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RESEARCH ARTICLE

Spatial targeting evaluation of energy and environmental performance of waste-to-energy processing

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Abstract Waste-to-energy supply chains are important potential contributors to minimising the environmental impacts of municipal solid waste by reducing the amounts of waste sent to landfill, as well as the fossil fuel consumption and environmental footprints. Accounting for the spatial and transport properties of the waste-to-energy supply chains is crucial for understanding the problem and improving the supply chain designs. The most significant challenge is the distributed nature of the waste generation and the household energy demands. The current work proposes concepts and a procedure for targeting the size of the municipal solid waste collection zone as the first step in the waste-to-energy supply chains synthesis. The formulated concepts and the provided case study reveal trends of reducing the net greenhouse gas savings and energy recovery by increasing the collection zone size. Population density has a positive correlation with the greenhouse gas saving and energy recovery performance. For smaller zone size the energy recovery from waste approaches and in some cases may surpass the energy spent on waste transportation. The energy recovery and greenhouse gas savings remain significant even for collection zones as large as 200 km^2. The obtained trends are discussed and key directions for future work are proposed.

Keywords waste-to-energy, supply chain optimisation, GHG savings, energy recovery ratio

1 Introduction

Reducing pollution and especially the release of greenhouse gases (GHG) is an important goal in environmental protection and contribution to sustainable development. There are two main approaches to reducing GHG emissions. One involves direct CO_2 capture from flue gases [1] and its potential sequestration. Another way involves a set of measures for substituting the direct use of fossil fuels and the use of various options for minimising waste and waste of energy, aided by the integration of renewable energy sources into the energy systems [2]. Managing and treating municipal solid waste (MSW) [3] offers a reduction of waste and emissions, contributing to the methods of the second group.

MSW has a diverse and varying composition, as discussed by Fodor and Klemeš [3] in an analysis of available technologies that use waste as fuel. MSW contains a sizeable organic fraction, part of which is moist. For efficient processing of this waste, it is necessary to apply different technologies. For the higher-moisture fraction, anaerobic digestion is usually most suitable, while the dry fraction, when appropriately separated, can be incinerated alone or in a co-firing mode [4]. MSW management comprises a number of important activities. The overall management involves a number of steps: collecting the waste from the households or collection points in the neighbourhoods, transportation to transfer stations and/or processing facilities, waste processing — including sorting, separation, treatment, thermal treatment, anaerobic digestion, etc. For existing systems and plants, the planning of collection and transportation of MSW is a well-established problem [5]. Another comprehensive study has been formulated by Zhang et al. [6], considering the operational planning of a multi-echelon supply chain for MSW management. The proposed model minimises the system operating cost, which comprises terms for waste collection, transportation, intermediate waste storage, and processing — by incineration and landfilling. While the provided mathematical model for the supply chain is quite comprehensive and includes all essential stages in the

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system, it is cost-oriented, and emissions and footprints are not considered. Moreover, the scope of the model is limited to the operational planning of existing municipal systems.

Operational management of existing waste-to-energy (WtE) plants in Italy, accounting for sustainability requirements, has been analysed by Cucchiella et al. [7]. The paper proposes the development of a national waste management plan, where WtE processing plays a significant role. The authors emphasize on the synergistic benefits from the proposed strategy of environmentally-responsible management of the WtE facilities, where investment into emission control and minimisation also improves the financial performance of the systems. The results of the study point towards the necessity to locate WtE facilities close to the waste generation points, in order to reduce the emissions and costs due to transportation. In terms of optimising the structure and operation of solid waste supply chains, Xu et al. [8] have discussed the issue from the global perspective. They have considered the resulting GHG emissions within a wider scope, where supply chains deliver recovered materials to manufacturers worldwide. While the logistics and associated costs are part of the analysis, this work's scope does not include energy recovery from the organic fraction of the generated waste.

MSW is generated by households, which are distributed within city districts [9]. On the other hand, the most used types of MSW treatment facilities — including WtE, require processing sizeable amounts of waste, to be efficient. For instance, typical existing incinerators in Europe range from 90 to 500 kt/y MSW processing capacity [9]. This defines a problem for collection and transportation of the MSW to the processing plants. In supply chain management, this is known as "reverse logistics" [8]. Household energy demands are distributed in a similar way — pointing to an important pattern in supply chains for cities. WtE should be considered as one of several options for final treatment of waste, in competition with landfilling and the other methods in the waste management hierarchy [10]. That analytical work has considered, on the example of waste incineration in New York, various organisational and political factors that were driving the adoption of WtE during the 1990s. The substantial reduction of landfill area demands has been identified as a key reason given by the waste incineration proponents. This reasoning can be supported by a case study on the waste management optimisation for Malta [11]. An analysis study from the viewpoint of external cost [12] has also pointed out the simultaneous reduction of GHG emissions and costs resulting from WtE. This principle has also precipitated to policy-making documents, as can be seen on the example of the waste management and land use policy review by Environmental Services Training and Education Trust in the UK, considering WtE as one of the factors to achieve sustainability goals by reduction of land use.

It has been previously shown that distributed WtE treatment can be economically viable, including thermal waste treatment of e.g., sewage sludge [13]. Incineration is the most mature and widely practised WtE technology. For example, the Spittelau Waste Incineration Plant is one of the significant waste processing and energy conversion facilities in Vienna (Austria). However, such waste treatment plants are usually large, containing thermal treatment and off-gas cleaning facilities [14], both parts usually requiring substantial investment — up to 1000 €/$(\mathrm{t\cdot y^{-1}})$ — based on the capacity for waste treatment [15]. While the reasons for building mainly larger facilities are rooted in the need to achieve high efficiency of traditional waste incinerators, incineration is not the only option for energy recovery from waste. Moreover, combustion of waste materials inevitably results in the formation of unwanted side products, typical for thermal treatment, which could sometimes be avoided if the treatment was biological. Therefore, such large facilities are generally suitable only for highly centralised processing, while distributed treatment and energy generation using anaerobic digestion or gasification is usually left out, missing possibly more efficient waste treatment options, releasing less harmful emissions. A representative study on the waste management strategy in a developing country (Bangladesh) including WtE, has been published by Nazmul Islam [16]. That work evaluates the GHG emissions of existing and proposed MSW management schemes in Bangladesh, based on several scenarios. The considered system components include landfills with landfill gas recovery, WtE, as well as material recovery. The waste logistics is modelled by specifying a fixed average distance for transporting the waste within the system, set to 30 km, with an additional 20 km average distance for transporting further separated recyclable materials. While this modelling approach somehow accounts for the emissions and cost of waste transportation, it still does not address the emission-distance trade-off and the related level of centralisation or distribution of the treatment.

It is clear from the analysis that understanding clearly the key trends and trade-offs of municipal WtE supply chains is important for developing better design and planning methods. Longden et al. [9] have discussed the possible policy implications when trading-off distributed *vs.* centralised WtE systems. They applied a portfolio of criteria — including environmental. The study concluded that distributed, smaller-scale WtE facilities are rated more favourably by experts and that, from the viewpoint of policy impact, the scale of the facilities is more important than the choice of specific technologies. A procedure has been proposed by Tavares et al. [17] for identification of sites for placing MSW incineration plants, minimising a combination of economic, environmental, health, and social costs. The procedure has been designed for and applied to make this choice for an island of the Cape Verde archipelago. The defined elaborate portfolio of criteria and the ranking system have allowed arriving at well-justified decisions, minimising the cost and environmental impacts. The degree of energy or emission savings, however, are not quantified in this study.

Spatial development challenges are typical also for biomass-based energy supply systems. This is due to a similar reason — the distributed availability of MSW and biomass resources over wide areas. In this context, an interesting parallel can be made with a study evaluating the potential of biomass to satisfy the energy supply goals of Ireland by the year 2020 [18]. The biomass availability has been estimated from official statistical data and an optimisation supply-chain model has been set up, involving a number of energy conversion plants and a logistics network. The objective of the model is the minimisation of the global warming potential (GWP), subject to the material balances and satisfaction of the targeted energy demands. The model also accounts for the competition of wood processing plants for the harvested biomass. The analysis indicates that the measures for higher fossil fuel displacement rate result in more GHG emission reduction, while the measures maximising the use of biomass have less potential, pointing to the influence of the logistics on the overall outcome. An important step towards modelling the identified problem is the model for optimal allocation of capacities among waste generation areas and waste processing facilities [19], which also includes energy recovery from waste. The proposed optimisation model minimises an objective function, based on a weighted sum of the transportation distances for waste collection and delivery to the processing centres. However, this consideration still leaves open the question of the optimal sizes and collection areas of the WtE facilities, the potential for GHG emissions reduction and the possible energy recovery rates in relation to the size of the collection zone. In general, the approach for WtE studies has been to undertake comprehensive WtE modelling including waste transportation for specific cities and regions. This has the distinct advantage of providing a rigorous solution from which decisions can be implemented. However, the disadvantage is that these studies require significant amounts of time and resources. Providing a preliminary performance target for a WtE supply chain system before undertaking comprehensive modelling and design represents a gap in the current literature.

The aim of this study is to apply a new model for preliminary targeting of WtE supply chains. Using the performance targets, the trade-off between the emissions, energy and cost reduction resulting from the potential WtE implementation may be understood, allowing the consideration of lower-scale WtE facilities alongside the large-scale ones. The work builds upon the WtE targeting model proposed in [20] and extends it by providing a derivation of the underlying targeting model and then applies it to a case study based on a set of price data from official statistical sources and performance specifications derived from the literature. The evaluation scheme investigates the WtE supply chain performance for ranges of area and population sizes and two levels of population density, typical for Europe. The final segment of the study looks to clearly address the challenges posed by the waste logistics and directions for future research.

2 Model description

This section presents the targeting concepts, assumptions and the applied model, based on the initial idea of representing the waste sourcing area with an equivalent collection area of a circular shape, presented in [20]. The potential for GHG savings and energy recovery from MSW at urban scale can be performed at several levels. An elaborate optimisation can be performed for MSW supply chain design or planning. This requires supplying detailed data on the waste generation and collection locations, potential waste processing points — transfer stations or processing facilities locations, the amounts of waste generated, equipment performance and capital cost data, maintenance and operating costs, etc. While this activity is necessary at final design stages, it is resource and time intensive.

Setting performance targets prior to detailed analysis and design can provide an early indication of the profitability and possible emission rates of a proposed idea. Analogies to the targeting concept, for example, include Pinch Analysis where energy targets may be determined from thermodynamic analysis to provide guidance during a final design. In the present context of a WtE supply chain, targets for energy, cost and emissions for different system structures provide insight into the fundamental trade-off of between level of centralisation as well as the order of magnitude of the potential benefits. Based on the performance targets, a detailed assessment of the most promising areas can then be undertaken with greater confidence that the time and effort will yield a positive implementation.

2.1 Supply chain workflow

It is assumed that the typical procedure for waste collection and processing (Fig. 1) is applied, having several options for performing the activities at each stage. Within the context of WtE, the supply chain would have the following stages: (1) Processing. The waste generated by the serviced area is mandatory to be processed. (2) Separation and collection. The model assumes waste separation at the source. This can be implemented in various ways. One option is to use different collection bins. The resulting waste stream is collected and has several fractions suitable for combustion, anaerobic digestion and for landfill. It has to be pointed out that this practice is successful in countries

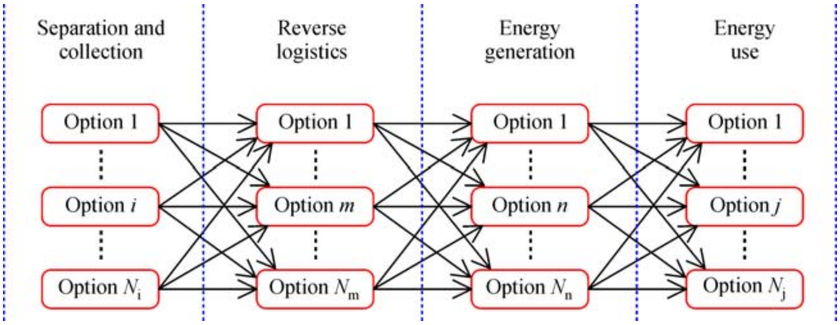

Fig. 1 WtE processing workflow (amended from [20])

as Germany [21] due to the well-formulated regulations, making the waste separation at source economically preferable. Due to the first assumption, failure to effect separation at source would only increase the cost of waste processing, which can be reflected by specifying a higher processing fee or tolerating smaller profit, depending on the final financial balance. (3) Reverse logistics [22]. This involves the transporting the waste to a processing plant or transfer station. This part results in a spatial optimisation problem for concentrating dispersed resources from a surrounding area — a typical task when optimising waste collection and renewable energy resources. (4) WtE. At this stage heat and power are generated from the usable organic and dry waste fractions. Because the goal of the current study is to evaluate how large can be the collection zone for a single WtE plant, in the current model, this is placed at a single location. (5) Energy distribution and use. It is important to realise that this energy substitutes fossil-based energy supply from conventional sources.

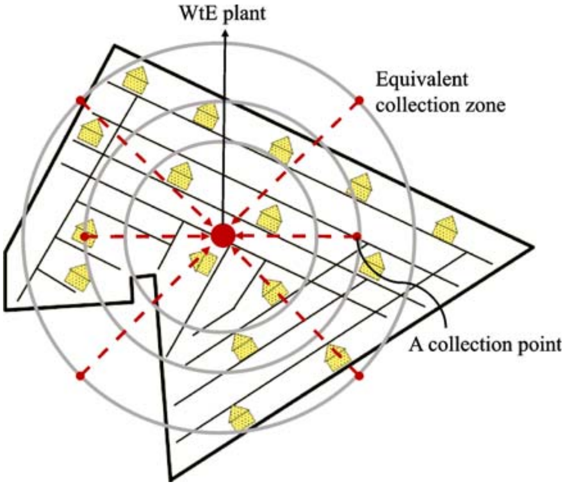

Fig. 2 The main modelling concept: approximating an actual collection zone (after Chalkias and Lasaridi [23]), with an equivalent collection zone (amended from [20])

2.2 Modelling concepts and model structure

The areas for waste collection generally are of different shapes, following the terrain and topology of the served settlements. One example is given in the work by Chalkias and Lasaridi [23] for a Greek town district. The WtE supply chain targeting model views the WtE conversion plant as the centre of the considered system. In Fig. 2, the actual collection zone is superimposed with a modelling circular-shape zone, approximating the area of the former. Following this modelling concept, the key input parameters to the proposed model are the number of inhabitants and the area that can be served by processing their waste and satisfying some of their energy demands.

In the actual districts served by the WtE plant, there can be various waste transportation routes. For obtaining the performance targets, the following approximations and modelling assumptions are adopted for the simplified plant-centric approach shown in Fig. 2: (1) A circular equivalent collection zone (ECZ) is considered (Fig. 2), with the same overall rate of waste generation, as the modelled district. It is also assumed that the waste generation is uniformly distributed over the equivalent circular area. The ECZ area may be based on the total area of an actual collection zone (district) such as the sketch in Fig. 2, providing the link to the equivalent circular representation. (2) The WtE plant is centrally located within the ECZ. For a given population size and waste collection area, the solution with the highest profit must minimise the average transportation distance. Positioning the WtE near the centre maximises the probability of achieving the minimum transportation distance. (3) The real waste collection and transportation paths are approximated with straight delivery paths from current points to the WtE plant, assuming that trucks start empty from the plant, pick-up the waste, and return fully to the WtE plant. In practice, trucks drive on the road network and so the length of each path is longer. As a result, the model includes a variable “β” — an additional transport distance performance coefficient — that estimates the ratio of actual to minimum transportation distance. The transportation costs and emissions are associated with the estimates of the travelled distance and fuel used. For more detailed and high-fidelity models, additional cost items and emissions will be necessary to add — such as those for investment and maintenance. (d) Elevation changes are assumed to offset each other out for up-hill and down-hill transportation and are neglected. This means that as a truck increases fuel consumption to travel up a hill, an approximately equivalent fuel saving is gained by coming back down the hill. This assumption should be adequate for cities located in flat regions, as well as for those which are located on more than one hill, which is the case for most sizeable urban settlements.

2.3 Separation and collection

This stage (Fig. 1) is modelled as a single operation. It applies the assumption of waste separation at the source (see 2.1 Supply chain workflow). As a result, the waste generated by the inhabitants represents the input to the modelling operation and there are three output streams: an organic waste fraction (OWF, digestible) — which can be treated e.g., by anaerobic digesters, a dry fraction (DF) suitable for incineration, and the remainder is a landfill fraction. The last should be appropriately treated before the disposal, to comply with landfilling regulations. An example of the main regulatory document for the European Union is the Directive 1999/31/EC [24]. In the current targeting model, any such treatment is assumed to be part of the landfill service.

2.4 Waste transportation

The overall waste transportation cost, *TC*, is modelled as a sum of waste transportation and handling items:

$$TC = C_{\mathrm{trans}} + C_{\mathrm{hand}}. \tag{1}$$

The unit cost of handling the waste is estimated using a constant handling fee:

$$C_{\mathrm{hand}} = \hat{c}_{\mathrm{hand}} \cdot m_{\mathrm{tot}}, \tag{2}$$

where $\hat{c}_{\mathrm{hand}}$ is the cost to handle 1 t of waste and m_{tot} is the total waste mass flow.

The cost of transporting the waste from the households to a central location is estimated based on an average transportation distance, d_{ave}:

$$C_{\mathrm{trans}} = p_{\mathrm{f}} \cdot d_{\mathrm{ave}} \cdot e_{\mathrm{t}} \cdot m_{\mathrm{tot}}, \tag{3}$$

where p_{f} is the price of the transport fuel and e_{t} is the average truck specific energy consumption on a *t* km basis.

Assuming the waste collection area may be estimated by a circular equivalent with the area, *A* (Fig. 2), the average distance travelled would be 2/3 of the ideal radius of the collection zone, *r*. However, waste collection trucks are unable to always travel the minimum distance. As a result, an additional transport distance performance coefficient (> 1), β, has been added.

$$d_{\mathrm{ave}} \approx \beta \cdot \frac{2}{3} r, \text{where } r = \sqrt{\frac{A}{\pi}}. \tag{4}$$

The value of coefficient β is a user specification, allowing to calibrate the targeting model to specific cases and terrain. Specifying $\beta = 1$ means that an ideal case would be assumed, where all trucks would travel exactly the average distance for the circle (equal to $\frac{2}{3}r$). Larger values (β>1) mean accounting for longer average distance. The value of this coefficient may be specified by the user within a range, performing a sensitivity analysis. Alternatively, it can be estimated using statistical data from supply chains or waste collection services in the considered specific areas.

For a known given total mass of waste, the circular equivalent collection area may be determined using their relationship as follows:

$$m_{\mathrm{tot}} = A \cdot P_{\mathrm{den}} \cdot \hat{m}_{\mathrm{w,gen}} \iff A = \frac{m_{\mathrm{tot}}}{P_{\mathrm{den}} \hat{m}_{\mathrm{w,gen}}}, \tag{5}$$

where P_{den} is the population density and $\hat{m}_{\mathrm{w,gen}}$ is the specific waste generation per individual.

After combining Eqs. (3–5), Eq. (6) is obtained after rearrangement:

$$C_{\mathrm{trans}} = \frac{2}{3\sqrt{\pi}} \cdot \beta \cdot e_{\mathrm{t}} \cdot p_{\mathrm{f}} \cdot P_{\mathrm{den}}^{-0.5} \cdot \hat{m}_{\mathrm{w,gen}}^{-0.5} \cdot m_{\mathrm{tot}}^{1.5}. \tag{6}$$

The total cost of transportation and handling is Eq. (6) plus Eq. (3):

$$TC = \frac{2}{3\sqrt{\pi}} \cdot \beta \cdot e_{\mathrm{t}} \cdot p_{\mathrm{f}} \cdot P_{\mathrm{den}}^{-0.5} \cdot \hat{m}_{\mathrm{w,gen}}^{-0.5} \cdot m_{\mathrm{tot}}^{1.5} + \hat{c}_{\mathrm{hand}} \cdot m_{\mathrm{tot}}. \tag{7}$$

The first term in Eq. (7) is the transportation function of the waste. It is assumed to be proportional to the product of total waste mass (m_{tot}) and the average distance between a collection point (Fig. 2) and the central processing hub. Following the ECZ representation, the average distance has been related to the square root of the collection area (Eq. (4)). In turn, based on the assumption for uniform distribution of waste generation over the ECZ, its area is related to the total mass flow of generated waste (Eq. (5)).

Combining these relationships results in the transportation cost term proportional to the waste mass flow to the power of 1.5. In addition, the term includes the energy use for transportation (e_{t}), the price of fuel (p_{f}), the population density (P_{den}), the waste generation rate per capita ($\acute{m}_{\mathrm{w,gen}}$), and targeting parameter β. When β is set at unity, Eq. (1) determines the absolute minimum cost of waste transportation. The meaning of $\beta = 1$ is that the transportation vehicles travel the minimum possible distance. This is useful for setting a theoretical lower bound on the transportation cost. For specific cases, however, it is not likely to be practical. The second part of Eq. (7) describes the waste handling. It has been assumed to be proportional to the flow of generated waste (m_{tot}) and the average unit cost of handling ($\hat{c}_{\mathrm{hand}}$). It is independent of the distance the waste needs to travel.

2.5 Energy generation and distribution, residual waste handling

Two WtE processing routes are considered: (a) anaerobic digestion, taking the OWF wet fraction of waste, produces biogas, which is used for combined heat and power (CHP) generation and (b) incineration, taking the DF (dry, combustible) fraction of waste, generating heat. The OWF flows are transported from the source locations to the WtE plant according to the described assumptions (2.2 Modelling concepts and model structure, Fig. 2). The biogas is passed to CHP units and the residues to landfill [25], where any further handling and treatment may also be applied — including composting. The produced heat and power flows are supplied to specified residential demands and any excess is sold onto the market. As an additional degree of freedom for energy conversion, an option for residential heat pumps is added to the model, for converting potential power excess to heat.

2.6 Model implementation

To solve the model, an optimisation tool is needed. From the available tools, P-graph was selected due to its simple interface and powerful combinatorial optimisation algorithms. These features make the tool suitable for simple process synthesis and especially for targeting models, which are inherently simple. P-graph is a combinatorial representation for process networks, complemented by efficient combinatorial algorithms. Previous implementations presented it as an effective tool for dealing with problems possessing high combinatorial complexity. It is possible to reduce the computational effort as the optimisation engine is based on the Accelerated Branch and Bound algorithm [26]. P-graph Studio is the software tool implementing the framework. For future implementations and for more detailed synthesis and design models, other process synthesis tools can be also used — including MipSyn [27] or a general mathematical programming environment, such as GAMS. However, the targeting model is implemented using the P-graph framework in P-graph studio due to the offered interface simplicity, streamlined modelling, and computational efficiency. The combination of all these factors has prevailed in the choice of tool.

The performance of each operating unit is specified by the user by means of conversion ratios between input and output streams. In the model implementation, the performance of the transport operations is specified as piece-wise linearised segments, derived from Eq. (7). This has been performed minimising the error between the linear segments and the curve, defined by Eq. (7). The GHG emissions from the transport are modelled as proportional to the travelled distance and waste mass flow. The efficiency targeting parameter β in Eq. (7) can be used for adjusting the transportation efficiency, as discussed at the end of section 2.5. Energy generation and distribution, residual waste handling. The further specifications include: (1) Number of inhabitants, commercial and institutional entities generating waste. (2) Required transport fuels and conventional energy sources prices and emission factors. (3) Waste composition in terms of an organic waste fraction, dry fraction, and landfill fraction. (4) Performance characteristics of the energy generation technologies, e.g., boilers and gas engines. (5) Association of the released GHG emissions with an emission levy, which adds to the system cost. Other types of emissions can be also quantified in detailed WtE process models — most notably potential toxins and particulates. This is especially important for incinerators.

The completed model is subjected to optimal process network synthesis minimising the total cost. The cost objective function is appropriate for the current setup of the model, as all emissions are also linked to the cost in a proportional way.

3 Case study

The concepts and the model have been implemented in a case study to evaluate the energy and environmental performance trends of the resulting system. Figure 3 represents the system superstructure as initial P-graph in P-graph studio. The considered factors include: (1) The ECZ size. It is specified in terms of population size as a number of inhabitants and then calculated to an equivalent area in (km^2). (2) Population density (inhabitants/km^2). Two levels of population density have been considered: 2500 and 5000 inhabitants/km^2, which are within the typical range for Europe. The population size has been varied between 20000 and 1000000 inhabitants for each of the levels of population density, to form ECZ sizes from 4 to 200 km^2. In this case study, it is assumed that trucks have to travel on average 50% longer distance than the minimum possible derived from the circular shape of the ECZ, which results in specifying the coefficient from Eq. (7) as $\beta = 1.5$. The waste generated by the population is processed to generate heat and power, to satisfy a portion of the total inhabitants' energy demands (Fig. 3, "Unit demand"). The waste composition and the generation rate by inhabitants have been specified based on official statistical data. According to Eurostat, the typical waste generated per inhabitant for EU is 476 kg/y, with the composition of 16.4% OWF, 26.5% DF, and 57.1% other.

It is assumed and specified in the superstructure that the waste is separated at the source (Fig. 3, Separation). The nominal fee for waste collection is set at 120 €/t waste, based on the EU-wide review by Branchini [28]. While the

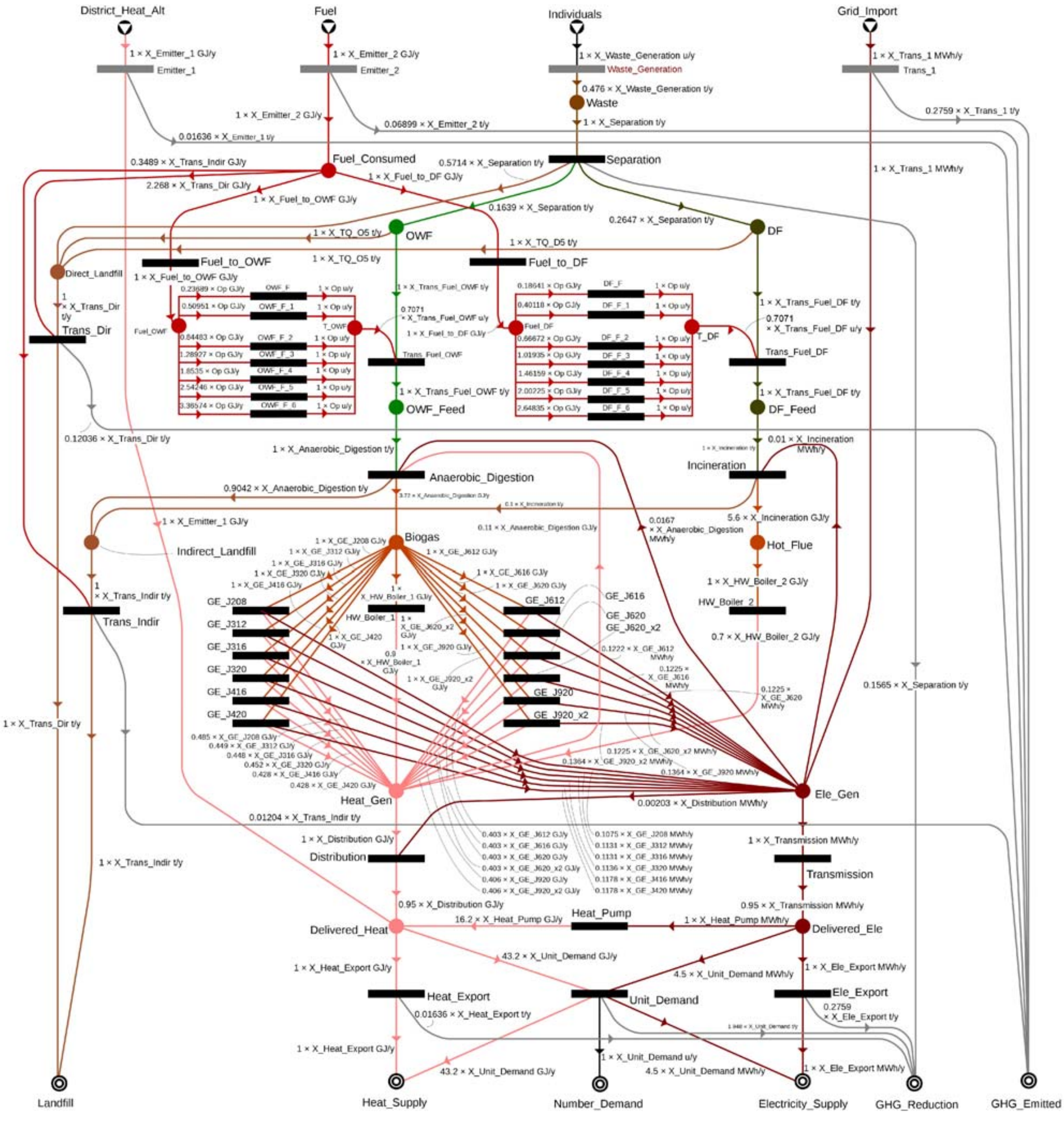

Fig. 3 A visual superstructure of the WtE problem in P-graph studio (amended from [20])

fee varies widely throughout the EU, the countries with higher values, above 100 €/t, tend to also to adhere to high levels of waste recycling and active management, while minimising the landfilling. For the evaluation, the fee variation does not influence the structure of the obtained optimal WtE networks. The reason is that all generated waste has to be processed by the system in one way or another. Once the waste is collected and the fee taken by the processor, this creates a fixed financial inflow. From there, any fraction of waste, directed to WtE, and any improvement in the efficiency of waste transportation and processing tends to reduce the associated costs and the resulting optimal point of minimum cost or maximum profit depends only on these factors, not on the waste collection fee.

The OWF and DF are transported to a central processing hub (Fig. 3, Waste transportation) with transport cost estimated based on the piece-wise linearisations of Eq. (1), assuming diesel fuel. The price of diesel is specified as 28.66 €/GJ and the transportation energy requirement as 0.2 GJ/(t·km) [29]. The remainder of the waste, not used for energy generation, follows the conventional path to treatment and landfill (Fig. 3). The landfill location is specified to be outside the city and ECZ bounds. The OWF is converted to biogas in anaerobic digesters (Fig. 3, Anaerobic digestion), with biogas output of 3.72 GJ/t of OWF [30] and the dry fraction was incinerated, generating useful heat. The biogas may be fed to any of the 10 optional CHP gas engines, of type “Jenbacher type 3” and/or to a boiler with an overall efficiency of 90% (Fig. 3, GE J… entries and HW Boiler 1). The estimated gas engine performance and cost specifications are provided in Table 1. The flue gas from the incineration generates hot water at 90°C, with an assumed 70% efficiency. Heat and power transmission losses were assumed 5% and the cost of pumping the hot water is set to 1.5 €/t. Heat pumps with a COP of 4.5 present the option to convert power to heat for satisfying heating demand. Heat (43.2 GJ/y) and power (4.5 MWh/y) are returned to households to fulfil some of their energy demands [36], while any excess heat or power may be sold on the market for 20.2 €/GJ of heat and 205.2 €/MWh of electricity.

GHG emissions are explicitly quantified in the model. This includes evaluating the GHG emitted by the waste transport to the WtE plant (Fig. 3, GHG emitted) and accounting for the effective emissions reduction from replacing fossil fuel energy sources by delivering the heat and electricity generated from the waste (Fig. 3, GHG reduction). GHG emissions from combustion of the waste-derived materials are considered as negligible because of the relative balance between reducing volatile methane from reduced landfilling and the CO_2 produced by the WtE process. The cost imposed for releasing GHG emissions is assumed 5.0 €/t, which is at the lower end of the range of carbon tax values published by the World Bank. The GHG emission savings are calculated as a difference of the GHG emitted by the waste transport and the GHG displaced by the energy delivered to the community. The latter is based on fossil fuel emissions, replaced by the power and heat provided by the WtE processes to the households:

$$GHG_{\text{Saving}} = GHG_{\text{Reduction}} - GHG_{\text{Emitted}}. \tag{8}$$

The spatial evaluation has been performed by running the described model for WtE network synthesis for the selected population density sizes, according to the plan in the first three columns of Table 2. It is important to point out that the WtE network size is given in terms of area and population. For a given population density, one of these parameters can be calculated from the other. However, the trends obtained from the evaluation can be analysed properly only by tracking both these quantities as factors. The rest of Table 2 shows the first part of the obtained results showing indicators of the economic, environmental and energy performance of the synthesized WtE networks with varying the population density and the WtE network size.

From the complete set of model outputs, the following ones have been specifically analysed: (1) Economic indicators: revenue, cost, profit, waste collection fee reduction from the realised profit. The P-graph model surveys all input and output streams, which have unit costs associated with them, and then sums up the investment costs associated with any operating units selected in the current network structure. These cost items are used to work out Total Annualised Cost. Since some flows bring revenues. For instance, the waste collection fee associated with the Waste node, as well as the proceeds from the nodes for heat and electricity supply (Figure 3) bring in revenues, which in the P-graph are modelled as negative

Table 1 CHP gas engine options—“Jenbacher type 3”

No.	Identifier	Power output /kW	Input /kW	NO_x /ppm	Thermal Efficiency	Electrical Efficiency	CHP Efficiency	Investment cost /€	Maintance cost / $(€\cdot y^{-1})$
1	J208	330	851	500	0.485	0.387	0.873	232438	9298
2	J312	637	1565	500	0.449	0.407	0.856	344892	13796
3	J316	850	2086	500	0.448	0.407	0.856	410063	16402
4	J320	1067	2608	500	0.452	0.409	0.861	470000	18800
6	J416	1189	2806	500	0.428	0.424	0.852	501543	20061
7	J420	1487	3508	500	0.428	0.424	0.852	573569	22943
8	J612	1820	4142	500	0.403	0.44	0.843	647503	25900
9	J616	2435	5523	500	0.403	0.441	0.844	771078	30843
10	J620	3047	6904	500	0.403	0.441	0.844	882110	35284
11	J620×2	6094	13808	500	0.403	0.441	0.844	1764220	70569
12	J920	10400	21181	500	0.406	0.491	0.897	1842550	73702
13	J920×2	20800	42363	500	0.406	0.491	0.897	3685099	147404

Table 2 Evaluation plan and results*

	Population /inhabitants		Operating profit /(€ · t waste^{-1})		Reduced waste collection fee /(€ · t waste^{-1})		Net GHG saving /(t · y^{-1})		Energy used /(GJ · y^{-1})		Energy delivered /(GJ · y^{-1})	
PD → /(inhabitants · km^{-2}) ECZ /km^2 ↓	2500	5000	2500	5000	2500	5000	2500	5000	2500	5000	2500	5000
4	10000	20000	51.64	55.19	68.36	64.81	37.43	85.98	6934	13707	7092	14184
8	20000	40000	53.58	62.78	66.42	57.22	49.49	384.90	14236	28042	14184	27707
10	25000	50000	53.82	**62.94**	66.18	**57.06**	51.33	458.82	17948	35376	17730	34634
16	40000	80000	**60.53**	62.81	**59.47**	57.19	282.66	648.47	29524	57843	27707	55414
20	50000	100000	60.37	62.48	59.63	57.52	313.53	767.36	37482	73320	34634	68838
32	80000	160000	59.48	61.79	60.52	58.21	347.3	1061.20	62208	120868	55414	109572
40	100000	200000	58.96	61.24	61.04	58.76	368.15	1147.10	79107	153683	68838	136965
60	150000	300000	57.44	60.87	62.56	59.13	269.13	1505.10	123833	238404	102724	209922
80	200000	400000	56.16	59.71	63.84	60.29	−3.60	1318.30	170363	327852	136965	279897
100	250000	500000	55.73	58.63	64.27	61.37	−117.13	910.40	218548	420503	174935	349871
120	300000	600000	54.43	57.87	65.57	62.13	−679.90	475.90	270075	513541	209922	419844
200	500000	1000000	50.69	54.33	69.31	65.67	−3586.5	−3546.70	485686	918808	349871	699740

* In the columns for operating profit and reduced waste collection fee, the most beneficial values are in boldface

costs. Based on this calculation model, the potential profit from the WtE network is estimated as the difference between the revenues and the true costs. (2) GHG indicators: direct emissions from the WtE network, GHG reduced by operating the network, net GHG savings. The calculation is fully described at the beginning of this section (3. Case Study). (3) Energy-related indicators: energy used for operating the network (energy invested), energy delivered to users, the degree of energy recovery.

The economic performance is represented by the specific operating profit of the network in [€/(t waste)] (Table 2). Realising that waste treatment as a public service is not supposed to generate official profit, the operating profit is directed to the reduction of the waste collection fee. For both given levels of population density, the highest profit and maximum reduction of the waste collection fee take place for the population size of 50000, equivalent to 10 and 20 km^2, while the exact values slightly differ in favour of the higher population density. Regarding the system GHG performance, Table 2 shows that for most ECZ sizes the WtE processing offers good emission saving while exhibiting a trend of reduced GHG saving with the growing size. In Table 2 the annual flows are given, providing an idea of the scale of the emissions and the savings, but an intensive indicator is necessary to understand the trends better.

The energy-related performance results, listed in Table 2, feature trends of better energy generation at smaller ECZ sizes, where only for the smallest evaluated ECZ size (4 km^2) the energy generated and delivered to the market surpasses the energy spent on waste transportation to the WtE plant. However, it should be pointed out that a similar or even larger amount of energy would be spent on transporting the waste to the landfill even in the case of no WtE applied. Consequently, any energy recovered from the waste should be considered as a saving. While the total annual energy flows provide the overall context and scale of the energy balances, the efficiency, saving and recovery trends need a different representation on an intensive basis. Following the reasoning for the need for intensive indicators, further analysis has been performed, involving the following ones: (1) Relative GHG saving in % of the emitted GHG for transportation. (2) Energy recovery ratio (ERR). The relative GHG saving (RS_{GHG}, %) is calculated as:

$$NS_{\mathrm{GHG}} = GHG_{\mathrm{Emitted}} - GHG_{\mathrm{Displaced}}, \tag{9}$$

$$RS_{\mathrm{GHG}} = \frac{NS_{\mathrm{GHG}}}{GHG_{\mathrm{Emitted}}} \times 100. \tag{10}$$

In these equations, GHG_{Emitted} (t/y) is the emission from transportation, $GHG_{\mathrm{Displaced}}$ is the equivalent amount of emissions reduced by replacing fossil-fuel generated heat and power on the marked by the WtE generation, $\mathrm{NS}_{\mathrm{GHG}}$ is the net GHG saving — listed in Table 2. Similarly, the ERR is defined as the sum of the heat and power flows for a WtE system, divided by the energy input:

$$ERR = \frac{E_{\mathrm{CHP}}}{FT}. \tag{11}$$

Plotting RS_{GHG} against the ECZ sizes, for both levels of the population density produces the chart in Fig. 4. The resulting trends are quite clear, featuring net GHG savings for the smaller ECZ sizes, dropping to negative values, i.e., generating additional GHG emissions for larger ECZ sizes. The break-even points for the current case study parameters take place at around 120 km^2 for 2500 inhabitants/km^2, and between 120–200 km^2 for 5000 inhabitants/km^2. This trend indicates that larger ECZ sizes are prohibitive from the viewpoint of emission savings and depending on the specific population density, available transportation fleet and fuels, it is not likely that ECZ of 120 km^2 and larger would help to reduce GHG emissions. It is also interesting to point out the maxima in the GHG savings, observed at ECZ = 8–16 km^2. After examining the specific solutions for the ECZ = 4–8 km^2 (20000 inhabitants), they feature only heat generation from the waste and no power generation, which is the reason also for the smaller GHG savings rate. Further plotting the ERR against the ECZ sizes, produces the chart in Fig. 5. Overall, the trend of better performance at smaller ECZ sizes is preserved for this indicator as well and, for population density 5000 inhabitants/km^2, there is even a small net energy gain from the smallest WtE network. For most sample points, the systems with higher population density outperform the ones with lower population density in terms of ERR, which results from the higher resource (waste) availability.

Comparing the charts in Fig. 4 and Fig. 5 reveals an interesting detail. On the one hand, the estimates show some GHG emission savings for most of the sampled ECZ sizes (Fig. 4) and only for the largest WtE networks the GHG emissions surpass the GHG savings. The amounts of energy, recovered from the waste, and the amounts of energy spent for transportation both follow growing trends with increasing the ECZ size, but the energy use seems to grow slightly faster, resulting in declining ERR values. While this is a clear trend, the variations are rather small and the evaluation of their significance should be examined further, during detailed WtE optimisation (design or retrofit). The energy recovery from waste is smaller than the fuel energy for transportation for most of the samples and becomes larger only for the smallest of the examined networks. This discrepancy is due to the additional GHG saving effect of reduced waste transportation to the WtE plant compared with the longer distance to the landfill site.

In summary, the obtained results feature a general common trend of better performance at smaller sizes of the ECZ, gradually worsening with increasing the size. The performance is quite sensitive to the population density, improving with its increase due to the increased resource (inhabitants, waste, energy) density per unit area. Clearly, the WtE arrangement helps to improve the sustainability metrics of the evaluated systems by realising up to 12% GHG savings and recovering large fractions of the invested fuel energy for transportation, with the potential to realise net energy gain for eventual higher population density or more efficient unit operations.

4 Conclusions

This work suggested and applied a new WtE targeting procedure based on the concept of ECZ and the evaluation

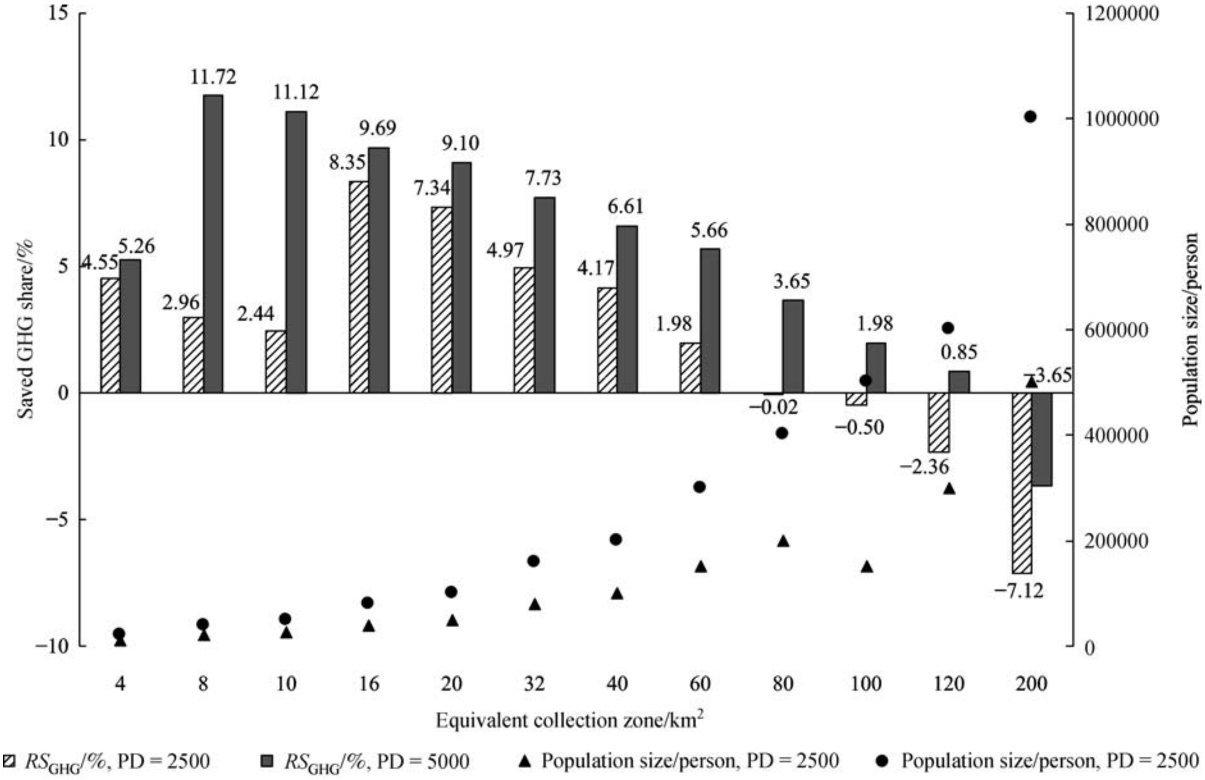

Fig. 4 Relative GHG saving trend

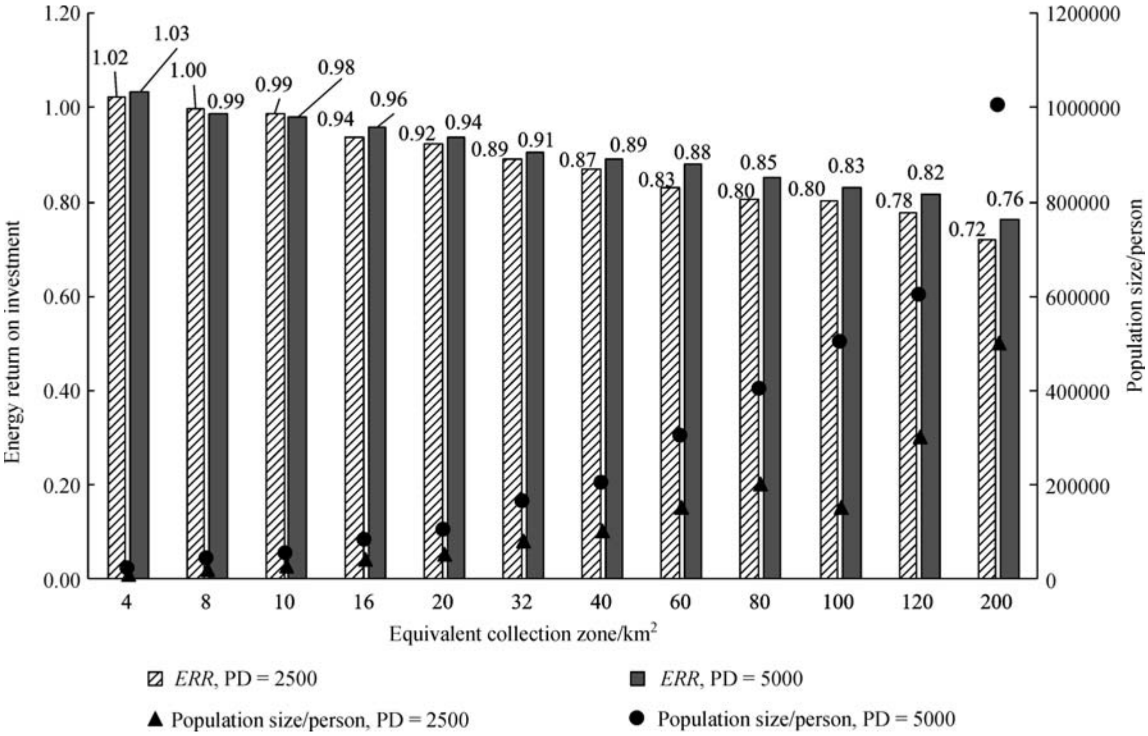

Fig. 5 ERR trend

of the performance trend of the zone for a range of sizes and different levels of population density. The obtained performance trends for GHG emission savings and energy recovery show that the influence of the transportation distance on the energy and GHG performance is substantial. The population density shifts the performance curves, where higher population density allows for higher Energy Recovery Ratio and GHG savings that can surpass the GHG emitted for waste transportation.

The developed model can easily be adapted to specific cases of population and waste density and evaluate the situation within European and wider context. The presented case study fully shows that the increased ECZ size and transportation distances lead to deteriorating performance, which is expected to be in addition to any implementation complexities.

The GHG displacement and energy recovery remain substantial and it is still better to process the waste for energy recovery compared with the simple landfilling. If maximum benefits should be sought in terms of real net GHG savings and maximum energy recovery with possible energy gain, the waste transportation distances should be minimised as much as practically possible, accounting for the potential investments, as well as for the relevant safety and environmental regulations, specific for each country.

In future work, several possible improvements of the method should be considered in terms of: (1) Considered technologies. (2) Comprehensive footprints assessment on an life cycle analysis (LCA) basis. (3) The implementation of the combustion of the dry waste fraction. (4) Supply chain synthesis and modification.

Considered technologies. More WtE technologies should be considered, in addition to the anaerobic digestion — especially incineration should be modelled closer to the practical conditions. The treatment operations such as composting and other waste treatment practices should be also considered, to cater for the cases and waste fractions not suitable for energy generation. Other supply chain stages should be also added, for instance, the further handling of the solid residues from anaerobic digestion and incineration. The presented targeting model should be refined by taking into account the specifics of the involved waste treatment and WtE technologies, such as the appropriate minimum and maximum capacities and possible implications of public acceptance. An especially sensitive issue in this regard is odour control. Appropriate technical solutions to this problem are readily available — including seals and facilities maintaining "negative pressure" [31]. These measures carry certain additional costs for investment and operation, which should be taken into account.

Comprehensive footprints assessment. In the presented study, only GHG emissions are considered. Future studies should consider all relevant and significant emissions and effluents from waste management represented as footprints. The evaluation should be on LCA basis, accounting for the relevant footprints exactly once. The LCA setup should also allow accounting for the GHG and other impacts from all system nodes, including the waste incineration and the biogas combustion.

Incinerators — capacity and placement. Most existing incinerators are large-scale facilities and the combustion of the dry waste fraction in smaller-scale incinerators are often considered impractical, mainly because of the potentially prohibitive investment. While the economy of scale is a commonly used heuristic, applicable to a wide range of industrial processes, in WtE networks pure industrial processing is in opposition to the challenges related to the spatial development and emissions resulting from transportation. An interesting point is that mobile incinerators are routinely offered, e.g., a company from Staffordshire in the United Kingdom offers incinerators for various uses, including trailer-mounted ones. This indicates that there are processes and applications where such equipment is considered economically attractive. Combined with the performance trends, identified in the current study, smaller-scale WtE facilities should be in a more detail to evaluate whether they can indeed bring economic and environmental benefits, tackling the challenge posed by waste transportation.

Another issue is the “Not in my back yard” line of thinking, due to the perceived unpleasant effects of waste processing. However, the example of the Spittelau Waste Incineration Plant in Vienna clearly demonstrates that, with appropriate construction and management efforts, an incinerator can be located inside a city, accepted by the public and realising the benefits from shortening the transportation distances.

The further development of the models should account for these issues. Due to the clear contradiction of this consideration with the revealed spatial performance trends, special attention should be paid to the waste separation practices and the minimisation of the fraction sent to incineration in the case of prohibitively long transportation distances. The trade-off between local landfilling and distance incineration should be evaluated on a life cycle basis. For completing the options assessment in the targeting model, smaller-scale incinerator facilities should be complemented with adding an option for large-scale incinerators with CHP generation. This will allow to better address the trade-off between the lager and smaller scale solutions.

Supply chain synthesis and modification. The regional supply chain synthesis for waste processing has to incorporate the developed model into an overall Supply Chain Synthesis procedure, providing the targeting phase functionality. Such a holistic procedure should also be defined within the context of the overall waste management hierarchy, widely accepted in practice and in official regulations. It is important to point out that, considering the demonstrated results from the current work, WtE can be considered only as one of the options for waste treatment, with the aim to minimise the energy use and footprints of overall waste management, as it has been shown that in most cases net energy gain from WtE would be unlikely and if can be realised, it would not be significant. A good candidate for a starting point of the synthesis method is the work by Tan et al. [32], which provides a comprehensive mathematical model, comprising all essential processing technologies. The future development should also add the transport to those operating units. Other parts of the optimisation procedure should be also considered — especially with the methods for data collection and reconciliation [33]. For the synthesis phase, regional specifics become relevant and should be modelled — for instance, the relief of the road can influence the energy consumption for transport quite significantly, as demonstrated recently by Nevrlý et al. [34], in which study also the potential impacts on the population near the transportation routes is also evaluated. A good tool that may help at the network design phase is ArcGIS, which is a set of tools for applying the location-based analysis of business processes, which depend on distributed locations.

Finally, while the current work provides clear and useful insights for the case of organising new WtE supply chains and investing in them, there are many existing urban settlements of various sizes, with already functioning waste processing systems. In this context, for the owners and decision makers, the consideration of how to modify or evolve their existing waste processing would be more relevant. The model, presented in the current study can be used for that purpose too, with adjustments concerning the cost of the waste transportation and processing facilities, including evaluation of the possibility to use more efficient power generating equipment such as gas turbines. While in the new design case all equipment is part of the investment plan, in the retrofit/modification case, all existing equipment is considered of zero cost for the retrofit operation.

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Symbols and indices

$\hat{c}_{\mathrm{hand}}$ / $(€\cdot\mathrm{t}^{-1})$	Waste handling fee
$\hat{m}_{\mathrm{w,gen}}$ /$(\mathrm{t}\cdot\mathrm{inhabitant}^{-1}\cdot\mathrm{y}^{-1})$	Specific waste generation per individual
C_{hand} /$(€\cdot\mathrm{y}^{-1})$	Waste handling cost item
C_{trans} /$(€\cdot\mathrm{y}^{-1})$	Waste transportation cost item
E_{CHP} /$(\mathrm{GJ}\cdot\mathrm{y}^{-1})$	The sum of the heat and power flows generated by the WtE processes
NS_{GHG} /$(\mathrm{t}\cdot\mathrm{y}^{-1})$	Net savings of GHG
RS_{GHG} /%	Relative GHG saving
d_{ave} /km	Average transportation distance
e_{t} /$(\mathrm{t}_{\mathrm{fuel}}\cdot\mathrm{t}_{\mathrm{waste}}^{-1}\cdot\mathrm{km}^{-1})$	Average truck specific energy consumption
p_{f} /$(€\cdot\mathrm{t}_{\mathrm{fuel}}^{-1})$	Price of the transport fuel

A /km^2	Area of the ECZ
COP /1	The coefficient of performance (heat pumps)
ERR /1	Energy recovery ratio
FT /(GJ$\cdot$y^{-1})	Fuel energy for transportation
i, m, n, j	Indices for facilities and operating units in the layer model (Fig. 1)
m_{tot} /(t$\cdot$y^{-1})	Total waste mass flow
N_{i}, N_{m}, N_{n}, N_{j}	Numbers of facilities and operating units within each of the layers in Fig. 1
NO$_x$ /ppm	Oxides of nitrogen (content)
P_{den}, PD/ihnabitants per km^2	Population density
r /km	The radius of the ECZ
TC / (€$\cdot$y^{-1})	Overall waste transportation cost
β /1	Additional transport distance performance coefficient

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