EFFECTIVE WASTE MANAGEMENT WITH EMPHASIS ON CIRCULAR ECONOMY

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. This article investigates energy and material flow of waste in 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 South Poland. The findings show the components of the reverse supply chain consuming the highest value of 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 facilities uses tipper semi-trailers and walking floor trailers. The findings of the study show production of RDF from municipal solid waste consumes 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. Transportation consumes the 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, no significant difference was found for the bulky waste collections. For mixed MSW and separately collected waste, the emissions are higher for garbage trucks. A recommendation for practitioners is optimization of routing to achieve a higher collection rate at a minimized route length. For transportation of RDF to WtE plants, vehicles with higher loading capacity are essential.

Keywords Waste transportation · Waste-to-energy · Refuse-derived fuel · Waste processing · Circular economy · Energy consumption · Calorific value of waste

Introduction
Management of municipal solid waste (MSW) is a challenge on a local and global scale. Developing countries follow MSW collection and treatment processes from developed countries (Malinauskaite et al. 2019, 2020). Also, in developed countries, more ambitious waste collection targets and 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. Household waste varies significantly depending on the country, gross domestic product (GDP), region, and other factors (Hoornweg and Bhada-Tata 2012). The composition of residual or municipal waste can also be evaluated depending on the season of the year. It can indicate trends of consumption, behavioural patterns of residents, and volume of consumed goods (Zhou et al. 2014; Abdel-Shafy and Mansour 2018). Three main methods of treatment of 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 commonly used for materials like plastics, metals, glass, or paper. In countries where selective waste collection in households is obligatory (i.e., in 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 have existed for a long time because residents have had time to learn proper waste disposal processes. Figure 1 shows Eurostat data of MSW fate for each European Union member (Eurostat 2021). Recycling, which currently makes up 48% of the waste stream, is the preferred method for treatment of MSW, with a requirement to increase the target and decrease landfill use, 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. Improved regulations considering waste management were also introduced in Poland (Journal of Laws - Poland 2013), and 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 such as paper, plastics, glass, metal, bio-degradable waste, hazardous waste (waste from electrical and electronic equipment), and bulky waste. Some other categories of waste require collection in specially designed containers, municipal collection centres, or by on-demand collection.

Private or municipal collection companies provide waste collection services. Waste collection companies provide a plan for households’ collections. A selection of vehicles requires details of the type of roads and buildings in a certain 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, which has to meet certain standards and not exceed allowed levels of contaminants. The waste must be pre-processed to achieve a homogeneous 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 are mostly designed for MSW processing without pre-treatment of the waste. Other WtE processes like the cement kilns require 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. The waste composition varies 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 each activity also 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).

**Fig. 1** Municipal waste management operations in the EU in 2018

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This study investigates energy consumption during waste collection 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). The comparison also includes 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 taken, which 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.

Material and methods

The collection of waste and production of RDF may be complex and usually involves several steps. One goal is to produce homogeneous 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 or bins 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 to roads, a collection company must use suitable vehicles. In narrow streets or residential access in a block of flats, large trucks have difficulties moving, therefore smaller vehicle types are necessary in these areas. After collection, a vehicle must unload the waste. After unloading, a waste-handling machine uploads 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 Fig. 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 and the calculated calorific value).

This case study is for the rural and urban communities in South Poland (Fig. 3). The process starts with waste collection from households. Various types of vehicles were used for the collection and shipping of RDF to a cement plant. The collection depends on the schedule and assigned

Fig. 2 Generic material and energy flow in the collection, transportation, processing, and handling of waste
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 (shown in Fig. 4a) and a GT (shown in Fig. 4b) with a waste compacting capability. Afterwards, 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: a tipper semi-trailer (TST) (shown in Fig. 4d) and a walking floor trailer (WFT) (shown in Fig. 4c). The vehicles for the collection and RDF shipment are shown in Fig. 4, including the handling machine for loading.

Waste collecting companies in Poland commonly use garbage trucks and light commercial vehicles. They are capable for the collections in urban and rural communities. Tipper semi-trailers and walking floor trailers are broadly used for transportation of RDF. Therefore, the results would apply to the majority of waste collecting and handling companies in Poland.

Waste separation 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 called bulky waste (Fig. 5).

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

The case study includes three categories of waste for collection, processing, and production of RDF (Fig. 6). For the collection of 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 and it is transferred to a shredder. The processing of bulky waste is simple. Bulky waste is composed of furniture, large garden equipment, upholstery, carpets, and various kinds of wood including chipboards and fibreboards. In a processing facility, a diesel engine mobile...
shredder with a magnetic separator is used for processing the waste. Approximately 90% of the mass of bulky waste is suitable for the production of RDF.

Calorific value RDF produced this 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 removal 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 a waste compaction capability is used for routing in communities for the collection of waste. The fuel consumption for GT is 30 L per 100 km. This processing is much more complex than that for 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, and then a conveyor belt transfers the waste onto two-stage shredding machines including preliminary and secondary shredding. A magnetic separator is installed for removing ferromagnetic parts aside from 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.

In the third scenario, separately collected waste enters the processing facility. The separation of waste in the first stage focuses on recycling materials, a lower quality fraction of polymers, and other mixed materials from the separately collected waste and sorting them on a conveyor belt. Optical, magnetic, and pneumatic sorting methods are applied in the facility. Approximately 60% 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 \( E_h \) in MJ per reference mass unit (RMU). Reference mass unit is calculated as the mass of RDF per one shipment to the WtE multiplied by the calorific value of RDF. The calorific value depends on the category of waste from the 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 \( E_{\text{loss}} \) in Formula 1.

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

\[
E_{\text{loss}} = \frac{E_C}{E_{\text{RMU}}} \quad \text{[\%]} \tag{1}
\]

where \( E_{\text{RMU}} \) is the calorific value of reference mass of RDF and \( E_C \) (2) is the energy required for transportation, handling, and processing waste to produce RDF. \( E_C \) is the 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).

\[
E_C = E_{\text{col}} + E_{\text{proc}} + E_h + E_t \quad \text{[MJ/RMU]} \tag{2}
\]

where:

\( E_{\text{col}} \) – the calorific value of fuel in waste collection and transportation,

\( E_{\text{proc}} \) – the calorific value of fuel or electric energy consumption in processing of waste

\( E_h \) – the calorific value of fuel for handling and loading machines in waste processing plant

\( E_t \) – the calorific value of fuel for RDF transportation to the WtE plant

All values are converted to MJ/RMU (reference mass unit) – single 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 CO2 and data from HBEFA emissions database (Keller and Wüthrich 2014).

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 the waste fraction for three categories of waste. The calorific value of the samples is the highest for separately collected waste (29.8 MJ/kg) because a high proportion of the shredded material is composed of 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, and is calculated from the data collected.
from a waste collection and transportation company in South Poland.

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 collection 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 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 amount of loaded waste. Another vehicle 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 for by lower fuel consumption than GT. In addition, higher capacity heavy goods vehicles like walking floor trailers for RDF shipment to the WtE plant are more profitable. Although fuel consumption is 34 L per 100 km, including TST vehicles, the difference in a fully-loaded vehicle is 5 tons per shipment.

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

Figure 7 shows the distribution of energy consumption for separately collected municipal waste. A process consuming the largest portion of energy for the most efficient collection phase is the transportation of produced RDF to the cement plant, which consumes about 60% of the total energy. For the collections with minimal load, the consumed energy reaches 32% for GT and 37% for LCV. It indicates the routes are long and the collection rate is insufficient.

For the collection of bulky waste (Fig. 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 collection of bulky waste with minimal load, the energy consumption reaches 32% for LCV, and for GT, the energy consumption is even higher than for transportation of RDF to the cement plant. This 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. However, it becomes very significant in cases where vehicles travel long routes

| Waste category | Chloride | Sulfur | 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           |

| Category of waste | Mass of waste in collection [t] | Vehicles routes’ length in communities close to company’s base [km] | Mass of waste in collection [t] | Vehicles routes’ length in remote communities [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 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 a collection [t] | Traveled distance per working day [km] | \( E_{\text{col}} \) [MJ/RMU] | \( E_{\text{proc}} \) [MJ/RMU] | \( E_{\text{h}} \) [MJ/RMU] | \( E_{\text{t}} \) [MJ/RMU] | Type of a vehicle and calorific value [MJ/RMU] of RDF in one shipment | As [%] of virgin calorific value of RDF |
|----------------------------------|------------------------------------------|----------------------------------------|-------------------------------|-------------------------------|-----------------|-----------------|-------------------------------------------------|---------------------------------|
| Collection of bulky waste       | 1—LCV 2.2–3.2                           | 70–170                                 | 440–1080 *690–1680 **         | 234                          | 315             | 3110            | TST – 110 000                                         | 3.7–4.3% 3.9–4.8%               |
|                                  | 1—LCV 2.2–3.2                           | 70–170                                 | 1040–2520 *1660–4040 **       | 560                          | 756             | 3920            | WFT – 264 000                                         | 2.3–2.9% 2.6–3.5%               |
|                                  | 1—GT 12–17                              | 70–170                                 | 250–605 *580–1410 **          | 234                          | 315             | 3110            | TST – 110 000                                         | 3.5–3.9% 3.8–4.6%               |
|                                  | 1—GT 12–17                              | 70–170                                 | 580–1410 *1410–3430 **        | 560                          | 756             | 3920            | WFT – 264 000                                         | 2.2–2.5% 2.5–3.3%               |
| Collection of municipal solid waste | 2—GT 6–12                              | 60–110                                 | 540–1300 *1620–3900 **      | 2700                         | 430             | 3110            | TST – 105 000                                         | 6.4–7.2% 7.4–9.6%               |
|                                  | 2—GT 6–12                              | 60–110                                 | 1620–3880 *3700–9070 **      | 6480                         | 950             | 3920            | WFT – 241 000                                         | 5.4–6.3% 6.3–8.5%               |
| Separately collected waste       | 3—LCV 2.9–4.2                           | 60–180                                 | 670–760 *1250–1580 **        | 1050                         | 430             | 3110            | TST – 149 000                                         | 3.5–3.6% 3.9–4.1%               |
|                                  | 3—LCV 2.9–4.2                           | 60–180                                 | 1600–1830 *3000–3790 **      | 2500                         | 950             | 3920            | WFT – 357 600                                         | 1.7–1.8% 2.9–3.1%               |
|                                  | 3—GT 4.2–4.9                            | 60–180                                 | 1370–1590 *580–1980 **       | 1050                         | 430             | 3110            | TST – 149 000                                         | 2.5–2.6% 2.9–3.1%               |
|                                  | 3—GT 4.2–4.9                            | 60–180                                 | 3300–3820 *1980–5020 **      | 2500                         | 950             | 3920            | WFT – 357 600                                         | 2.9–3.1% 2.6–3.5%               |

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

Fig. 7 Distribution of energy consumption in collection, handling, processing, and transportation of RDF from separately collected waste, a—LCV (maximal load), b—LCV (minimal load), c—GT (maximal load), d—GT (minimal load)
and collect minimal load. In this case, the processing contributes to 18% of the total energy consumption (Fig. 9).

Figures 7, 8, 9 show that 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 higher than 85% for separated collection and bulky waste, and 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 collection and two categories of vehicles, LCV and GT.

**Fig. 8** Distribution of energy consumption in collection, handling, processing and transportation of RDF from separately collected waste, a—LCV (maximal load), b—LCV (minimal load), c—GT (maximal load), d—GT (minimal load)

**Fig. 9** Distribution of energy consumption in collection, handling, processing and transportation of RDF from mixed MSW, a—GT (maximal load), b—GT (minimal load)

**Fig. 10** Emissions of carbon monoxide, carbon dioxide, nitrogen oxides, and particulate matters in the collection of waste for transportation and production 1 ton of RDF
The emission results show the values for Euro 5 standard vehicles. The vehicles meeting the requirements of Euro 3 and Euro 4 standards would have proportionally higher emissions. The transportation companies in Poland focus on replacement of the vehicles in the fleets to meet higher environmental and low emission requirements.

The reference value of the output mass is 1 ton of RDF in Fig. 10. For bulky waste collection, the emissions are similar for both categories of vehicles. For other categories, 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.

Discussion

One of the potential 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 research 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 addresses the need 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 (Nevrly 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 of 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 life cycle analysis (LCA) considering reverse supply chain, including emissions from 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 components 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 between 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 for this 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 and 4.6%. For separately collected waste, it is between 1.7 and 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 facilities to the final destination in the cement plant. In total, more than 85% of energy consumption is in the collection of waste and transportation of RDF to WtE plants for bulky waste 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 between 54 and 79%.

The results show the high importance of vehicle selection. For the transportation of RDF, vehicles with maximum loading capacity should be utilised. Higher fuel consumption and longer loading of walking floor trailers are compensated for by a much larger 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 and is the only parameter to be improved as 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 improvement of the performance of transportation concerning environmental and social criteria (Mostafayi Darmian et al. 2020; Cao et al. 2021; Bavaghar Zaeeimi and Abbas Rassafi 2021). The results of the study show the importance of not only 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 waste collection, especially as one of the contributors to decreasing air quality. Koç et al. investigate pollution from routing problem emissions based on a hybrid evolutionary algorithm. The results show the benefits of using a heterogeneous fleet of vehicles over a homogeneous fleet (Koç et al. 2014). Hasemi proposes a fuzzy multi-objective optimization model for municipal waste collection. Maimoun discusses waste collection vehicle emissions in a case study of the USA (Maimoun et al. 2013).

The emission factors contribute to lowering air quality, especially in densely populated towns and cities. In this case, a collection vehicle has multiple stops for waste pickup and emptying a bin or container. Therefore, the local contamination of air is harmful to residents in the nearby area.

The transportation of RDF to WtE is on a fixed route, and it is difficult to minimize emissions, but the collection phase is an example of where route optimization 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 of the waste. If possible, a recommendation 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, and employees can be included as a future project or 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.

Conclusions

This 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, or 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 units, 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, which 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 that transportation consumes the highest portion of energy. For mixed MSW, the energy consumption reaches 79%; for separately collected waste, 90%; and for 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 transportation of the RDF to the WtE plant.

Future work will include multi-criteria modelling, 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 vehicles, can provide some additional data for the managers of waste collection companies and practitioners responsible for the design of the reverse supply chain.

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Declarations

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