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Waste to Carbon Energy Demand Model and Data Based on the TGA and DSC Analysis of Individual MSW Components

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Abstract
The pioneering developed simplified mathematical model can be used to determine the energy consumption of the torrefaction process. Specifically, the energy balance model was developed for torrefaction of municipal solid waste (MSW; a combustible fraction of common municipal waste). Municipalities are adopting waste separation and need tools for energy recovery options. This type of model is needed for initial decision-making, evaluation of cost estimates, life cycle analysis (LCA), and for optimizing the torrefaction of MSW. The MSW inputs are inherently variable and are site-, location-, and country-dependent. Thus, in this model, MSW inputs consist of eight types of common municipal waste components: chicken meat, diapers, gauze, eggs packaging, paper receipts, cotton, genuine leather, and polypropylene. The model uses simple experimental input consisting of thermogravimetric (TGA) and differential scanning calorimetry (DSC) analyses for each type of individual MSW material. The model was created in a Microsoft Office Excel spreadsheet and is available for download and use for site-specific waste mixes and properties. The model allows estimating the energy demand of the process depending on the percentage composition of the MSW and the final torrefaction temperature. The model enables initial optimization of the torrefaction process regarding its energy demand by changing the proportion of MSW mix and the final temperature.

Keywords
torrefaction, energy balance, municipal solid waste, recycling, waste to carbon, carbonized refuse-derived fuel, specific heat, waste management, energy recovery, waste to energy, circular economy

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data

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Data Descriptor

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Abstract: The pioneering developed simplified mathematical model can be used to determine the energy consumption of the torrefaction process. Specifically, the energy balance model was developed for torrefaction of municipal solid waste (MSW; a combustible fraction of common municipal waste). Municipalities are adopting waste separation and need tools for energy recovery options. This type of model is needed for initial decision-making, evaluation of cost estimates, life cycle analysis (LCA), and for optimizing the torrefaction of MSW. The MSW inputs are inherently variable and are site-, location-, and country-dependent. Thus, in this model, MSW inputs consist of eight types of common municipal waste components: chicken meat, diapers, gauze, eggs packaging, paper receipts, cotton, genuine leather, and polypropylene. The model uses simple experimental input consisting of thermogravimetric (TGA) and differential scanning calorimetry (DSC) analyses for each type of individual MSW material. The model was created in a Microsoft Office Excel spreadsheet and is available for download and use for site-specific waste mixes and properties. The model allows estimating the energy demand of the process depending on the percentage composition of the MSW and the final torrefaction temperature. The model enables initial optimization of the torrefaction process regarding its energy demand by changing the proportion of MSW mix and the final temperature.

Dataset: Available as Supplementary File S1.

Dataset License: CC0

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1. Summary

Torrefaction, a low temperature, thermal treatment of municipal solid waste offers a 'Waste to Carbon' type recovery of energy and saving of resources [1]. This concept is of great importance at a time of growing demand for energy and goals calling for zero waste and a circular economy. Torrefaction of municipal solid waste (MSW) is still at the discovery phase, and more scaling up research is needed for wider adoption of this technology. Modeling of MSW torrefaction can help to maximize energy recovery even at this early stage.

Today's MSW in the form of refuse-derived fuel (RDF) is used as a source of heat in cement plants. Eighty percent of cement installations in Europe use alternative fuels. RDF produced from municipal waste is the main alternative fuel in cement plants in Poland. Other types of waste used include used tires and rubber waste, waste from floatation enrichment of coal, sludge, and waste from power plants. In 2014, cement plants used about 1.2 million tons of alternative fuel. Heat recovered from their incineration constituted about 47% of the total energy used to sinter clinker [2]. Over the next few years, the cement industry is planning to increase the share of alternative fuels; the demand for fuel is expected to be about 1.6 million tons per year [3]. Another aspect conducive to this trend in waste management is 'co-processing'—a process of co-incineration (co-firing) of alternative fuels in a cement plant which makes simultaneous energy and material recycling possible. Co-processing encompasses several recovery operations in one process: recovery of energy, recycling/recovery of other non-organic materials, or recycling/recovery of metals and metal compounds [4]. Yet, owing to two tendencies—the cement industry's demands concerning high-quality alternative fuels and falling prices of the RDF transferred to cement plants—other methods of thermal treatment and improvement of RDF are being investigated. One of them is torrefaction.

Torrefaction (a.k.a. 'roasting') is a process of thermal-chemical processing of organic compounds under the following conditions: terminal temperature ranging from 200 to 300 °C, reactor interior heating rate <50 $°C \cdot min^{-1}$, process residence time <60 min, no oxygen access, and atmospheric pressure [5]. The torrefaction process can be divided into five phases: preheating, pre-drying, drying and transitional heating, torrefaction, and product cooling [6]. The product created in the torrefaction process is biochar: char, which is characterized by high energy density, very low moisture content, and a higher calorific value compared to the unprocessed material. Research continues on densifying torrefied RDF [1] to make it more user-friendly and adaptable to existing technologies for (e.g.,) pelletization.

There is a lack of research on the effects of morphological properties of individual materials consisting of RDF fraction of municipal waste on the torrefaction process. Specifically, little is known how the MSW composition inputs affect the energy consumption of the process. This is one of the key areas for the development and possible adoption of torrefaction, i.e., by enhancing MSW to maximize energy recovery and lower the cost of the process.

The pioneering simplified model allows determining energy data such as change of specific heat and overall energy demand in the torrefaction process of MSW from varying raw input materials in a common municipal waste. For the first time, the model allows users to change the percentage composition of the processed MSW mixture and determine the final temperature of the torrefaction process. The proposed solution solves the problem of determining the amount of energy needed to process a given MSW mixture. In addition, the model allows optimization of the selection of the torrefaction temperature and composition of the MSW in order to minimize the energy consumption of the process. The model calculates only the energy demand as an effect of all chemical and physical transformations of raw organic matter in MSW and may be a tool for initial decision making on the required characterization of MSW feedstock to torrefaction reactors. It may be incorporated into a holistic model covering such parameters of MSW as porosity, ash content, dimensions, and process parameters such as heat transport, mixing, heat loses, reactor type, dimensions, etc.

2. Data Description

The developed model is partially based on experimental data from thermogravimetric (TGA; spreadsheet "TGA results" in Supplementary File S1, columns: B–J) and differential scanning calorimetry (DSC; spreadsheet "DSC results" in Supplementary File S1, columns: B–J) analyses for each type of individual MSW input. From TGA, the mass loss of the MSW sample type over time is used (spreadsheet "TGA results" in Supplementary File S1, columns: W–AD). From the DSC analysis, the specific heat of the MSW sample for an increasing process temperature is used (spreadsheet "DSC results" in Supplementary File S1, columns: B–J). The temperature during torrefaction changes during all five phases of the process, and thus, the specific heat also changes as the MSW material undergoes transformations that can include both exothermic and endothermic reactions. When the mass of the sample at a given temperature is known, the specific heat of the processed sample can be calculated by the model.

First, the mathematical model calculates the mass of each MSW ingredient (1):

$$M_i = m_0 \cdot \%_i \tag{1}$$

where:

M_i = mass of the ingredient, g,

i = chicken meat, diapers, gauze, egg packaging, paper receipts, cotton, genuine leather, polypropylene,

m_o = the sample mass set, g,

$\%_i$ = percentage of individual MSW waste, %.

Then the mass loss of the individual components of the mixture is calculated from TGA analysis inputs (2):

$$M_{TGA,i} = \%_{TGA,\ i} \cdot M_i \tag{2}$$

where:

$\%_{TGA,\ i}$ = remaining percentage of the given MSW ingredient, %.

After obtaining the mass remaining at a given temperature, this mass is multiplied by the specific heat values (3) obtained experimentally (via DSC) at a given temperature.

However, by multiplying the sample mass by the value of specific heat (3), it is possible to calculate the amount of energy needed to heat the material as it is being processed at a given temperature, the energy that is needed or recovered as part of torrefaction process, and the energy balance that can involve both exothermal and endothermic reactions (spreadsheet "Total energy calculation" in Supplementary File S1, columns: B–J file).

$$E_{SH,i} = E_{SH,i,T} \cdot M_{TGA,i} \tag{3}$$

where:

$E_{SH,\ i}$ =the specific heat of a given MSW component at a given temperature, J,

$E_{SH,\ i,\ T}$ = experimental value of the specific heat of a given component at a specific temperature, $J \cdot g^{-1}$.

By obtaining specific values from equations (3) for all components of the MSW mixture, it is then possible to estimate the amount of energy to be delivered to the process at a given temperature step (e.g., 1 °C) (4) (spreadsheet "Total energy calculation" in Supplementary File S1, column: K).

$$E_{P,T} = \sum E_{SH,i} \tag{4}$$

where:

$E_{P,\ T}$ = process energy in one temperature step, J.

Then, by summing up all the values obtained from equation (5), the energy balance of the whole process can be obtained (5) (spreadsheet "Total energy calculation" in Supplementary File S1, column: L):

$$E_P = \sum E_{P,T} \tag{5}$$

where:

$E_{P,T}$ = the energy of the entire process, J.

The main output of the software is the energy demand results of the whole process and specific heat.

3. Methods

The TGA and DSC data of the following MSW (example) components were acquired according to Stępień et al. [7]: chicken meat (as biodegradable waste), diapers (as hygienic waste), gauze (as hygienic waste), egg packaging (as cardboard waste), paper receipts (as a paper waste), cotton (as textile waste), genuine leather (as leather waste), and polypropylene (PP) (as 2D plastic waste). The selected groups of materials represent the main groups of high caloric waste that can be potentially used as material for the production of refuse-derived fuel. The selection of the chicken meat as a biodegradable material was made based on the scale of production (i.e., 48% of all meat produced in Poland [8] is poultry) and consumer preferences. In the case of other wastes, they were used due to their availability. The presented waste base can be extended to other waste material types and can be more site-specific. Each waste subjected to testing was purchased from one source (e.g., a supermarket chain store) to ensure its homogeneity and representativeness of post-consumption waste streams. A 5 kg sample of each material was prepared for the tests. Before TGA and DSC analyses, each waste was dried and milled to a grain size of 0.4 mm and mixed. TGA analysis was performed in triplicate and DSC analysis in one run.

To run the model, the user must only enter the initial MSW data and desired torrefaction temperature (spreadsheet "Input data" in Supplementary File 1, yellow frames):

- sample mass,
- percentage composition of the sample,
- the final torrefaction temperature.

Table 1 presents the comparison of the boundary (range) and initial values that can be added as inputs into the model, as well as the data entered to verify the mathematical model.

Table 1. Municipal solid waste properties data needed as inputs to the mathematical model.

Property	Value
Simple weight (m), g	$0 < m < \infty$
Temperature (T), °C	$20 \leq T \leq 300$ (interval 1 °C)
Percentage composition of chicken meat, diapers, gauze, egg packaging, paper receipts, cotton, genuine leather, polypropylene, %	$0 \leq x \leq 100$ (sum of all waste must be 100%)

Due to the execution of the code in the Microsoft Office Excel spreadsheet, it cannot be presented. However, the principle of its operation is described below.

The spreadsheet calculates the energy required to heat the sample. After entering the data on the percentage composition of the mixture and the final temperature of the process, the sheet calculates the mass of the components of each material. It then calculates the change in sample weight for each stage. When the model calculates the mass of the sample for each temperature, it multiplies it by the value of specific heat. In this way, it is known how the heat demand changes when the sample is heated, taking into account its temperature degradation. In this way, the total energy demand for the process as a degree Celsius may be determined. The sum of these values allows estimating the total energy needed for the process.

The user's panel is shown below in Figure 1. The values entered by the user are marked in yellow and the calculated values in green (spreadsheet "Input data" in Supplementary File S1).

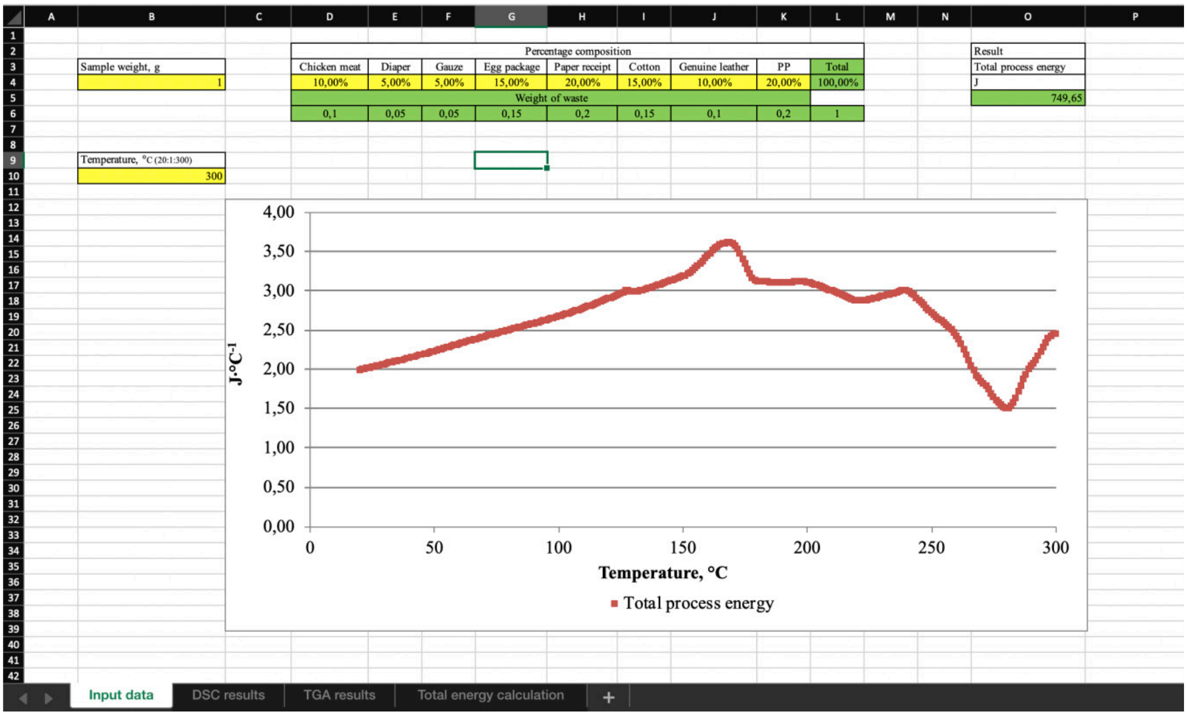

Figure 1. User panel for municipal waste properties inputs and energy demand output in MS Office Excel.

4. User Notes

The software will optimize the carbonized refuse-derived fuel (CRDF) production process before its valorization in the torrefaction process. In addition, the appropriate selection of the MSW mixture will help determine the cost-effectiveness of MSW mechanical pre-treatment and torrefaction of individual, site-specific wastes, waste streams, and their mixtures, such as municipal sludge [9] or compost [10].

Using this novel software model, new energy optimization studies of the torrefaction process can be carried out considering a wide range of site-specific choices of MSW mixture and torrefaction process temperatures. The development of this model represents the next logical step in the development of technology for MSW torrefaction. It allows for optimization of MSW inputs for the energy balance.

The type of analyses presented in this model will eventually allow end users to optimize the torrefaction process for highly variable (both in site/location and in time) MSW. The dissemination of the software will allow further research of MSW torrefaction, site-specific cost analyses, LCA, and decision-making for its scaling up and implementation at industrial and municipal scales.

It is projected that the software will allow the initial determination of the energy demand and costs of MSW torrefaction for particular, site-specific waste types and properties. Additional estimates of heat loss from the reactor, reactor heating, and potential energy recovery from the burning of the gaseous products released during torrefaction should be considered for the next generation of this model or in a more developed holistic model. This first-generation model should be useful to estimate the energy consumption of the process and the design of an optimized technological line for mechanical sorting, mixing, and the production of CRDF, and optimization of MSW torrefaction.

Supplementary Materials: The following are available online at http://www.mdpi.com/2306-5729/4/2/53/s1, The following file containing the TGA and DSC data and described model is available online as Supplementary File S1: Waste_to_Carbon_Energy_Demand_Model_1.0.xlsx.

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References

1. Bialowiec, A.; Micuda, M.; Koziel, J.A. Waste to carbon: Densification of torrefied refuse-derived fuel. *Energies* **2018**, *11*, 3233. [CrossRef]
2. Nowak, M.; Szul, M. Possibilities for application of alternative fuels in Poland. *Arch. Waste Manag. Environ. Prot.* **2016**, *18*, 33–44.
3. Kraszewski, A. The market for alternative fuels produced for the needs of the cement industry in Poland. In Proceedings of the 11th Seminar on Co-Processing of Alternative Fuels in Cement Pants, Cracow, Poland, 7 October 2015.
4. Radzięciak, T. 20 years of co-processing of alternative fuels in cement plants in Poland. In Proceedings of the 11th Seminar on Co-processing of Alternative Fuels in Cement Pants, Cracow, Poland, 7 October 2015.
5. Tumuluru, J.S.; Sokhansanj, S.; Hess, J.R.; Wright, C.T.; Boardman, R.D. A review on biomass torrefaction process and product properties for energy applications. *Biotechnology* **2011**, *7*, 384–401. [CrossRef]
6. Bergman, P.C.A.; Boersma, A.R.; Zwart, R.W.R.; Kiel, J.H.A. *Torrefaction of Biomass Co-Firing in Existing Coal-Fired Power Stations*; ECN Publication ECN-C-05-013: Petten, The Netherlands, 2005.
7. Stępień, P.; Pulka, P.; Serowik, M.; Białowiec, A. Thermogravimetric and Calorimetric Characteristics of Alternative Fuel in Terms of Its Use in Low-Temperature Pyrolysis. *Waste Biomass Valoriz.* **2018**, *8*, 1–9. [CrossRef]
8. Statistics Poland, Farm Animals in 2017. Available online: https://stat.gov.pl/files/gfx/portalinformacyjny/pl/defaultaktualnosci/5508/6/18/1/zwierzeta_gospodarskie_w_2017_roku.pdf (accessed on 15 April 2019).
9. Pulka, J.; Manczarski, P.; Koziel, J.A.; Bialowiec, A. Torrefaction of sewage sludge: Kinetics and fuel properties of biochars. *Energies* **2019**, *12*, 565. [CrossRef]
10. Stegenta, S.; Sobieraj, K.; Pilarski, G.; Koziel, J.A.; Bialowiec, A. The spatial and temporal distribution of process gases within the biowaste compost. *Data* **2019**, *4*, 37. [CrossRef]