# The Evaluation of Energy Consumption in Transportation and Processing of Municipal Waste for Recovery in A Waste-To-Energy Plant A Case Study of Poland

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# Abstract

Refuse-derived fuel (RDF) can be produced from combustible materials contained in municipal waste. After pre-treatment of waste it is possible shipping RDF a waste-to-energy plant (WtE). This article investigates energy and material flow of waste for different scenarios for production of RDF from bulky waste, separately collected waste, and mixed municipal solid waste (MSW). We compare the proportion of energy consumption in transportation, handling waste, and processing using data from the waste collection company in the South of Poland. The findings show the components of the reverse supply chain consuming the highest value of the energy.

A model of material and energy flow has taken into consideration collection of waste and transportation by two categories of waste collection vehicles light commercial vehicles and garbage trucks. The shipping of RDF from pre-treatment facility uses – tipper semi-trailers and walking floor trailers.

The findings of the study show production of RDF from municipal solid waste is consuming almost 10% of energy potential in RDF. Less energy is required for the production of RDF from bulky waste 2.2% – 4.8% or separately collected waste 1.7% – 4.1% depending on the efficiency of collection and selected vehicles. The transportation is consuming greatest portion of energy. For mixed municipal solid waste (MSW) it can reach 79%, for separated collection waste 90% and for bulky waste up to 92% of the total energy consumed. Comparing emissions for two categories of the collection vehicles there is no significant difference for the bulky waste collections. For mixed MSW and separately collected waste the emissions are higher for garbage trucks. As a recommendation for practitioners is optimization of routing to achieve higher collection rate for minimized route length. Transportation of RDF to WtE plant the vehicles with higher loading capacity are essential.


# 1. Introduction

Management of municipal solid waste (MSW) is a challenge on a local and global scale. Developing countries follow MSW collection and treatment experiences from developed countries (Malinauskaite et al. 2019, 2020). Also, in developed countries, more ambitious waste collection targets or minimization of landfills have been introduced (Coelho et al. 2020; Chand Malav et al. 2020). More demanding for individuals is the separation of waste into several categories. The waste generated from households has significant variations depending on the country, Gross Domestic Product, region, and other factors (Hoornweg and Bhada-Tata 2012). The composition of the residual or municipal waste can be also evaluated depending on the season of the year. It can indicate trends of consumption, behavioral patterns of residents, and volume of consumed goods (Zhou et al. 2014; Abdel-Shafy and Mansour 2018). Three main methods of treatment MSW are recycling, waste-to-energy (WtE), and landfill. For the circular economy approach, the least preferable method of MSW management is landfill. Other methods focus on the recovery of secondary raw materials or energy included in the waste. Recycling is common for materials like plastics, metals, glass, or paper. In countries where selective waste collection in households is obligatory i.e. the European Union (EU), these materials can be relatively easily extracted and recycled (European Commission 2018a). Waste management is much easier where selective collection systems existed for a long time because residents had time to learn proper waste disposal. Figure 1 shows Eurostat data of MSW fate for each European Union member (Eurostat 2021). Recycling – currently at 48% of the waste stream – is the preferred method for treatment MSW with a requirement to increase the target and landfill is supposed to decrease, although it is still the dominant method for Malta, Romania, Cyprus, or Greece. WtE is a popular method of processing waste in Scandinavian countries. Finland, Sweden, and Denmark recycle about 50% of MSW. A novel and improved regulations considering waste management were also introduced in Poland (Journal of Laws - Poland 2013). The number of landfills decreased. Several agglomerations decided to build WtE plants in various regions of Poland. MSW collection has been divided into several categories of waste like paper, plastics, glass, metal, bio-degradable waste, hazardous waste (waste electrical and electronic equipment), and bulky waste. Some other categories of waste require collection in specially designed containers, municipal collection centers, or on-demand collection.

Private or municipal collection companies provide waste collection. Waste collection companies provide a plan for households' collections. A selection of vehicles requires details of the type of roads and buildings in a collection area. The vehicles must be adapted for rural and urban communities to access each household. Many categories of waste are suitable for recycling. A significant fraction of the collected waste stream can also be used as refuse-derived fuel (RDF). WtE plants require high-quality RDF. It has to meet standards and not exceed allowed levels of contaminants. The waste must be pre-processed to achieve a homogenous fraction without unnecessary materials for the production of RDF.

Energy recovery in WtE plants can be achieved by various methods. Commonly used are municipal solid waste incinerators – combustion without pre-treatment, with energy recovery, co-incineration of waste with coal-fired power plants, and co-incineration of waste in cement kilns or RDF incinerators (Friege and Fendel 2011). Municipal solid waste incinerators mostly are designed for MSW processing without pre-treatment of the waste. Other WtE processes like the cement kilns require a pre-treatment and preparation of the required quality of the RDF including particle size and calorific value (Reza et al. 2013). WtE recovers the energy included in the secondary raw materials by combustion. The mixture of the secondary materials has variable calorific values. There are variations in the waste composition depending on the season, municipality, climate, population, economy, and other factors (Reza et al. 2013; Dianda and Munawar 2017).

Pre-treatment of waste requires several waste processing steps to achieve the required quality of the RDF. It incurs not only costs but also each activity needs energy for transportation and processing (Bhatt et al. 2021). Therefore, the reverse supply chain can be analyzed in the context of energy consumption required in the collection, transportation, handling, and processing of waste (Yousefloo and Babazadeh 2020; Hashemi 2021).

This study investigates energy consumption during waste collections from households, handling, pre-treatment of waste to produce RDF, and shipping to WtE plant – cement plant. To compare energy consumption for various categories of waste, we use an indicator of a proportion of energy required for transportation and waste processing related to the calorific value of RDF as a final product from a pre-treatment plant. A case study of Poland uses data from a waste collection company cooperating with a cement plant. The research aim is to evaluate energy consumption for transportation and processing of the waste and compare it with the total energy potential of RDF. A comparison includes three categories of household waste: bulky waste, municipal solid waste, and separately collected waste. Each activity in the reverse supply chain requires energy for collection from households (fuel), handling of waste in the waste processing company's base (fuel), processing line (fuel, electricity), and finally shipping to the WtE plant by heavy-duty trucks (fuel). The study explores a selection of two categories of vehicles for waste collection – light commercial vehicles (LCV) and garbage trucks (GT). A comparison includes also two categories of vehicles for the shipment of RDF from pre-treatment plant to cement plant – Tipper Semi-Trailer (TST) and Walking Floor Trailer (WFT). For each category of waste laboratory tests of calorific values of RDF samples have been made. It was required for the calculation of the reference value of energy potential in one shipment unit of RDF. We examined the proportion of energy for each process that is consumed for the production of RDF and vehicles' emissions in the households' collection phase. The results are useful for practitioners and decision-makers for the selection of suitable vehicles for the collection and potential methods for the reduction of energy consumption and emissions by a selection of vehicle type, route, or collection schedules optimization.

## 2. Material And Methods

The collection of waste and production of RDF may be complex and usually includes several steps. A goal is to produce homogenous material without substances or other categories of waste unsuitable for combustion. The first step is household waste collection. The requirements of regulations in Poland assume containers, bins, or containers should be placed in front of the property to allow a collection company to conveniently pick up the waste. Depending on housing type and access roads a collection company must use suitable vehicles. In narrow streets or residential access in a block of flats area, large trucks have difficulties in moving, therefore smaller vehicle types are necessary. After collection, a vehicle must unload the waste. After unloading a waste handling machine upload the waste onto the processing line for removal of unnecessary objects, other waste categories unsuitable for combustion, and hazardous materials. The remaining material for the production of RDF is shredded into small particles and is loaded onto a heavy goods vehicle (HGV) for shipping to the WtE plant. Material and energy flow analyses are useful to identify a volume or mass of collected waste and power requirements – as energy consumption for each process (Rotter et al. 2004). The main concept of our study is presented in Figure 2.

The calorific value of produced RDF is the reference value of energy potential. The tests of calorific values complied with PN-EN 15403:2011 standard – (Solid recovered fuels — Determination of ash content. The calculated calorific value).

The case study is for the rural and urban communities in the South of Poland (Figure 3). The process starts with waste collection from households. The collection is for urban and rural communities. Various types of vehicles for the collection and shipping RDF to cement plant. The collection depends on the schedule and assigned plan of routing therefore the distances for a scheduled collection vary.

The collection vehicles’ routes are selected to access each household in the area. Two categories of vehicles have been compared in this study – a specially adapted LCV – Figure 4a, and a GT – Figure 4b, with a waste compacting capability. After a vehicle’s loading capacity is reached the vehicle has to unload in a pre-treatment facility. For the shipment of RDF from the pre-treatment facility two types of vehicles were selected for comparison in this research – Tipper Semi-Trailer (TST) - Figure 4d, and Walking Floor Trailer (WFT) Figure 4c. The vehicles for the collection and RDF shipment are shown in the Figure 4 including the handling machine for loading.

The separation of waste is a helpful method for selecting households' various waste categories depending on the main material. It helps to classify materials of categories having similar calorific values. In this process, output materials are fractions of combustible materials like plastics, paper, and cardboard. Other materials like glass or metal can be recycled. Another category of waste from households containing materials of high calorific value is textiles, wood, and furniture belonging to another waste stream – bulky waste (Fig. 5).

This study focuses on the estimation of energy consumption in the entire reverse supply chain of the bulky and MSW. The primary source of waste in households and the final destination is a WtE plant – the cement plant. This study estimates the energy consumption for waste collection, transportation, handling, processing, compacting, and shipping to a WtE plant - cement plant. The case study will focus on the separately collected waste stream – bulky waste and mixed MSW from municipalities in the Silesian region in the south of Poland.

The case study includes three categories of waste for collection, processing, and production of RDF (Fig. 6). For the collection of the bulky waste and separately collected waste specially adapted LCV with a cage can be used. Another vehicle is a GT with a waste compacting capability. The GT is also used in the collection of MSW. The calorific value of diesel is 37 MJ/l (National Statistics UK 2021).

After traveling to a waste processing company the vehicles unload collected waste ant it is transferred into a shredder. The processing of bulky waste is simple. Bulky waste comprises furniture, large garden equipment, upholstery, carpets, and various kinds of wood including chipboards and fiberboards. In a processing facility, a diesel engine mobile shredder with a magnetic separator is used for processing the waste. Approximately 90 percent of the mass of bulky waste is suitable for the production of RDF.

Calorific value RDF produced that way is higher when the fraction of polymers is higher than a wood-related fraction. MSW has a lower calorific value and includes many fractions and impurities that require to be removed from the waste stream (Zhou et al. 2014; Dianda and Munawar 2017). The second scenario is for the production of RDF from mixed MSW. GT with waste compacting capability is used for routing in communities for the collection of waste. The fuel consumption for GT is 30 liters per 100 km. The processing is much more complex compared to bulky waste. In this scenario after unloading the waste-collecting truck – the hydraulic grip waste loading machine fills the bunker with the MSW. At the first stage after passing the bag opener, the Trommel screen removes fine fractions from the waste stream. Then a belt conveyor transfers the waste onto two-stage shredding machines including preliminary and secondary shredding. A magnetic separator is installed for removing ferromagnetic parts other than the RDF fraction. Finally, a wind shifter is used for the efficient removal of plastics, film and foils, cardboard, and paper from screened overflow particles. The percentage of fraction

In the third scenario separately collected waste enters the processing facility. The separation of waste is at the first stage focus on recycling materials, a lower quality fraction of polymers and other mixed materials from the separately collected waste goes through sorting on a conveyor. Optical, magnetic, and pneumatic sorting methods are applied in the facility. Approximately 60 percent of the waste stream is processed as RDF.

The final transportation of RDF to the WtE plant is by using large trucks with a trailer. Commonly used vehicles are TST and WFT. Processed RDF is loaded and shipped to WtE – the cement plant located 100 km from the RDF pre-treatment facility.

Depending on the category of waste several operations are required to achieve purity of the material and fraction size. In this case, the power supply and several processing machines and conveyors have the main impact on energy consumption per weight of the processed waste. Finally, loading the RDF and shipping to the WtE plant are the last energy-consuming processes evaluated in this study. The waste transportation company can select different types of vehicles. In Formula (1) energy required for the collection, handling, processing, and transportation of waste is expressed as $E_c$ in MJ per reference mass unit (RMU). Reference mass unit is calculated as the mass of RDF per one shipment to WtE multiplied by the calorific value of RDF. The calorific value depends on the category of waste from three scenarios. The coefficient of energy consumed for the production of RDF concerning energy for recovery in one total load of RDF can be expressed as $E_{loss}$ in formula 1.

Energy consumption of fuel and electricity in transportation and processing of waste can be calculated from the formula:

$E_{loss} = E_C/E_{RMU}$ [%] (1)

where: $E_{mru}$ – is the calorific value of reference mass of RDF and $E_C$ is the energy required for transportation, handling, and processing waste to produce RDF. $E_C$ is energy from fuel combustion in vehicles and electric energy required in the processing (conveyors, shredders, separators, etc.). It is expressed as MJ per reference mass unit (mass of RDF in one shipment).

$E_C = E_{col} + E_{proc} + E_h + E_t$ [MJ/rmu] (2)

where:

$E_{col}$ – the calorific value of fuel in waste collection and transportation,

$E_{proc}$ – the calorific value of fuel or electric energy consumption in processing of waste

$E_h$ – the calorific value of fuel in handling and loading machines in waste processing plant

$E_t$ – the calorific value of fuel in RDF transportation to the WtE plant

All values are converted to MJ/rmu (reference mass unit) – one shipment to the WtE plant.

The study evaluates also the environmental burden of emissions in the transportation phase of the waste collection. For the comparison of emission for three scenarios, the research includes NOx, PM, CO, and $CO_2$ and data from HBEFA emissions database (Keller and Wüthrich 2014).

# 3. Results

The reference value for a shipment of RDF from the processing facility to a cement plant depends on the loaded mass of the material and the calorific value. Table 1 includes results of laboratory tests of waste fraction for three categories of waste. The calorific value of the samples is the highest for separately collected waste – 29,800 kJ/kg because a high proportion of the shredded material are polymers. The bulky waste sample of processed RDF is 22.8 MJ/kg and the lowest calorific value RDF – 20.1 MJ/kg is for RDF produced from MSW. The values shown in Table 1 are used in calculations to evaluate energy potential in the RMU. The mass reference unit is a total mass of one shipment for a heavy-duty vehicle from a waste processing plant to a cement plant calculated from the data collected from a waste collection and transportation company in the South of Poland.

Table 1
Results of sample analysis of RDF Gross Calorific Value

| Waste category | Chloride | Sulphur | Carbon | Ash | Gross Calorific Value |
|---|---|---|---|---|---|
| Bulky waste | 0.58% | 0.12% | 53% | 21% | 22.8 MJ/kg |
| Municipal solid waste | 0.5% | <0.1% | 51% | 15% | 20.1 MJ/kg |
| Separately collected waste (main fraction plastics, paper) | 0.5% | <0.1% | 69% | 13% | 29.8 MJ/kg |

The collected mass for three categories of waste using LCV and GT has some differences depending on the location of the communities and distances from the waste processing facility where the vehicles must unload. For some urban communities, the collection allows to fully load a vehicle and return to a company’s base traveling a shorter distance. In rural areas, a vehicle must travel a much longer route to collect a similar mass of waste.

The calculations of total fuel consumed in waste collections include variations for the categories of waste and the type of vehicles used in the urban and rural collections. Table 2 shows the results of scheduled routes for the collection of three categories of waste. These values are used for the calculation of energy consumed for the collection of the mass of waste for the production of RDF for one shipment.

Table 2
Examples of waste collections parameters for urban and rural communities

| **Category of waste** | **Mass of waste in collection** | **Distance for routes of communities close to company's base** | **Mass of waste in collection** | **Distance for routes of remote communities** |
|---|---|---|---|---|
| | [t] | [km] | [t] | [km] |
| **Garbage truck (GT)** | | | | |
| Bulky waste | 12.5 | 62 | 17.5 | 189 |
| Municipal solid waste | 8.8 | 79 | 8.7 | 121 |
| Separately collected waste | 4.5 | 60 | 8.5 | 188 |
| **Light commercial vehicle (LCV)** | | | | |
| Bulky waste | 3.2 | 110 | 2.5 | 183 |
| Separately collected waste | 2.9 | 112 | 4.9 | 169 |

Table 3 shows the results for the energy consumption for each process of production of RDF. Each scenario has several variants. The bulky waste collection uses LCV like vans with special cage construction (Fig. 4a) to increase the number of loaded waste. Another vehicles used for the collection are GT. The results show more beneficial use of GT than LCV in the context of energy consumption. The difference is not significant because a lower mass of collected bulky waste by LCV is compensated by lower fuel consumption than by GT. In addition, higher capacity heavy goods vehicle like or walking floor trailer for RDF shipment to the WtE plant is more profitable. Although fuel consumption is 34 liters per 100 km for this vehicle compared to 27 liters per 100 km, including TST vehicle the difference in a fully-loaded vehicle is 5 tones per shipment.

MSW requires much more energy for processing and transportation in the collection phase. As from the mixed MSW fraction only, approximately 30-35% of the waste mass can be processed for the production of RDF. Therefore, the distance traveled to collect MSW and needs more fuel and the volume of waste for processing requires much more energy than the simpler line for processing bulky waste.

Table 3

Results of energy consumption in transportation, handling, and processing of the bulky, MSW, and separately collected waste for various transportation modes.

| **Scenario – collection vehicle type** | **Average mass of waste in collection [t]** | **Traveled distance per working day [km]** | **$E_{col}$ [MJ/RMU]** | **$E_{proc}$ [MJ/RMU]** | **$E_h$ [MJ/RMU]** | **$E_t$ [MJ/RMU]** | **Type of vehicle and calorific value [MJ/RMU] of RDF in one shipment. Average load of RDF: TST – 5 [t]; WFT – 12 [t];** | **Total energy consumption for all processes. As [%] of virgin calorific value of RDF** |
|---|---|---|---|---|---|---|---|---|
| **Collection of bulky waste** | | | **Calculated per mass of full load depending on a type of heavy goods vehicle** | | | | | |
| 1 - LCV | 2.2-3.2 | 70 - 170 | 440 – 1080 * <br> 690 – 1680 ** | 234 | 315 | 3110 | TST – 110 000 | 3.7% - 4.3% <br> 3.9% - 4.8% |
| 2 - LCV | 2.2-3.2 | 70 - 170 | 1040 – 2520 * <br> 1660 – 4040** | 560 | 756 | 3920 | WFT – 264 000 | 2.3% - 2.9% <br> 2.6% - 3.5% |
| 3 - GT | 12 - 17 | 70 - 170 | 250 – 605 * <br> 580 – 1410 ** | 234 | 315 | 3110 | TST – 110 000 | 3.5% - 3.9% <br> 3.8% - 4.6% |
| 4 - GT | 12 - 17 | 70 - 170 | 580 – 1410 * <br> 1410 – 3430** | 560 | 756 | 3920 | WFT – 264 000 | 2.2% - 2.5% <br> 2.5% - 3.3% |
| **Collection of municipal solid waste** | | | **Calculated per mass of full load depending on a type of heavy goods vehicle** | | | | | |
| 5 - GT | 6 - 12 | 60 - 110 | 540-1300 * <br> 1620-3900 ** | 2700 | 430 | 3110 | TST – 105 000 | 6,4% - 7.2% <br> 7.4% - 9.6% |

| |
|---|
| *- maximal load – more efficient related to the traveled distance |
| **- minimal load – less efficient related to the traveled distance |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 6 - GT | 6 - 12 | 60 - 110 | 1620-3880 * <br><br> 3700-9070 ** | 6480 | 950 | 3920 | WFT – 241 000 | 5.4% - 6.3% <br><br> 6.3% - 8.5% |
| **Separately collected waste** | | | **Calculated per mass of full load depending on a type of heavy goods vehicle** | | | | | |
| 1 - LCV | 2.9-4.2 | 60 - 180 | 670 – 760 * <br><br> 1250 – 1580** | 1050 | 430 | 3110 | TST – 149 000 | 3.5%-3.6% <br><br> 3.9%-4.1% |
| 2 - LCV | 2.9-4.2 | 60 - 180 | 1600 – 1830 * <br><br> 3000 – 3790** | 2500 | 950 | 3920 | WFT – 357 600 | 1.7%-1.8% <br><br> 2.9%-3.1% |
| 3 - GT | 4.2 – 4.9 | 60 - 180 | 1370 – 1590 * <br><br> 580 – 1980 ** | 1050 | 430 | 3110 | TST – 149 000 | 2.5% - 2.6 % <br><br> 2.9% - 3.1% |
| 4 - GT | 4.2 – 4.9 | 60 - 180 | 3300 – 3820 * <br><br> 1980 – 5020 ** | 2500 | 950 | 3920 | WFT – 357 600 | 2.9% - 3.1% <br><br> 2.6% - 3.5% |
| *- maximal load – more efficient related to the traveled distance | | | | | | | | |
| **- minimal load – less efficient related to the traveled distance | | | | | | | | |

For the collections of bulky waste (Figure 8), the main contributing factor is the energy consumption of the shipment to the cement plant. The processing and handling consume only a fraction of energy not exceeding 8%. For the collections of bulky waste with minimal load, the energy consumption reaches 32% for LCV, for GT the energy consumption is even higher than for transportation of RDF to cement plant. It indicates the necessity for better route planning for the vehicles or adaptation of collection schedules.

The collection stage for mixed MSW is the least energy-consuming component in the RDF production chain when collection vehicles' routes are efficient. Although, it becomes very significant in a case when vehicles travel long routes and collect minimal load. In this case, the processing contributes to 18% of the total energy consumption (Figure 9).

Figures 7-9 show the transportation is the most energy-consuming process for all categories of waste included in this study. The fuel consumption in waste collections and transportation of RDF to cement plant reaches above 85% for separated collection and bulky waste, and from 54% – 79% for mixed municipal waste of the total energy needed for the production of the RDF.

The environmental impact was evaluated for averaged distances for both categories of vehicles used in the waste collection phase. Figure 10 shows four selected emission factors – carbon monoxide (CO), carbon dioxide ($CO_2$), nitrogen oxides (NOx), and particulate matters (PM) for the three scenarios of waste collections and two categories of vehicles LCV and GT. The reference value of the output mass is 1 ton of RDF in this Figure. For bulky waste collections, the emissions are similar for both categories of vehicles. For other categories of the waste contribution of GT in emissions is higher. The only exception is carbon dioxide. In this case, the emission levels do not exceed 25%. On an operational level – the waste collection is the only component of the reverse supply chain with the possibility of major changes. Waste collection companies can use the results to optimize route planning, frequency of schedules, selecting different vehicles, or even considering purchasing new low emission collection vehicles.

## 4. Discussion

One of the possible choices for municipal waste is WtE. Energy recovery by combustion of municipal solid waste or RDF became popular and necessary for various regions in the world including developing countries in various regions in Asia (Mani 2020; Chand Malav et al. 2020) and Latin America (Coelho et al. 2020; Reis Neto 2021). Reduction of energy consumption in industry is one of the priorities of the EU. The energy efficiency Directive was introduced in 2012 and amended in 2018 (European Commission 2018b). Case studies presented in researches indicate the necessity of energy reduction in Italy and the UK (Malinauskaite et al. 2019), and in Slovenia, and Spain (Malinauskaite et al. 2020). This research is addressed to investigate energy consumption in each component of the reverse supply chain. The case study presents the production of RDF from three categories of municipal waste and shipping to a cement plant.

The selection of the most suitable method and technology for the production of RDF depends on the structure of the reverse supply chain. Waste collection requires the selection of vehicles and adequate processing technology in waste pre-treatment plants (Mukherjee et al. 2020). A location of a plant where RDF can be recovered is a final task in the design of a reverse supply chain structure (Nevrlý et al. 2019). This task is similar for RDF and other categories of waste like end-of-life tires (Creazza et al. 2012), or waste electrical and electronic equipment (Marinello and Gamberini 2021). Broader research considering WtE and RDF–related subjects can focus on environmental aspects, economic analysis, or material flow analysis (Tabasová et al. 2012; Põldnurk 2015). Although some studies covered LCA analysis considering reverse supply chain including emissions in waste collection (Larsen et al. 2009; Malijonyte 2016), our research focuses on the analysis of the energy flow in the three categories of municipal waste.

Evaluation of the existing reverse supply chain of RDF proposed in this study uses energy consumption for each process in the reverse supply chain of RDF. This method allows us to identify the component of a supply chain that consumes the most energy. The proposed method can help in decision-making on the managerial level for practitioners to modify energy-consuming parameters of the existing or inefficient logistic chain.

The findings of this study show the difference of variants of vehicle selection for waste and RDF transportation. Mixed MSW collection, processing, and transportation consume the highest proportion of energy compared to the energy potential of RDF produced from this category. The reason is that only 30-35% of the total mass of collected waste is suitable as RDF. Therefore up to 9.6% of RDF energy potential is consumed in the collection, handling, processing, and shipping of the waste to the cement plant. For bulky waste, it is only between 3.3% – 4.6%. For Separately collected waste is between 1.7% - 4.1%.

Comparing the contribution of each process: waste collection, handling, waste processing and final transportation – the majority of energy consumption is for transportation. It includes collection from households and transportation from waste pre-treatment facility to final destination in cement plant. In total, more than 85% of energy consumption is in the collection of waste and transportation of RDF to WtE plant for bulky and waste from the separated collection. For mixed municipal waste, the proportion of transportation of the energy consumed in the reverse supply chain of RDF is from 54%-79%.

The results show the high importance of vehicles selection. For the transportation of RDF, vehicles with maximal loading capacity should be applied. Higher fuel consumption and longer loading of walking floor trailers are compensated by a much higher mass of RDF due to the properties of the shredded fractions and the possibility of compressing RDF in WFT vehicles. The final shipment of the RDF is the most efficient by using vehicles with high capacity. It is the only parameter to be improved because the location of the waste collection or processing plant and the distance to the cement plant is fixed. The most profitable method of collecting waste from households is by waste compacting GT.

Several studies applied various models for the minimization of energy consumption and improving the performance of transportation concerning environmental and social criteria (Mostafayi Darmian et al. 2020; Cao et al. 2021; Bavaghar Zaeimi and Abbas Rassafi 2021). The results of the study show importance not only for shorter routes but also for higher mass of waste collected. To improve this factor the managers of waste collection companies should consider revision and verification of the schedules and timing of the collections (Hannan et al. 2018). For some areas where the collected mass of waste is low – the frequency of the collections should be decreased.

The emission factor is one of the environmental burdens in the waste collections especially as one of the contributors to decreasing air quality. Koç et al. investigate pollution routing problem emissions based on a hybrid evolutionary algorithm. The results show the benefits of using a heterogeneous fleet of vehicles over a homogenous fleet (Koç et al. 2014). Hasemi proposes a fuzzy multi-objective optimization model for municipal waste collection. Maimoun discusses waste collection vehicles emissions in a case study of the USA (Maimoun et al. 2013). The transportation of RDF to WtE is on a fixed route and it is difficult to minimize emissions but the collection phase is a contributor where route optimizing can be performed (Markov et al. 2016; Asefi et al. 2019). To lower energy consumption by a selection of appropriate heavy-duty vehicles for transportation of waste. The recommended solution is to select a low-fuel-consuming vehicle with the highest loading capacity.

The results will be useful for the evaluation of the energy potential of RDF compared to the energy required for collection and processing the waste. As possible, recommendations would be a reconfiguration of the reverse supply chain, including using different vehicles and technologies for waste processing and handling. Additional parameters including operational costs like fuel, vehicle use, employees, etc. can be included as a future work – multi-criteria analysis. The calorific value of RDF and the energy consumption in transportation, processing, and handling are objective measures independent of the above–mentioned parameters.

# 5. Conclusions

The study investigated the reverse supply chain of RDF in a case study of a logistic network in Poland. A model of material and energy flow takes into consideration the collection of waste and transportation by two categories of vehicles – LCV and GT. The calculations included energy consumption in handling and pre-treatment of waste in facilities for the production of RDF. The last process examined in this study was the transportation of RDF to the WtE plant – cement plant. The study included three scenarios for bulky waste, separated collection waste, and mixed municipal waste. A reference value was the energy potential of the shipping unit – TST and WFT. Each of the four investigated activities: waste collection, material handling, pre-treatment of waste, and shipping of RDF to WtE consumes energy. It is a portion of the energy required for the production and transportation of RDF.

The findings of the study show production of RDF from municipal solid waste consumes almost 10% of the energy potential in RDF. Less energy is required for the production of RDF from bulky waste 2.2% – 4.8% or separated collection waste 1.7% – 4.1% depending on the efficiency of collection and selected vehicles. A comparison of the processes in the reverse supply chain – transportation, waste pre-treatment, and handling indicates the transportation is consuming the highest portion of energy. For mixed MSW the energy consumption reaches 79%, for separately collected waste up to 90%, and bulky waste up to 92% of the total energy consumed.

Comparing emissions for two categories of the collection vehicles – LCV and GT there is no significant difference for the bulky waste collections. For mixed MSW and separately collected waste, the emissions are higher for GT.

A recommendation for practitioners is the optimization of routing to achieve a higher collection rate for minimized route length. For municipalities with low collection rates, it is important to schedule a less frequent waste pick-up. Vehicles with a higher loading capacity are essential for the RDF to the WtE plant.

Future work will include multi-criteria modeling including findings of this study and other factors having an influence on the efficiency of transportation and processing of waste for RDF. Different categories of vehicles, including electric-powered, can give some additional data for the managers from waste collection companies and practitioners responsible for the design of the reverse supply chain.

# Declarations

### Ethics approval and consent to participate

Not applicable

### Consent for publication

Not applicable

### Availability of data and materials

All data generated or analysed during this study are included in this published article

### Competing interests

The authors declare that they have no competing interests


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### Author contributions

Conceptualization: [Piotr Nowakowski], Methodology: [Piotr Nowakowski, Mariusz Wala], Formal analysis and investigation:[Piotr Nowakowski, Mariusz Wala], Writing - original draft preparation: [Piotr Nowakowski, Mariusz Wala]; Writing - review and editing: [Piotr Nowakowski], Resources: [Mariusz Wala, Piotr Nowakowski], Supervision: [Piotr Nowakowski]


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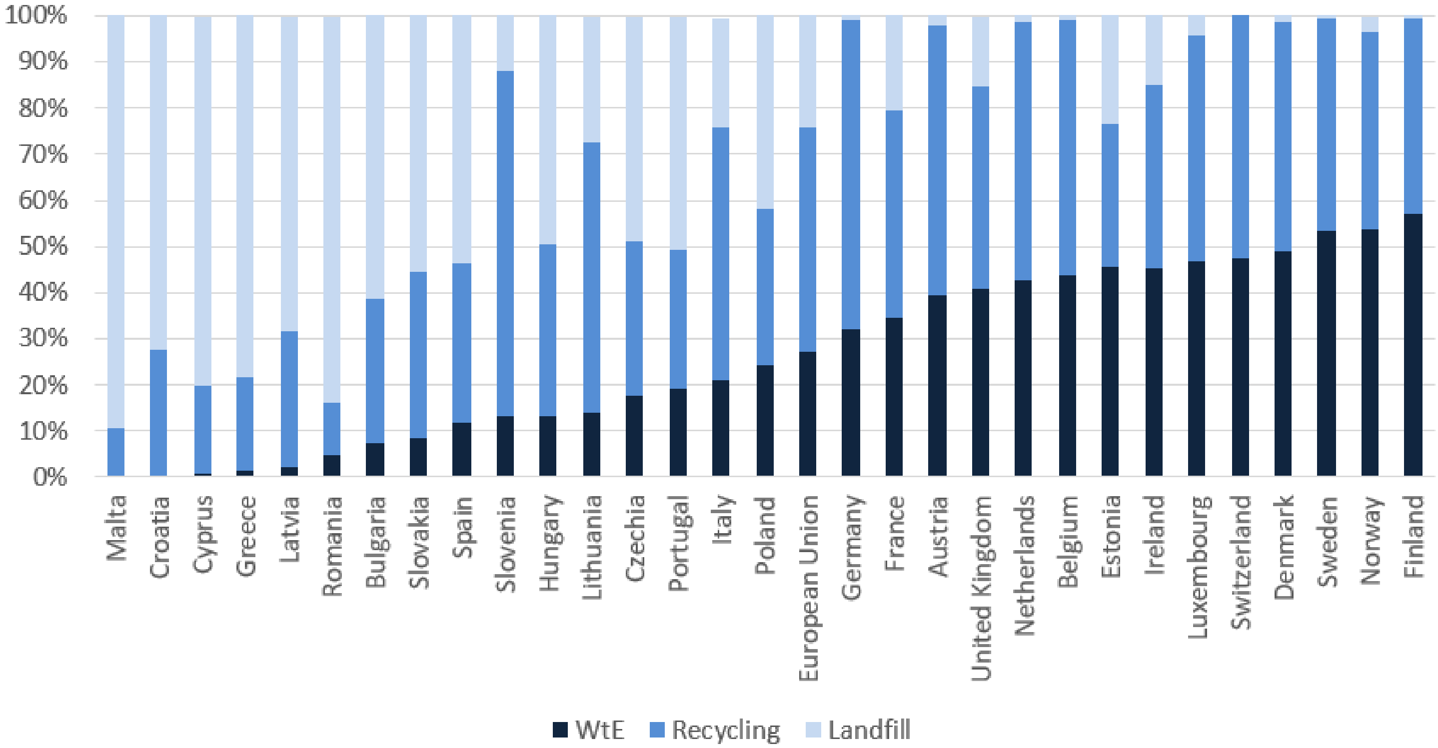
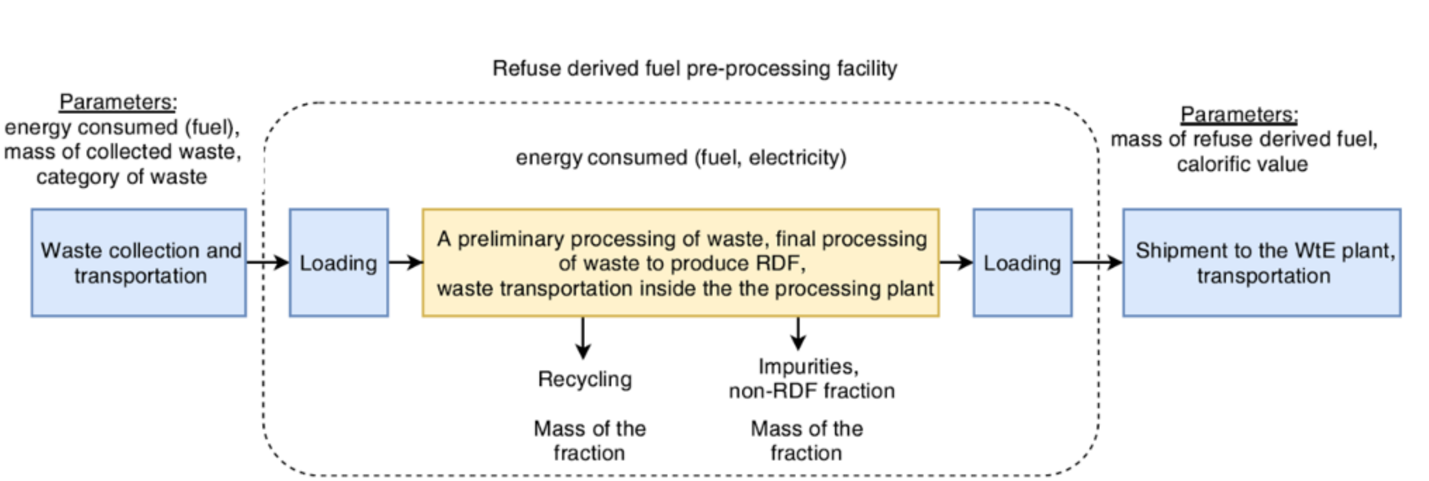
## Figures




## Figure 1

<p>Municipal waste management operations in the EU in 2018</p><p><br></p>




## Figure 2

<p>Generic material and energy flow in the collection, transportation, processing, and handling of waste.</p>

## Figure 3

<p>Map of urban and rural communities and location of waste pre-treatment plant in Poland</p>

## Figure 4

<p>Vehicles used in waste collection companies in Poland (a – LCV with special cage, b – garbage truck with compacting facility, c – WFT, and d – TST.</p>

**Figure 5**

<p>Collected bulky waste and RDF after processing of waste for shipping to WtE</p>

**Figure 6**

<p>Three scenarios of collection and processing for bulky waste and MSW</p><p><br></p>

**Figure 7**

<p>Distribution of energy consumption in collection, handling, processing, and transportation of RDF from separately collected waste</p>

**Figure 8**

<p>Distribution of energy consumption in collection, handling, processing and transportation of RDF from separately collected waste</p>

**Figure 9**

<p>Distribution of energy consumption in collection, handling, processing and transportation of RDF from municipal mixed solid waste</p>

**Figure 10**

<p>Emissions of carbon monoxide, carbon dioxide, nitrogen oxides, and Particulate Matters in the collection of waste for production 1 ton of RDF</p>