed for longer
	Ec3	Treating renovation and recycling as key economic activities that are important to CE development
	Ec4	Substituting natural resources with waste. Using natural resources more efficiently during production, including sustainable bio-based and other raw materials
	Ec5	Labor requirements
	Ec6	Cumulative energy costs
	Ec7	Cumulative material costs
	Ec8	Repair and maintenance costs
	Ec9	Process costs
	Ec10	Investment range and level
	Ec11	Optimum location
	Ec12	Degree of adaptation to local conditions
	Ec13	Consistency with programs within the national economy and of the EU
	Ec14	Obtaining the legal authorizations required
	Ec15	Value of investment outlays. Time required for the recovery of investment outlays and obtaining implementation efficiency
	Ec16	Measuring the effectiveness (burdens/profits) of technical cycles on economical ground, e.g., RRR benefit rate
	Ec17	Organizational innovation
	Ec18	Rethinking the economic model to evaluate possibilities for developing major worth and the development of incentives through an economic model that builds interactions between products and services
Societal behavior (Sb)	Sb1	Participating in new types consumption (e.g., sharing, goods–services models, readiness to pay well for permanence)
	Sb2	Reuse (required change in approach to repair and renovation)
	Sb3	Maintaining the high worth of raw materials and wares
	Sb4	Job creation in regions with higher unemployment
	Sb5	Hiring of highly skilled employees
	Sb6	Influence of distribution of parts of society with different amounts of revenue
	Sb7	Decreasing hazard to human health
	Sb8	Changes in consumption standards. Socially responsible consumers may use less of a good, energy or service
	Sb9	Positive impact of higher-quality products on human health
	Sb10	Improving relations with stakeholders and consumers
	Sb11	Improving relations with the public
	Sb12	Measuring the profits of technical cycles in terms of social impacts, e.g., RRR benefit rate
	Sb13	Marketing innovations
	Sb14	Social innovations
	Sb15	Product innovations
	Sb16	Creating joint value by working together internally with other organizations and the public sector throughout the supply chain to create transparency and shared value
	Sb17	Extending of product life
	Sb18	Improving living conditions through achieving a better-quality ecosystem

The individual score for each option is an arithmetic average value calculated on the basis of the data supplied by the three experts who assessed each option, which are presented below in Table 4. Further calculations using Equations (7)–(12) made it possible to obtain the values of the partial CE indicators, together with an overall assessment of all group options—the CEI indicator.

Table 4. Assessment of CE micro-level indicators for the comparison of municipal waste management systems: Scenario 1—Incineration; Scenario 2—Renasci Smart Chain Process; Scenario 3—BioRen-Renasci process.

Option Group Framework	Option Symbol *	Single Option Score S for each Scenario			Degree of Validity a_j	Single Score S*a_j Multiplied by the Degree of Validity a_j for each Scenario		
		1	2	3		1	2	3
Technological/technical					$Ta_j = 1 + (a_2 + a_3 + a_4)/3$			
Technological/technical (T) Degree of validity $a_1 = 1$	T1	9	9	8	4	36	36	32
	T2	5	8	9	4	20	32	36
	T3	7	8	7	4	28	32	28
	T4	7	8	8	4	28	32	32
	T5	5	8	8	4	20	32	32
	T6	5	7	9	4	20	28	36
	T7	7	9	9	4	28	36	36
	T8	7	8	9	4	28	32	36
	T9	4	8	9	4	16	32	36
	T10	5	8	9	4	20	32	36
	T11	5	8	9	4	20	32	36
	T12	6	9	10	4	24	36	40
	T13	5	8	9	4	20	32	36
	T14	6	8	9	4	24	32	36
	T15	7	7	9	4	28	28	36
	T16	5	8	8	4	20	32	32
	T17	4	8	9	4	16	32	36
	T18	2	8	9	4	8	32	36
Technological/technical group CE_T partial indicator$\sum S_T \cdot Ta_j$						*404*	*580*	*628*
Environmental					$Ena_j = 4 + (a_1 + a_3 + a_2)/3$			
Environmental (En) Degree of validity $a_4 = 4$	En1	5	8	9	6	30	48	54
	En2	5	8	9	6	30	48	54
	En3	4	7	8	6	24	42	48
	En4	0	7	8	6	0	42	48
	En5	0	7	8	6	0	42	48
	En6	5	7	8	6	30	42	48
	En7	9	9	9	6	54	54	54
	En8	6	9	9	6	36	54	54
	En9	6	9	9	6	36	54	54
	En10	4	7	9	6	24	42	54
	En11	2	8	9	6	12	48	54
	En12	2	8	9	6	12	48	54
	En13	5	8	9	6	30	48	54
	En14	2	8	9	6	12	48	54
	En15	3	8	9	6	18	48	54
	En16	5	8	9	6	30	48	54
	En17	2	7	8	6	12	42	48
	En18	5	8	9	6	30	48	54
Environmental group CE_{En} partial indicator $\sum S_{En}\ E_n a_j$						*420*	*846*	*942*
Economic					$Eca_j = 3 + (a_1 + a_2 + a_4)/3$			
Economic/business (Ec) Degree of validity $a_3 = 3$	Ec1	8	10	10	5	40	50	50
	Ec2	2	7	8	5	10	35	40
	Ec3	5	8	9	5	25	40	45
	Ec4	6	8	9	5	30	40	45
	Ec5	7	9	9	5	35	45	45
	Ec6	6	8	9	5	30	40	45
	Ec7	5	7	7	5	25	35	35
	Ec8	6	8	9	5	30	40	45
	Ec9	6	7	7	5	30	35	35
	Ec10	4	8	8	5	20	40	40
	Ec11	6	6	6	5	30	30	30
	Ec12	2	8	9	5	10	40	45
	Ec13	7	10	10	5	35	50	50
	Ec14	8	10	10	5	40	50	50
	Ec15	5	8	9	5	25	40	45
	Ec16	5	8	9	5	25	40	45
	Ec17	4	8	9	5	20	40	45
	Ec18	4	8	9	5	20	40	45

Table 4. *Cont.*

Option Group Framework	Option Symbol *	Single Option Score S for each Scenario			Degree of Validity a_j	Single Score S^*a_j Multiplied by the Degree of Validity a_j for each Scenario		
		1	2	3		1	2	3
Economic/business group CE_{Ec} partial indicator $\sum S_{Ec} \cdot Eca_j$						*480*	*730*	*780*
Societal					$Sba_j = 2 + (a_1 + a_3 + a_4)/3$			
Societal behavior (Sb) Degree of validity $a_2 = 2$	Sb1	5	8	9	5	25	40	45
	Sb2	5	7	8	5	25	35	40
	Sb3	5	8	9	5	25	40	45
	Sb4	2	2	2	5	10	10	10
	Sb5	5	8	9	5	25	40	45
	Sb6	7	8	9	5	35	40	45
	Sb7	4	7	8	5	20	35	40
	Sb8	5	7	8	5	25	35	40
	Sb9	6	8	9	5	30	40	45
	Sb10	7	8	9	5	35	40	45
	Sb11	3	8	9	5	15	40	45
	Sb12	7	8	9	5	35	40	45
	Sb13	5	7	8	5	25	35	40
	Sb14	5	7	8	5	25	35	40
	Sb15	5	8	9	5	25	40	45
	Sb16	5	7	8	5	25	35	40
	Sb17	4	7	8	5	20	35	40
	Sb18	6	8	9	5	30	40	45
Societal behavior group CE_{Sb} partial indicator $\sum S_{Sb} \cdot Sba_j$						*455*	*655*	*740*
Comparison of partial indicator values for Scenarios (%)						***3/1***	***2/1***	***3/2***
Technological/technical CE_T						155.4	143.6	108.3
Environmental CE_{En}						224.3	201.4	111.3
Economic CE_{Ec}						162.5	152.1	106.8
Societal CE_{Sb}						162.6	144.0	113.0
The total assessment of all group options—RI_{CEI} = CEI indicator						**1759**	**2811**	**3090**
Comparison of RI_{CEI} values for Scenarios (%)						***3/1***	***2/1***	***3/2***
RI_{CEI} = (CEI3—CEI1)/CNI1 · 100%							75.7	
RI_{CEI} = (CEI2—CNI1)/CNI1 · 100%							59.8	
RI_{CEI} = (CEI3—CNI2)/CNI2 · 100%							9.9	

Analyzing the assessments of the CE quality micro indicators for the three municipal waste management scenarios presented, it can be concluded that the greatest number of low ratings for the single option score S for each scenario was obtained by municipal waste incineration (Scenario 1) for all four of the groups of options assessed. The other two scenarios, i.e., the Renasci Smart Chain process (Scenario 2) and the BioRen-Renasci process (Scenario 3), had much higher scores. In the group of technological/technical options, the lowest number of points obtained in Scenario 1 was option T18 (2 points), which is related to the application of digital technology, and the options related to the improvement of the quality and stability of the product (T9), as well as the recycling and processing of materials (T17), at 4 points each. The highest number of points, i.e., 9, was assigned to the T1 option, which is related to the degree of difficulty of the production technology. For Scenario 3, the technological/technical option group the T12 option, concerning consistency with the goals of sustainable development and cleaner technology, received the most points (10 points). The scores for Scenario 3 in the group of technological/technical options were greater than or equal to the scores assigned under Scenario 2, with the only exception being the T1 option, which is related to production difficulty (8 points), and the T3 option, which is related to the simplification of the production process and/or easier production and control (7 points).

In the evaluation of the environmental the option group, Scenario 3 dominates, obtaining a number of points equal to or higher than either of the other scenarios for each of the assessed options. The En7, En8 and En9 options, which are related to energy recycling, obtained the same number of points in both Scenarios 2 and 3. For Scenario 1, the scores in the environmental option group were much lower than those in Scenario 2 and 3, and for the En4 and En5 options, which are related to the in-process and on-site recycling of materials, 0 points were assigned. However, all three scenarios obtained the same number of points—9—for the En7 option, on-site recycling of energy.

In the economic/business option group, the incineration process described in Scenario 1 still obtained a lower number points for individual options than Scenarios 2 or 3, and differences were visible for the Ec2 and Ec12 options (which relate to increasing the durability of goods and the degree of adaptation to local conditions). However, all three scenarios obtained the same number of points—6—for the Ec11 option, which is related to optimal location. Scenarios 2 and 3 obtained the maximum number of points for the following options: managing waste and by-products (Ec1), consistency with programs within the national economy and of the EU (Ec13), and obtaining the legal authorizations required (Ec14).

In the group of societal behavior options, Scenario 3 also scored higher than Scenarios 1 and 2, apart from option Sb4, which is related to job creation in areas with high unemployment, and was assessed as having a score of 2 points for each of the assessed scenarios.

Table 4 shows that the Renasci Smart Chain (Scenario 2) or BioRen-Renasci (Scenario 3) methods of RDF processing achieved rather similar scores to one another, but much higher than the incineration of MSW (Scenario 1). It can be observed from the partial indicators calculated that the environmental indicators achieved by Scenarios 2 and 3 were greater than the indicators achieved by Scenario 1 by 201% and 224%, respectively. This confirms that environmental indicators have the greatest influence on the value of the total CEI indicator.

The calculated Relative Increase in CEI (RI_{CEI}) for Scenarios 2 and 3, which were 60% and 76%, respectively, higher than Scenario 1, show the considerable advantage of these methods. This confirms that the Renasci methods (Scenarios 2 or 3) are more than 1.5 times better in technical, ecological and economic terms, and more socially beneficial than the MSW incineration process.

The calculated Relative Increase in CEI (RI_{CEI}) between Renasci Smart Chain and BioRen-Renasci methods of RDF processing was 10%, indicating that Scenario 3 possesses a certain advantage over Scenario 2. The RI_{CEI} indicators obtained can be regarded as being objective due to the qualitative evaluation RI_{CEI} of the three waste management system scenarios compared being based on the same qualitative expert assessment in each analyzed MSW case.

4. Conclusions

This study assessed three municipal waste management scenarios on the basis of circular economy quality indicators (CEI), including an analysis of four groups of option categories: technical, environmental, economic, and social. Three different MSW management systems were compared as scenarios: Scenario 1—the MSW incineration method, the Cracow Incineration Plant as an example; Scenario 2—Renasci Smart Chain Processing, consisting of the recycling and reuse of segregated municipal waste and the treatment of selected elements of MSW into biofuels and biocarbon pellets; and Scenario 3—upgraded Scenario 2 that included the reduction and recycling of MSW streams and the processing of paper/cardboard and non-recycled parts of selected municipal waste into biochar pellets and second-generation biofuels.

Cracow Incineration Plant is a typical high-temperature MSW treatment unit that has a significant impact on the natural environment, combusting 219,569 t/y of unsegregated MSW with a low calorific value of 9 GJ/t. This results in energy recovery with low efficiency, at 49.1%. The CO_2 emissions are very high, and amount to 212,715 t/y. The amount of waste generated by the plant corresponds 27.4% of the amount of MSW incinerated. The Renasci and BioRen-Renasci smart chain processes described contain a series of low-temperature, zero waste, physicochemical processes that make it possible to produce valuable products such as bio-coal pellets, Renasci bio-diesel, inert materials used in construction materials, and second-generation biofuel GTBE. Other products that are returned to the market include recycled PET/PVC, reground plastics, and metals (ferrous and nonferrous). Over 78% of the energy contained in the input waste is used.

The assessment of the three municipal waste management scenarios described above, which was performed by a panel of experts using the complex method of quality assessment, showed that:

- The lowest scores for individual options in all four groups of options assessed were obtained for MSW incineration (Scenario 1), while the Renasci Smart Chain process (Scenario 2) and the BioRen-Renasci process (Scenario 3) received much higher scores, and obtained similar results.
- The calculated Relative Increase in CEI was 60% higher in Scenario 2 and 76% higher in Scenario 3 than in Scenario 1, thus demonstrating their considerable advantage over Scenario 1 and confirming that Renasci methods (both Scenarios 2 and 3) are much more beneficial in technical, ecological, economic and social terms than the MSW incineration process.
- Environmental indicators have the greatest impact on the total value of the CEI index.
- In the assessed groups of technical, environmental, economic, and social options, in each case, the highest value of the partial CE index was obtained in Scenario 3, corresponding to the BioRen-Renasci process.

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