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Spatial Influence on Waste-to-Energy Sustainability: A Life Cycle Assessment of RDF Transport and Plant Siting

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Abstract

The spatial configuration of Waste-to-Energy infrastructure plays a decisive role in determining the environmental and economic performance of municipal solid waste (MSW) management systems. This study applies a Life Cycle Assessment methodology to evaluate the environmental implications of centralized and decentralized siting strategies for Refuse-Derived Fuel utilization in Greece. Two alternative scenarios were modeled: (i) a centralized approach based on six large WtE plants as proposed by the Greek Ministry of Environment and Energy (gr. YPEN), and (ii) a decentralized approach involving smaller, regionally distributed units located closer to Recycling and Recovery Facilities. Using the SimaPro software and the ReCiPe method, environmental impacts were quantified across categories including global warming potential, acidification, eutrophication, and particulate matter formation. The results indicate that the decentralized scenario yields substantial environmental advantages, with reductions ranging from 33% to 45% across all impact categories and displaying a 35% decrease in CO_2-equivalent emissions compared to the centralized scenario. Economic analysis confirms these findings, showing a 31% reduction in total transport and emissions-related costs due primarily to minimized long-distance and maritime transport. The study concludes that decentralized RDF-to-energy systems offer a more balanced and sustainable pathway, enhancing operational flexibility, lowering environmental burdens, and improving social acceptance. These results underscore the importance of integrating spatial and logistical parameters in national WtE planning to align with EU waste hierarchy principles and circular economy objectives.

Keywords: spatial analysis; municipal solid waste; life cycle assessment; transport emissions; decentralized waste systems; Refuse-Derived Fuel

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1. Introduction

Municipal solid waste (MSW) management remains among the most pressing environmental, economic and social challenges in Europe, reflecting the combined pressures of increasing urbanization, changing consumption patterns, and the need to align with climate-neutrality objectives [1]. The European Union (EU) has established an ambitious policy framework aimed at transforming waste from a liability into a valuable source of raw materials and energy [2,3]. Central to this framework is the implementation of the waste hierarchy (Figure 1), which prioritizes prevention and minimization at source, followed by reuse, recycling, composting or anaerobic digestion and recovery. Recovery operations include energy recovery through Waste-to-Energy (WtE) systems that utilize Refuse-Derived

Fuel (RDF), a standardized fuel produced from the non-recyclable combustible fractions of municipal waste after mechanical or mechanical–biological treatment in Recovery and Recycling Facilities (RRFs) [4]. Finally, disposal (landfilling or incineration without energy recovery) constitutes the last and least preferred option [5,6].

The persistent rise in municipal waste generation, coupled with projections indicating continued growth even under optimistic recycling scenarios, underscores a structural challenge in current waste governance. As long as waste generation trajectories remain uncoupled from recycling progress, even ambitious 2025–2030 recycling targets risk being insufficient to curtail residual waste to desired levels. This tension between growing waste flows and the finite capacities of recycling systems makes it clear that technical end-of-pipe improvements alone cannot deliver the systemic reductions needed [7–9].

Figure 1. EU waste hierarchy scheme [10].

The waste hierarchy, institutionalized in the EU Waste Framework Directive and widely adopted internationally, establishes a graded prioritization of waste management options based on their overall environmental desirability. Its overarching logic is straightforward: the highest sustainability outcomes stem from avoiding waste altogether, while the lowest result from uncontrolled disposal. Over time, this framework has evolved from a narrow "3R" conception to a multi-layered model integrating prevention, reuse, recycling, recovery, and disposal, reflecting both technological advancements and the broader transition toward circular economy systems [11].

At its core, the waste hierarchy reflects the principle that the most environmentally beneficial waste is the waste that is never generated. This top tier—waste prevention—encompasses design, consumption, and policy interventions that minimize material throughput. Recent scholarship underscores that, although waste prevention is the most environmentally beneficial option, it is also the most challenging to implement, requiring cross-sector coordination, product redesign, behavioral change, and new business models [12].

Below prevention, the hierarchy emphasizes preparation for reuse and reuse. These stages extend product lifetimes through repair, refurbishment, and secondary use. Reuse is materially efficient and energy-saving, but it hinges on system-level conditions such as product durability, reverse-logistics infrastructure, and service-oriented consumption models.

Recycling, positioned at the mid-level, aims to reintroduce materials into productive loops. While recycling has been a dominant focus of municipal waste management for decades, it is now widely recognized that recycling alone cannot counterbalance rising waste generation, partly because recycling requires energy and often leads to downcycled outputs with limited material value [7,13].

Energy recovery constitutes a lower tier, capturing residual calorific value through controlled incineration or anaerobic digestion. Although preferable to landfilling, its environmental benefits are circumscribed, and it risks locking cities into disposal-oriented infrastructures that disincentivize prevention.

Finally, landfilling and open dumping represent the least desirable outcomes, associated with long-term ecological burdens, climate-intensive emissions, and significant public-health risks—challenges that continue to affect both high-income and low-income regions globally [11,14].

An important conceptual development in recent years is the integration of waste hierarchy principles with circular economy (CE) frameworks. While the hierarchy provides a sequence of preferred waste management options, CE expands this into a systemic vision in which waste prevention, resource efficiency, and material recirculation are embedded across production, consumption, and end-of-life stages. The synergy of these frameworks clarifies that the hierarchy is not merely a disposal guideline but a governance tool that shapes how products are designed, how consumption unfolds, and how material loops are closed at scale. CE-oriented innovations—eco-design, material substitution, product-service systems, and high-value recycling—strengthen the upper tiers of the hierarchy, ensuring that waste management becomes aligned with holistic resource governance [9,11].

Insights from zero-waste scholarship further reinforce the environmental and socio-economic rationale for privileging the upper tiers. Zero-waste frameworks argue that waste is not an inevitable by-product of economic activity but a symptom of inefficient systems [13,15]. Accordingly, waste prevention and reuse address root causes rather than symptoms, generating benefits that cascade across climate mitigation, resource conservation, and urban sustainability. They also generate employment in repair, remanufacturing, and refurbishment sectors, while reducing dependency on raw materials and waste-intensive supply chains.

Importantly, empirical analyses show that regions most successful in implementing the hierarchy—particularly in construction, packaging, and municipal waste streams—combine stringent policy frameworks with high stakeholder engagement, data transparency, and technological innovation. This reinforces the view that hierarchy compliance is not merely a technical challenge but an institutional one.

Positioning the waste hierarchy at the center of municipal waste governance has direct implications for the design of integrated waste management systems. It necessitates a rebalancing of policy attention and investment: shifting from downstream treatment capacities toward upstream measures targeting product design, consumption patterns, and circular business models. It also requires embracing multi-stakeholder collaboration, as highlighted by global comparative research, which shows that successful systems rely on cooperation between governments, producers, municipalities, informal sectors, and citizens [14].

In this sense, the waste hierarchy is not an isolated conceptual model but a strategic foundation for the broader transition toward sustainable waste management. The hierarchy provides normative direction, while integrated waste management systems operationalize it through infrastructure, policy instruments, and economic incentives.

Recent analyses demonstrate that the integration of energy recovery technologies, when applied within a circular economy approach, can significantly contribute to decarbonization efforts, resource efficiency, and reduced environmental impacts [5,16]. However, disparities persist among Member States in achieving recycling and recovery targets, indicating the need for further innovation, decentralized waste treatment systems, and harmonized policy implementation [17].

The EU's legal framework for MSW is built primarily around the Waste Framework Directive (2008/98/EC, revised), the Landfill Directive (1999/31/EC, amended 2018/850), and specific directives on packaging waste, biodegradable waste, extended producer responsibility (EPR), and separate collection. Under these, legally binding targets compel Member States to increase recycling/preparing for reuse rates of municipal waste progressively: 55% by 2025, 60% by 2030, and 65% by 2035. Simultaneously, the share of MSW sent to landfill is to be reduced to no more than 10% by 2035. Member States, like Greece, with historically high landfill rates in 2013 may have temporary derogations, but the trend is clear.

The revised Landfill Directive also imposes limits on the landfilling of biodegradable waste, such as caps expressed as percentages relative to baseline years, in order to reduce methane emissions and leachate generation. Legislative push is also strong for the separate collection of organics, textiles, packaging materials, and e-waste. The Packaging & Packaging Waste Regulation has introduced measures to improve the recyclability of packaging, set reuse and refill targets, require recycled content, and reduce overpackaging [18].

Figure 2 shows that the EU has made respectable progress, although not uniformly across Member States. As of 2022, the average MSW recycling rate in EU-27 is approximately 48.6%, just under the 50% mark. For packaging waste, the EU average recycling rate is around 64%, although differing by material: paper/cardboard and glass are generally high, whereas plastics lag behind [19]. Many Member States are "at risk" of missing the 2025 targets: combinations of the municipal waste recycling/preparing for reuse target (55%) and the packaging waste target (65%) are not yet assured in several states. Countries at particular risk include those with low infrastructure, high reliance on landfill, or challenges in separate collection systems [20]. Trends in waste generation also pose challenges: projections indicate that total municipal waste generation may increase unless changes in consumption, waste prevention and circular product design are implemented. Even achieving the 2025–2030 recycling targets might not be sufficient to reduce residual waste (which remains after recycling & reuse) to the levels desired, unless waste generation is also curbed.

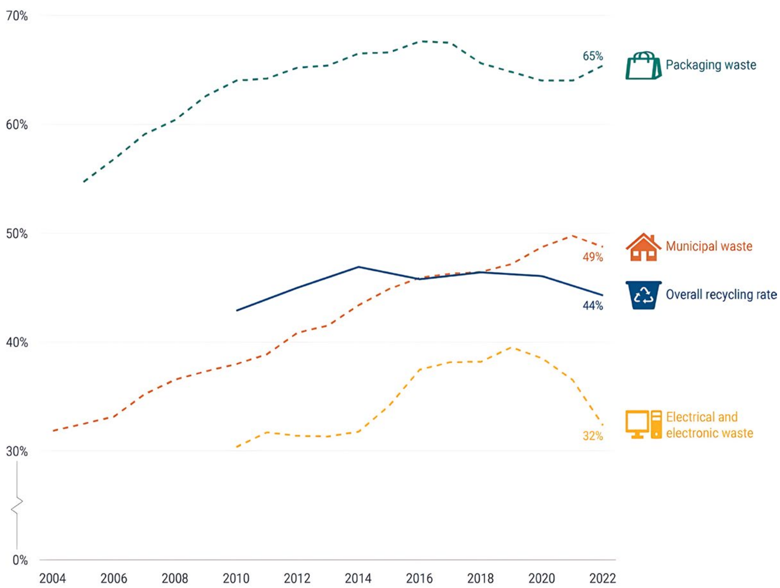

Figure 2. Recycling rates in Europe by waste stream [21].

Across the European Union, MSW management follows a harmonized framework structured around the waste hierarchy. Thus, waste streams that cannot be feasibly recycled or reused are directed towards recovery pathways, where they are treated, sorted, and processed into, amongst other streams, alternative fuels. This process represents the final stage of material valorization before final disposal. In practice, mixed residual waste undergoes mechanical and biological treatment (MBT) or similar pre-treatment processes in Resource Recovery Facilities (RRFs) that separate recyclable fractions, remove inert and non-combustible materials, and refine the remaining combustible fraction into Refuse Derived Fuel (RDF). RDF is therefore the product of a systematic European waste management scheme that aims to maximize material recovery while minimizing landfill dependency and greenhouse gas emissions. The common pathway can be summarized as: separate collection → recycling and composting of recoverable materials → mechanical–biological or mechanical–thermal treatment of residual waste → RDF production → energy recovery through Waste-to-Energy (WtE) plants or co-incineration in industrial facilities (Figure 3).

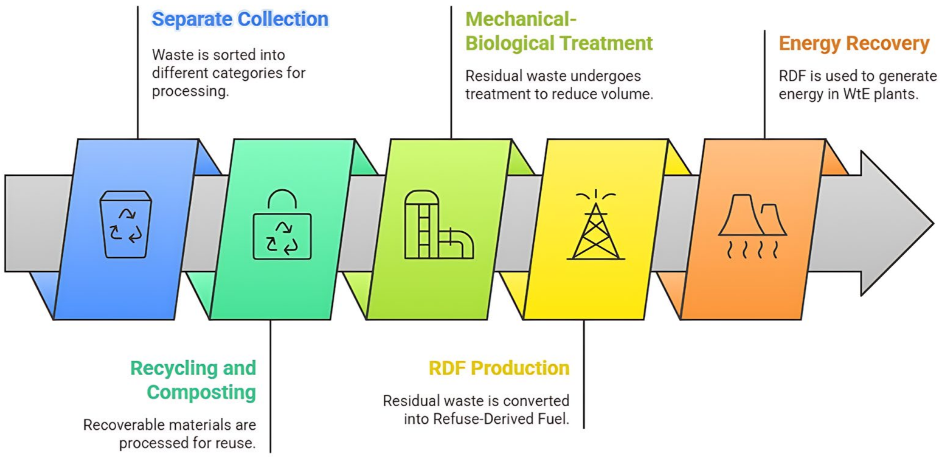

Figure 3. Waste management pathway.

RDF and WtE technologies constitute a cornerstone of the European Union's strategy for managing residual waste that cannot be feasibly reintroduced into material recycling loops [1,5]. RDF enables the recovery of embedded energy from non-recyclable fractions of MSW, provided that the fuel produced meets specific standards for calorific value, moisture, and contaminant levels [4,22]. Once refined, RDF can be valorized through dedicated WtE plants or co-incinerated in energy-intensive industrial processes such as cement kilns, where it substitutes fossil fuels and supports industrial decarbonization efforts [23,24]. These applications are generally recognized as environmentally preferable to landfilling, due to their potential for partial greenhouse gas mitigation, controlled emissions, and reduced leachate generation, particularly when high-efficiency energy recovery systems and advanced flue-gas cleaning technologies are deployed [5,25]. The energy recovered from WtE operations can be converted into electricity and thermal energy for district heating/cooling networks, thereby enhancing local energy security and supporting the EU's transition toward a low-carbon, circular economy [16].

However, the environmental and economic performance of the RDF and WtE chain depends heavily on upstream processes, including the efficiency of waste collection, the level of source separation, and the effectiveness of sorting and preprocessing technologies [26,27]. Among these factors, transportation logistics exert a decisive influence: extended hauling distances for either unsorted MSW or pre-processed RDF can substantially increase greenhouse gas (GHG) emissions, thereby offsetting part of the environmental benefits achieved through energy recovery [27,28]. While large-scale, centralized WtE facilities generally achieve higher thermal efficiencies [29,30], their operation often entails long-distance waste transport and higher associated fuel, GHG emissions (specifically Scope 2 emissions that account for indirect GHG emissions from fuel combustion occurring during waste transport and preprocessing) and infrastructure costs. Conversely, decentralized or regionally distributed treatment facilities, strategically sited near the RRFs, can minimize transport-related GHG emissions and improve integration with local recycling networks. Moreover, recent technological developments lead to reduction of investment costs per unit of capacity, and full compliance with emission performance of smaller decentralized WtE plants. This improvement results from continuous technological advances in modular gasification, small-scale incineration, and emission-control systems, which have mitigated many of the limitations traditionally associated with smaller WtE plants [28].

Although large centralized WtE facilities are often assumed to yield superior thermal efficiency, evidence suggests that small-scale or modular systems, when properly engineered, can approach comparable performance while achieving lower local environmental impact and full compliance with emissions standards. In real-world application, the case study in Northern Italy finds that a well-operated WtE plant's contribution to local air pollution is orders of magnitude lower than major urban sources like road traffic, indicating that even "smaller scale" plants with proper controls can have negligible environmental burden [28]. Moreover, life-cycle assessments show that with optimal design (including heat recovery, emissions control, and possible carbon capture), even moderately scaled WtE systems can yield favorable climate outcomes [31].

Studies consistently show that the carbon footprint of RDF systems is dominated by fuel combustion from collection and long-haul transport activities, with transport often representing the single largest contributor to GHG impacts in RDF supply chains [32,33]. EU-level guidance similarly stresses the importance of minimizing logistics distances in RDF/SRF management due to both climate and cost penalties associated with long transport corridors [34].

LCA evidence show that beyond certain transport thresholds, the emissions from vehicle fuel use and the electricity-intensive SRF/RDF preprocessing chain outweigh the benefits of high-efficiency thermal treatment, effectively eroding or even reversing the net climate advantage of centralized WtE systems [35,36]. Conversely, decentralized systems, when optimized for logistics and waste composition, may yield lower per-ton environmental burdens despite operating at smaller scales. Similar findings in decentralized wastewater and resource-recovery systems show that distributing treatment capacity closer to generation points can significantly reduce per-ton impacts by minimizing transport intensity and enabling higher alignment between waste composition and treatment technology [37]. In the context of RDF, decentralized deployment similarly supports logistics optimization and enhances the circular use of locally generated resources [38]. The optimal configuration for RDF and WtE therefore lies in balancing efficiency, logistics, and spatial distribution of energy recovery plants within each national or regional context [38]. This underscores that plant siting and transport optimization are key parameters in designing sustainable WtE systems consistent with the proximity and self-sufficiency principles embedded in the EU Circular Economy Action Plan, which urges Member States to reduce transport-related environmental burdens and establish territorially optimized waste and resource management infrastructures that support Green Deal climate objectives [39]. Collectively, these studies underline that spatial configuration—not only plant-scale efficiency—governs the environmental performance of RDF-to-energy chains. As a result, transport minimization and regionalized siting are increasingly recognized as essential criteria for sustainable WtE planning in EU policy and investment frameworks.

Within this context, Member States face a strategic choice: pursue centralized large WtE/RDF hubs—concentrated capacity with longer transport routes—or adopt decentralized networks of smaller plants co-located with RDF preparation facilities (i.e., RRFs), characterized by shorter transport distances but more dispersed infrastructure. Each choice carries inherent trade-offs. Centralized, larger WtE plants typically achieve higher thermal efficiencies and can justify the use of sophisticated emission control technologies [40]. However, they also concentrate waste transport flows, potentially increasing truck-kilometers and associated emissions [41]. Decentralized, smaller WtE variants, on the other hand, can reduce haulage distances and integrate more effectively with local recycling RRFs, often improving social acceptance and system resilience [38]. Nonetheless, they may face challenges such as reduced economies of scale and higher unit capital or operational expenditures although this is improved nowadays due to important technological advances and know-how during development of smaller WtE units. Therefore, assessing these trade-offs requires a life-cycle perspective that considers not only GHG emissions generated by the WtE plant but also Scope 2 emissions related to upstream collection, preprocessing, transport, and RDF production [39].

Given the above context, plant siting and transportation distances are not peripheral considerations but central determinants of environmental sustainability in RDF and WtE systems [42]. Their importance is underscored by the transport-related GHG emissions associated with heavy-duty vehicle (HDV) fleets—strongly influenced by fuel type, load factor, distance, and road conditions [43]—and by the energy demands of preprocessing operations such as sorting, drying, and shredding, which vary with waste composition, moisture content, and residual waste quality. The trade-off between economies of scale achieved in centralized WtE plants and the penalties of long transport distances and higher vehicle GHG emissions remains a key design challenge [44]. Moreover, the spatial distribution of infrastructure can influence social acceptance, local environmental impacts (noise, traffic, and emissions), and regional disparities in environmental burdens or costs. Consequently, sustainability assessments that omit or oversimplify these spatial and logistical factors risk overestimating the environmental benefits of centralized WtE systems or failing to identify optimal configurations that minimize total life-cycle impacts.

Despite substantial progress in the evaluation of Waste-to-Energy systems, important knowledge gaps remain regarding how national geography, transport logistics, and facility scale jointly influence the sustainability of RDF management. Existing LCAs often treat WtE infrastructure as spatially neutral, overlooking the way that transport intensity, vehicle characteristics, and siting patterns shape greenhouse gas emissions, operational costs, and wider environmental burdens. This omission is particularly significant in Greece, where long road corridors, island regions, and extensive maritime links create spatial conditions that fundamentally alter the performance of centralized waste systems. Addressing these gaps requires an assessment framework capable of examining how alternative siting configurations modify transport-related emissions, how changes in transport demand affect system-wide economic efficiency, and how shifts in spatial layout influence impacts beyond climate change. The present study adopts this perspective by integrating spatial planning principles into a national-scale LCA of centralized and decentralized RDF-to-energy scenarios, with the objective of clarifying how infrastructure geography can support a more coherent alignment between waste-system design, circular-economy goals, and long-term climate commitments.

2. Case Study: Greece

Greece presents a compelling case for evaluating integrated solid waste management (ISWM) systems incorporating WtE technologies due to its persistent reliance on landfilling, regional disparities in waste infrastructure, and the national drive to meet EU environmental targets [45]. Historically, the country has faced significant challenges in diverting MSW from landfills, with over 75% of waste still being disposed of through landfilling as of 2022 [46]. Despite gradual improvements in recycling and composting, Greece remains among the lowest performers in waste recovery rates within the European Union and still suffers from the enforcement of large penalties from the European Commission for non-performance.

The national waste generation rate averages 1.45 kg/capita/day, corresponding to approximately 5.4 million tons of MSW annually [47]. Waste generation is highest in the Attica region—which includes the metropolitan area of Athens—and in Central Macedonia, which together account for nearly half of the total waste produced nationwide [48]. The composition of MSW in Greece is dominated by biodegradable organic waste (≈44%), followed by paper and cardboard (20%), plastics (17%), glass (5%), metals (3%), and other residues (11%) [49]. The high organic and plastic fractions indicate strong potential for both biological and thermal recovery pathways, especially in the non-recycled residues of the RRFs.

In alignment with the National Waste Management Plan (NWMP 2020–2030) and the Circular Economy Action Plan, Greece aims to reduce landfilling to below 10% of total waste by 2030 and to achieve 55% recycling of municipal waste by 2025, in compliance with EU Directive 2018/851. To achieve these objectives, the Greek government has introduced new waste valorization infrastructure through public–private partnerships (PPPs) and EU Cohesion Fund-supported projects, including the construction of MBT plants, anaerobic digestion (AD) units, and thermal valorization facilities (WtE plants) [50].

However, current energy and waste management frameworks remain constrained by high dependence on imported fossil fuels and uneven regional infrastructure. Approximately 65% of the country's electricity is still generated from natural gas and petroleum derivatives, while renewable sources—mainly wind and solar—account for the remaining 35% [51]. Although Greece has made substantial progress in renewables deployment, seasonal demand fluctuations and grid limitations create opportunities for WtE plants to provide stable, dispatchable energy while simultaneously diverting waste from landfills.

Recent environmental and political developments have accelerated national discussions on WtE deployment. The Integrated Waste Management Plan for Attica foresees the establishment of a large-scale WtE plant with a processing capacity of approximately 350,000 tons/year, intended to serve as the final treatment option for residual waste following separation and recycling [52]. Parallel projects have been proposed for Central Macedonia and Western Greece, focusing on RDF and SRF (Solid Recovered Fuel) utilization in co-processing facilities or dedicated incineration units. Such initiatives aim to reduce the significant volume of RDF currently transported to cement kilns or exported abroad, which contributes to high transport-related emissions and logistical costs.

The waste composition and quantities for Greece are summarized in Table 1, illustrating the predominance of organics and recyclable materials within the total waste stream.

Table 1. Waste composition and quantities in Greece.

Waste Type	Paper	Plastic	Glass	Metals	Textile	Organic	Others	Total
Fraction (%)	20	17	5	3	3	44	8	100
Quantity (tons)	1,080,000	918,000	270,000	162,000	162,000	2,376,000	432,000	5,400,000

The existing waste management model in Greece (business-as-usual, BAU scenario) consists of mixed-waste collection followed by landfill disposal, with limited pre-treatment or energy recovery. There are several MBT or waste treatment units in Greece, some operational, some under construction, which produce limited RDF/SRF streams. However, none of them includes integrated energy recovery, and the majority of the RDF/SRF generated is co-incinerated in cement kilns or exported. Current MBT capacity (≈0.8 million t/year) covers only about 30% of the target set in the National Waste Management Plan [52]. This results in increased greenhouse gas (GHG) emissions from transportation and underutilization of local energy potential.

The waste sector in Greece contributes approximately 7.97% of total national emissions [53]. Most of these GHG emissions originate from methane released by unmanaged or semi-controlled landfills. Implementation of advanced WtE systems—particularly when integrated with pre-sorting, material recovery, and AD units—can potentially reduce GHG emissions by 40–60% relative to baseline scenarios, while generating renewable energy from the biogenic fraction of RDF.

Given its geographical configuration, Greece also faces unique logistical challenges in waste transportation. Many of its islands and remote mainland areas experience high per-unit transport costs for RDF and SRF, often exceeding the environmental benefits of centralized processing. The spatial distribution of WtE plants, therefore, is a key factor influencing both environmental and economic performance.

The case of Greece exemplifies a Southern European context where regulatory reforms, circular economy objectives, and decarbonization commitments intersect with persistent operational inefficiencies and infrastructural gaps. Applying the proposed ISWM–LCA framework allows for a comprehensive evaluation of how the deployment and spatial optimization of WtE facilities can enhance national resource efficiency, reduce landfill dependency, and align Greece with the EU's Green Deal objectives for 2050.

3. Materials and Methods

A systematic and structured methodology was applied in the present study to perform a comprehensive Life Cycle Assessment (LCA) of alternative Waste to Energy (WtE) plant siting strategies. The approach followed a sequential framework to ensure transparency, comparability, and reproducibility of results.

- In the first stage, the proposed management scenarios were defined, each incorporating WtE systems as key components for the valorization of residual municipal waste that could not be economically or technically recycled. The scenarios reflected different sizes of treatment infrastructure, plant location, and RDF transport distances, thus capturing a range of spatial and operational conditions.
- In the second stage, a detailed life cycle model was developed to represent the examined strategies by integrating all relevant processes, system boundaries, material and energy flows, and project phases.

The environmental performance of the proposed systems was quantified through multiple impact categories, focusing primarily on global warming potential (GWP), primary energy demand, air pollutant emissions, and resource depletion. To illustrate the applicability and adaptability of the proposed framework, the methodology was implemented in the Greek context, where integrated and sustainable waste management solutions are increasingly required to meet ambitious environmental and circular economy targets.

3.1. Waste Management Scenarios

In the context of this study, an attempt is made, using the Life Cycle Analysis methodology, to compare a scenario, which concerns the management of RDF in large WtE plants, with an alternative, decentralized management scenario in smaller, locally implemented WtE plants.

Figure 4 presents the maps of the two spatial organization schemes applied in this study, depicting both the regional units of the WtE plants and their corresponding serviced areas, with each serviced area distinguished by a unique color.

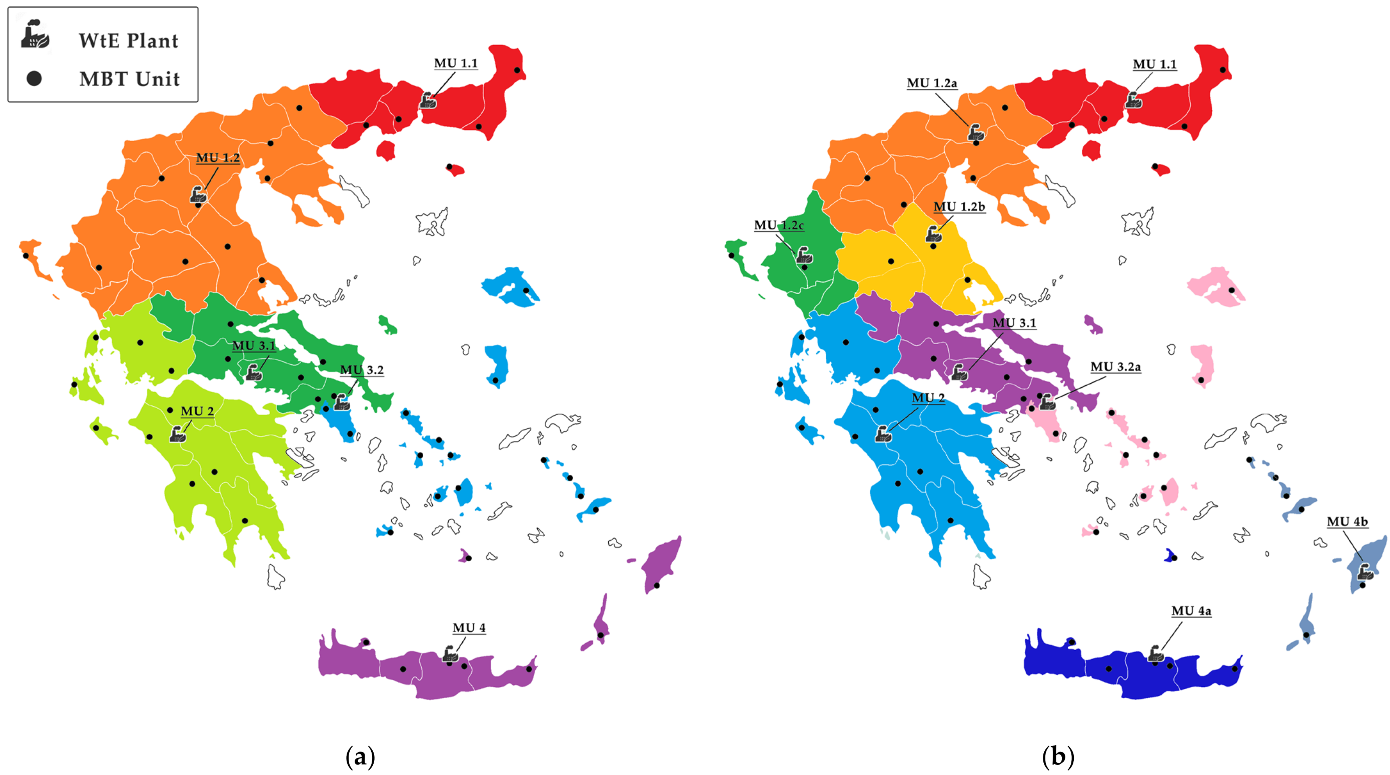

Figure 4. Comparison of two spatial structuring approaches for (**a**) Centralized scenario and (**b**) Decentralized scenario.

A critical assumption is the stability of the RDF and residue flows resulting from the existing (WtE) and future WtEs. The analysis considers that these quantities are sufficient to supply both the central and decentralized units, with different locations and combinations. At the same time, the hierarchical priority given to recycling is considered, so that WtE units operate exclusively as a complementary solution for managing the constantly decreasing quantities, due to increase in recycled materials, of non-recyclable residues. Overall, the above parameters and assumptions define the methodological framework of the analysis, enabling a comparative assessment between centralized and decentralized models of WtE plants development in terms of cost, environmental footprint, and operational flexibility.

3.1.1. Centralized Scenario

The centralized scenario that is also proposed by the Greek Ministry of Environment and Energy includes six WtE plants. Table 2 presents the spatial characteristics of the centralized scenario in terms of regional unit, service area and capacity.

3.1.2. Decentralized Scenario

In the context of the comparative assessment, the possibility of decentralized development of WtE plants is examined, in comparison with the centralized scenario which foresees fewer but larger centralized facilities. The analysis that follows presents variations in management units 1.2, 3.2 and 4, with the aim to reduce transportation requirements, achieve better geographical distribution of capacities and limit the overall environmental consequences (carbon footprint).

In the case of MU1.2, the centralized scenario foresees the development of a single large unit in the Regional Unit of Kozani, with a total capacity of 309,000 tons of RDF per year. The alternative scenario proposes the development of three smaller units: one in the Western Sector of Western Macedonia with a capacity of 225,711 tons per year, one in Larissa with a capacity of 44,839 tons and one in Epirus with a capacity of 38,599 tons. In this way, better geographical coverage is met and a significant reduction in the need for RDF transport over long distances is achieved.

Table 2. Characteristics of centralized scenario in terms of management unit, regional unit, service area and capacity.

Management Unit (MU)	Regional Unit	Serviced Area	Capacity (t/y)
MU1.1	Regional Unit of Rhodopes	Eastern Macedonia–Thrace	54,000
MU1.2	Regional Unit of Kozani	Central Macedonia, West Macedonia, Epirus, Thessaly and part of the Ionian Islands (Corfu)	309,000
MU2	Regional Unit of Arcadia or Elis or Achaea	Western Greece, Peloponnese and part of the Ionian Islands (except Corfu)	125,000
MU3.1	Regional Unit of Boeotia	Central Greece and part of Attica	244,000
MU3.2	Administrative region of Attica	Attica Region (part), North Aegean, part of South Aegean	215,000
MU4	Regional Unit of Heraklion	Region of Crete and part of the South Aegean	105,000
Total			1,052,000

Accordingly, in MU3.2, the centralized scenario includes the construction of a central unit in Attica, with a capacity of 215,000 tons per year. The alternative scenario proposes the development of two units: one in Attica with a capacity of 189,086 tons per year, which also serves the Cyclades (Andros, Tinos, Syros, Mykonos, Paros, Naxos and Milos), and one in Lesvos with a capacity of 13,657 tons, which covers the needs of Lesvos and Chios. This option significantly reduces the cost and environmental burden of maritime transport.

In MU4, the centralized scenario foresees a central unit in Heraklion with a capacity of 105,000 tons per year. The alternative scenario is differentiated by the creation of two smaller facilities: one in Heraklion with a capacity of 82,590 tons per year, serving Santorini, Chania, Amari, Heraklion, Sitia and Hersonissos, and one in Rhodes with a capacity of 34,477 tons, covering the islands of Rhodes, Patmos, Leros, Kalymnos, Kos and Karpathos. This proposal allows for better coverage of the island regions and limits the extensive and costly maritime transport.

Overall, the capacity of the alternative scenario remains essentially the same as that of the centralized scenario (approximately 1,052,000 tons per year) as reflected in Table 3. The main differentiation is found in the decentralized location of the units, which leads to a reduction in long-distance transport and consequently to a reduction in the overall transport cost and environmental footprint.

Table 3. Characteristics of decentralized scenario in terms of management unit, regional unit, service area and capacity.

Management Unit (MU)	Regional Unit	Serviced Area	Capacity (t/y)
MU1.1	Regional Unit of Rhodopes	Eastern Region Macedonia–Thrace	54,000
MU1.2a	Western Sector of the P.D.M.	Western Macedonia, Serres, East/West Sector of the PKM	225,711
MU1.2b	Regional Unit of Larissa	Larissa, West Thessaly, Magnesia	44,839
MU1.2c	Administrative region of Epirus	Epirus, Corfu	38,599
MU2	Regional Unit of Arcadia or Elis or Achaea	Regions of Western Greece, Peloponnese and part of the Ionian Islands (except Corfu)	125,000
MU3.1	Regional Unit of Boeotia	Region of Central Greece and part of Attica	244,000
MU3.2a	Administrative region of Attica	Attica (part), Cyclades (Andros, Tinos, Syros, Mykonos, Paros, Naxos, Milos), Lesvos, Chios	202,743
MU4a	Regional Unit of Heraklion	Santorini, Chania, Amari, Heraklion, Sitia, Hersonissos	82,590
MU4b	Regional Unit of Rhodes	Rhodes, Patmos, Leros, Kalymnos, Kos, Karpathos	34,477
Total			1,052,000

3.2. Life Cycle Assessment

3.2.1. Goal and Scope Definition

The goal of this study is to evaluate the environmental footprint of an alternative element of the MSW management strategies, namely the energy exploitation of the produced RDF stream, through an LCA approach. The analysis compares a centralized scenario with an alternative scenario involving a higher number of smaller, decentralized WtE plants.

The assessment was carried out using the SimaPro software package (9.2.0), which enables quantification and comparison of environmental impacts across complex waste management systems. The LCA methodology follows the international standards ISO 14040 and ISO 14044, ensuring methodological consistency, transparency, and comparability with similar studies [54,55].

The functional unit (FU) is defined as the total annual transport of residual waste at the national level (t/year), representing the overall quantity of material transferred from Recovery and Recycling Facilities (RRFs) to WtE plants. The system boundaries extend from the exit point of residual streams at RRFs to their delivery at WtE plants, covering both road and maritime transport. This unit enables a direct comparison of siting configurations by standardizing the mass of RDF requiring transport while explicitly capturing distance, modal choice, and vehicle characteristics. It is acknowledged that this functional unit does not incorporate potential differences in energy-conversion efficiency between large and small WtE plants. However, these technological variations fall outside the scope of the present transport-focused assessment. The functional unit therefore reflects a deliberate methodological choice to prioritize the quantification of spatial and logistical effects within the national waste-management system.

The scope includes all processes related to the transport of RDF, including fuel consumption, transport work (tkm), and associated emissions of GHG emissions and air pollutants.

3.2.2. Life Cycle Inventory (LCI)

The LCI phase involved the systematic collection and organization of quantitative data describing RDF transport flows under each scenario. For each management region, information was compiled on:

- RDF quantities (t/year),
- Transport distances (km),
- Mode of transport (road or maritime), and
- The resulting transport work (tkm) for each route.

Transport distances were categorized as either road or sea to reflect the differences in energy consumption, emission factors, and operational costs associated with each mode. Road transport was modelled using a 16–32-ton Euro 4 truck, whereas maritime transport was represented using ferries operating on actual national shipping routes. The ecoinvent database (version 3.9.1) was employed to model background processes, providing standardized energy, fuel, and emissions data. All collected information was then organized into two comprehensive LCI datasets corresponding to the centralized and decentralized scenarios as shown in Table 4.

3.2.3. Life Cycle Impact Assessment

This phase was conducted in SimaPro software, following a problem-oriented (midpoint) approach based on the ReCiPe 2016 Midpoint (H) methodology to quantify the environmental impacts associated with each scenario. The assessment covered all relevant midpoint impact categories to ensure a comprehensive evaluation of environmental performance, presented in Table 5.

Table 4. Input data for the compared scenarios.

Scenario	Management Unit (MU)	Road Transport (tkm)	Sea Freight (tkm)
Centralized	MU1.1	4,516,745	19,787
	MU1.2	49,028,152	424,303
	MU2	14,622,441	480,131
	MU3.1	40,778,875	N/A
	MU3.2	4,845,348	12,001,809
	MU4	6,741,542	7,180,788
	Total	120,533,103	20,106,818
Decentralized	MU1.1	4,516,745	19,787
	MU1.2a	7,816,003	N/A
	MU1.2b	2,323,001	N/A
	MU1.2c	993,848	424,303
	MU2	14,622,441	480,131
	MU3.1	40,778,875	N/A
	MU3.2a	4,089,456	5,289,410
	MU4a	5,215,267	658,935
	MU4b	1,077,906	1,866,046
	Total	81,433,542	8,738,613

Table 5. ReCiPe 2016 Midpoint impact categories and units.

Impact Category	Unit
Global Warming Potential	(GWP, 100-year, kg CO_2-eq)
Stratospheric Ozone Depletion	(ODP, kg CFC-11-eq)
Ionizing Radiation	IR, kg Co-60-eq
Ozone Formation, Human Health	kg NO_X-eq
Ozone Formation, Terrestrial Ecosystems	kg NO_X-eq
Fine Particulate Matter Formation	kg $PM_{2.5}$-eq
Terrestrial Acidification	kg SO_2-eq
Freshwater Eutrophication	kg P-eq
Marine Eutrophication	kg N-eq
Terrestrial Ecotoxicity	kg 1,4-DCB-eq
Freshwater Ecotoxicity	kg 1,4-DCB-eq
Marine Ecotoxicity	kg 1,4-DCB-eq
Human Carcinogenic Toxicity	kg 1,4-DCB-eq
Human Non-Carcinogenic Toxicity	kg 1,4-DCB-eq
Land Use	m^2·year crop-eq
Mineral Resource Scarcity	kg Cu-eq
Fossil Resource Scarcity	kg oil-eq
Water Consumption	m^3

Characterization factors and equivalence units were applied according to ReCiPe 2016 Midpoint (H) to ensure methodological consistency and comparability with established waste management LCAs. The results highlight the relative environmental performance of each management scenario, demonstrating the influence of transport distances, transport mode, and decentralization level on greenhouse gas emissions, energy efficiency, and broader environmental impacts within the national waste management system.

3.3. Operational Cost Estimation

The operational cost estimation for RDF transport was developed using a procedure based entirely on the available technical and logistical data. The aim was to quantify the transport-related economic implications of each scenario without extending the analysis beyond the scope of the study or introducing assumptions not supported by data.

For each MU, key inputs include the annual RDF quantity Q, the one-way distance to the WtE plant d, vehicle payload limits, cargo volume, the density of RDF, and operational characteristics such as the number of working days per year, available daily driving hours, average travel speed v, and loading/unloading times.

The effective load per trip is determined by comparing the maximum payload with the volume-constrained load derived from the product of cargo volume and RDF density. The resulting load per trip is therefore expressed as:

$$L = \min(\text{payload},\ \text{volume} \times \text{RDF density})$$

Transport cycle duration is estimated by combining travel and handling times. Round-trip travel time is obtained from:

$$t_{\text{travel}} = \frac{2d}{v}$$

and the total cycle time is defined as:

$$t_{\text{cycle}} = t_{\text{travel}} + t_{\text{loading}} + t_{\text{unloading}}$$

The annual number of trips required to move the total quantity Q is given by:

$$N_{\text{trips/year}} = \frac{Q}{L}$$

This value is distributed across the number of working days to derive the daily trip requirement. The maximum number of trips that one vehicle can perform per day is determined by:

$$\text{Trips/day/vehicle} = \frac{\text{working hours/day}}{t_{\text{cycle}}}$$

which enables the computation of the required fleet size:

$$N_{\text{vehicles}} = \frac{N_{\text{trips/day}}}{\text{Trips/day/vehicle}}$$

Transport activity is subsequently quantified through the total annual distance travelled, computed as:

$$\text{km/year} = N_{\text{trips/year}} \times (2d)$$

while the corresponding ton-kilometers are expressed as:

$$\text{tkm/year} = Q \times (2d)$$

Fixed and variable cost components are then calculated. Fixed annual costs include vehicle depreciation, defined as:

$$\text{Depreciation/year} = \frac{\text{Purchase price}}{\text{Lifetime}}$$

as well as driver labor cost, insurance, taxes, and administrative overheads. Variable costs consist of fuel consumption, maintenance expenditure, and toll charges. Fuel cost per kilometer is quantified as:

$$C_{\text{fuel/km}} = \frac{\text{Fuel consumption (L/100 km)}}{100} \times \text{Fuel price}$$

and the variable cost incurred per trip is given by:

$$C_{\text{var/trip}} = (C_{\text{fuel/km}} + C_{\text{maint/km}}) \times (2d) + \text{tolls}$$

Total variable cost is obtained by multiplying this value by the annual number of trips. A profit margin, defined per trip, is then added to reflect operator pricing practices:

$$C_{profit} = \text{Profit per trip} \times N_{trips/year}$$

The overall annual transport cost is therefore described by:

$$C_{total} = C_{fixed} + C_{variable} + C_{profit}$$

Finally, specific transport costs are derived by normalizing the total annual cost for the transported quantity and the transport work. The cost per ton of RDF is:

$$€/t = \frac{C_{total}}{Q}$$

and the primary economic indicator used for scenario comparison, the specific cost per ton-kilometer, is:

$$€/tkm = \frac{C_{total}}{tkm/year}$$

This cost indicator enables a direct and consistent comparison between the centralized and decentralized RDF transport configurations assessed in this study.

The input data used in the transport cost model are presented in Table 6, summarizing all logistical, operational, and economic parameters required for the calculation of the specific transport cost (€/tkm).

Table 6. Input parameters used in the transport cost model.

Parameter	Symbol	Unit	Value *
Annual RDF quantity	(Q)	t/year	25,000–250,000
Average load per trip	(L)	t/trip	20
Average distance producer–plant (one-way)	(d)	km	30–250
RDF bulk density	–	t/m^3	0.35
Delivery days per year	–	days/year	300
Average vehicle speed	(v)	km/h	70
Average loading time	–	min	45
Average unloading time	–	min	30
Vehicle cargo volume	–	m^3	70
Gross vehicle weight	–	t	40
Maximum payload	–	t	26
Vehicle purchase cost (used truck)	–	€	100,000
Vehicle economic lifetime	–	years	5
Other vehicle fixed costs (taxes, permits, insurance)	–	€/vehicle	3000
Driver salary	–	€/month	1500
Benefits, insurance etc.	–	% of salary	0.4
Salary months	–	months/year	14
General overheads (admin, office, etc.)	–	% of salary	0.2
Taxes & social insurance	–	%	0.0327
Vehicle maintenance cost	–	€/100 km	7.1682
Fuel consumption	–	L/100 km	31.1
Fuel price	–	€/L	1.67
Tolls per round trip (average)	–	€/trip	50.46
Transporter profit margin	–	% of OPEX	0.1

* All input values were derived from authoritative data provided by official institutions and agencies of the Hellenic Republic.

4. Results

4.1. Environmental Assessment

The application of the LCA methodology to the two approaches allowed for the comparative assessment of their environmental impacts across a wide range of categories, as defined by the ReCiPe 2016 Midpoint method. The results are presented in relative indices, where the centralized scenario is set as the base (100), and the values of the alternative scenario with decentralized siting are expressed proportionally (Figure 5). In this way, the relative improvement or burden resulting from the adoption of the alternative approach is clearly recorded.

The analysis of the results shows that the alternative scenario with decentralized WtE plants presents environmental superiority over the centralized one. In all impact categories of the ReCiPe Midpoint method, the alternative scenario displays lower values, with improvements ranging from 33% to 45%. The most significant improvement is recorded in the planet's Global Warming Potential-Global Warming up Potential (CO_2eq emissions), where approximately 35% reduction is achieved for the decentralized scenario. Similarly, in the categories directly linked to transport, such as acidification (terrestrial acidification) and the formation of suspended particles (fine particulate matter formation), the reduction exceeds 40%, which demonstrates the role of decentralized siting of WtE plants and the reduction of long-distance maritime transport and road haulage. In secondary categories—such as resource consumption and human and ecological toxicity—the reductions range from 33% to 37%, further confirming the environmental advantages of the decentralized scenario.

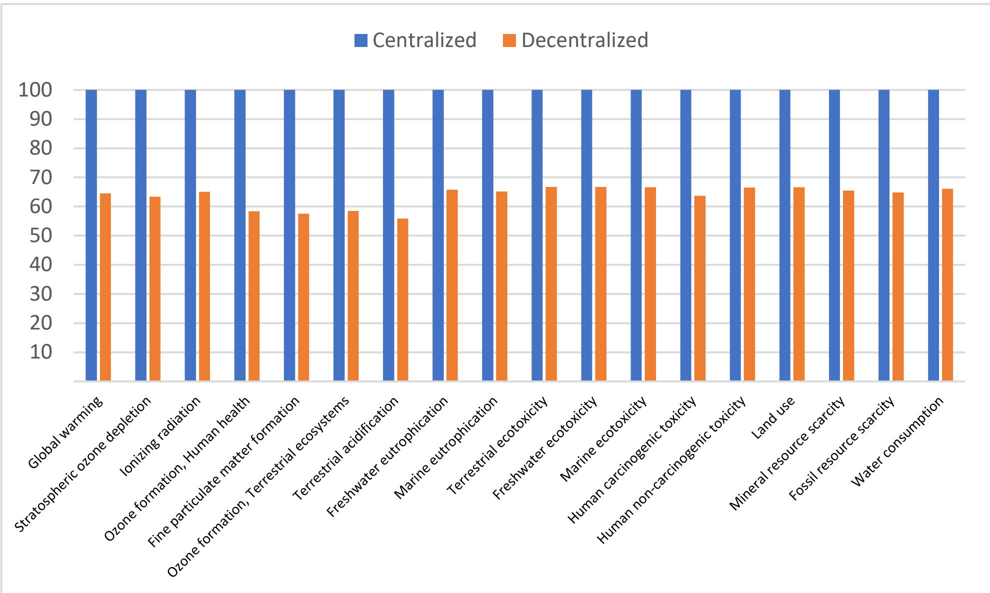

Figure 5. Comparative assessment of environmental impacts by category (ReCiPe Midpoint) for the compared scenarios.

The most pronounced reduction occurs in Global Warming Potential (GWP), where the decentralized configuration achieves a 35% decrease in CO_2eq emissions relative to the centralized scenario. More specifically, the emissions results for each scenario are presented in Tables 7 and 8.

The total emissions for the centralized scenario amount to 2.22×10^7 kg CO_2eq. The picture is highly concentrated, as only two management plants, MU1.2 (36.8%) and MU3.1 (30.4%), cover almost 67% of total emissions. The remaining plants exhibit a clearly smaller contribution: MU2 participates with 11.1%, MU3.2 with 9.6%, MU4 with 8.6%, while MU1.1 is limited to only 3.4%. This shows that large centralized WtE plants indirectly create a high environmental footprint due to extensive transport (Scope 2 emissions).

In the alternative scenario with decentralized location, emissions are reduced to 1.43×10^7 kg CO_2 eq, i.e., approximately 35% lower. The picture is more decentralized, as MU1.2 has been split into three sub-units (1.2a, 1.2b, 1.2c), with a corresponding redistribution of emissions: 9.0%, 2.7% and 0.5% respectively. The largest contribution remains at MU3.1 (47.2%); however, the remaining units now have smaller values and a more balanced participation. Also, the new units in Heraklion and Rhodes contribute to the reduction of long-distance maritime transport, with small but significant percentage contributions (0.7–6.6%).

Table 7. CO_2eq emissions results per management unit for the centralized scenario.

Management Unit	CO_2eq Emissions (kg)
MU1.1	7.50×10^5
MU1.2	8.17×10^6
MU2	2.47×10^6
MU3.1	6.75×10^6
MU3.2	2.12×10^6
MU4	1.91×10^6
Total	2.22×10^7

Table 8. CO_2eq emissions results per management unit for the decentralized scenario.

Management Unit	CO_2eq Emissions (kg)
MU1.1	7.50×10^5
MU1.2a	1.29×10^6
MU1.2b	3.85×10^5
MU1.2c	7.04×10^4
MU2	2.47×10^6
MU3.1	6.75×10^6
MU3.2a	1.26×10^6
MU4a	9.36×10^5
MU4b	3.84×10^5
Total	1.43×10^7

4.2. Cost Assessment

Table 9 presents the total ton-kilometers of the waste transport system for each scenario.

Table 9. Total ton-kilometers for each scenario.

Scenario	Road Transport (tkm)	Sea Transport (tkm)
Centralized	120,533,103	20,106,818
Decentralized	81,433,542	8,738,613
Reduction (%)	32.4%	56.5%

Based on the data above, the cost estimate for one year of operation is estimated in Table 10.

In road transport, a reduction of approximately 33% in ton-kilometers is observed, which is reflected in lower costs for fuel, vehicles and personnel. The difference is even more pronounced in maritime transport, where the reduction in ton-kilometers exceeds 50%, leading to a significant reduction in the corresponding cost. The lower transport activity is also reflected in the environmental cost, which is reduced by almost 33% in the alternative scenario. Combined, these differences lead to a total cost expressed at €23,971,608/year for the decentralized scenario, compared to €34,462,521/year for the centralized scenario, i.e., approximately 31% lower. The results show that the rational geographical distribution of WtE plants decisively affects the economic and environmental balance of the transport system.

Table 10. Cost estimation results per year.

Type	Centralized	Decentralized
Road transport costs (€/y)	24,106,621	16,286,708
Sea transport costs (€/y)	8,912,900	6,755,400
Environmental cost (€/y)	1,443,000	929,500
Total cost transportation (€/y)	34,462,521	23,971,608
Specific cost (€/ton)	32.76	22.79

A simple sensitivity analysis was performed to evaluate the effect of the carbon price on the total and specific management costs under the centralized and decentralized configurations. Varying the carbon price between €60 and €120 per ton of CO_2 resulted in only a marginal change in total system costs (Table 11). For the centralized scenario, total annual costs increased from approximately €34.4 million to €35.7 million, while for the decentralized system they rose from €23.9 million to €24.8 million. On a specific cost basis, this corresponds to an increase of roughly €1.3/t for the centralized option and €0.8/t for the decentralized one. These results indicate that the comparative economic advantage of the decentralized configuration remains robust within plausible carbon price ranges, reflecting its lower emission intensity and more balanced cost structure.

Table 11. Carbon Price Sensitivity Analysis (€/tCO_2: 60–120).

Scenario	Total Annual Cost (M€/y)	Specific Cost (€/t Waste)
Centralized (60 €/tCO_2)	34.35	32.65
Centralized (120 €/tCO_2)	35.68	33.92
Decentralized (60 €/tCO_2)	23.90	22.72
Decentralized (120 €/tCO_2)	24.76	23.53

5. Discussion

5.1. Effects of Decentralization

The results of this study clearly demonstrate that decentralizing RDF-to-energy infrastructure reduces environmental impacts in the Greek MSW system. Across all ReCiPe categories, decentralization leads to 33–45% lower impacts, including a 35% reduction in GWP, compared with a centralized siting strategy. These findings confirm that the spatial configuration of WtE systems is a primary determinant of their environmental performance, consistent with evidence that transportation often dominates waste-system emissions [56].

The underlying mechanisms are driven by logistics. In the centralized scenario, long-distance transport—and especially maritime transport, which has higher emission factors due to fuel type and energy intensity—accounts for a disproportionate share of total impacts. Reducing transport distances thus yields systemic benefits that exceed the marginal differences between treatment technologies themselves. This pattern aligns with prior LCAs showing that environmental burdens rise sharply when organic or combustible waste streams must be moved over long distances [57].

Studies of organic waste systems in China show that decentralized strategies (e.g., black soldier fly treatment and local composting) achieve dramatic reductions in GWP and acidification—up to 96–97% and 80–81%, respectively—by eliminating long-distance transport and central incineration [58]. Additionally, LCA research in Thailand similarly finds that integrating on-site or near-site treatment significantly reduces transport-related emissions and improves overall environmental performance [59].

In Montreal, decentralization of recyclable-waste sorting facilities reduced CO_2 emissions by 20% and operating costs by 8%, mainly by shortening collection routes and decreasing the distance traveled per ton of waste [60].

Spatial optimization studies highlight that treatment-facility service areas have clear break-even distances, beyond which environmental and economic performance rapidly deteriorates [61]. These models show that transport distance—not plant size—often determines the viability of waste-recovery chains. More importantly, evidence from thermal treatment systems supports the conclusion that losses in energy-conversion efficiency associated with smaller-scale WtE units are modest. While large plants may reach efficiencies close to 30%, well-designed small and medium plants typically operate at 20–24%, indicating that scale losses are real but not prohibitive [62]. When considered alongside the substantial logistic savings demonstrated in our study, these moderate scale penalties are outweighed by the transport-related benefits of decentralization. In other words, the environmental penalties associated with smaller capacity are minor compared with the gains from reducing long-haul and maritime waste transport.

Collectively, these studies reinforce a general conclusion: when treatment performance is comparable, system impacts are dominated by transportation, especially for bulky, high-moisture, or energy-dense materials such as organics or RDF. The reductions observed in our study therefore reflect mechanisms well-documented in international literature, indicating that the environmental advantages of decentralization are not Greece-specific but structurally inherent to waste-logistics dynamics.

These results underscore the importance of incorporating spatial planning into national WtE policy. Greece's geographic fragmentation and reliance on maritime transport amplify the environmental penalties of centralized infrastructure. A decentralized RDF-to-energy network could:

1. Reduce transport emissions and costs;
2. Enhance system resilience by distributing capacity;
3. Improve alignment with EU circular-economy objectives by minimizing avoidable environmental burdens.

5.2. Limitations

Several limitations should be noted. First, this study focuses on environmental and transport-cost impacts and does not incorporate social acceptance, siting conflicts, or investment requirements—factors that can influence the feasibility of decentralized systems. Second, differences in plant-level emissions performance or operational efficiencies across technologies could alter absolute results, even though transport remains the dominant factor. Finally, dynamic factors such as evolving RDF composition or future grid decarbonization were not modeled.

Despite these limitations, the consistency of the results with broader international patterns indicates that decentralized RDF-to-energy infrastructure constitutes a more environmentally robust and spatially appropriate configuration for the Greek MSW system.

5.3. Further Challenges

Centralized WtE plants present a range of challenges that must be carefully considered within the framework of strategic waste management planning. A fundamental issue concerns the long-term security of feedstock supply, particularly the availability of RDF and SRF over operational lifetimes of 20–25 years. Ensuring a consistent flow of secondary fuels requires the collection of waste from dispersed regions, often involving complex contractual arrangements among multiple municipal and private actors. This creates uncertainties regarding both the stability of supply quantities and the consistency of fuel quality [63]. As a result, the uninterrupted long-term availability of suitable feedstock constitutes a critical factor for the technical and economic viability of large WtE plants.

A second challenge lies in the interaction between large-scale WtE capacity and national recycling objectives. Large plants require a continuous input of combustible waste to operate efficiently, which can create an indirect disincentive for enhancing source separation, recycling, and material recovery. This approach is in direct conflict with the waste hierarchy, Figure 1, which prioritizes waste prevention, reuse, and recycling above energy recovery. Experience from international examples such as Italy, the United Kingdom, and certain regions of Germany, indicates that over-reliance on large WtE infrastructure can, in some cases, hinder the progress of recycling and prevention initiatives by locking waste streams into long-term incineration contracts [64].

Financial considerations further complicate the feasibility of large WtE projects. These facilities are characterized by high capital expenditure (CAPEX) and significant upfront financial commitments, which increase exposure to market and regulatory risks. Concentrating investment in a small number of large installations reduces system flexibility and may impede future adaptation to evolving conditions. This is particularly relevant given the forthcoming inclusion of WtE facilities in the EU Emissions Trading System (ETS), expected from 2028 onwards. The incorporation of WtE plants into the ETS will necessitate additional significant investments for emissions monitoring, carbon accounting, and offset purchases, thereby increasing the overall operational costs and financial burden, especially for high-capacity plants with large combustion volumes.

Moreover, the operational costs of centralized WtE plants tend to escalate due to the extensive transportation of RDF and SRF required from wide geographical catchment areas. It is important to mention that extensive recycling rates in northern EU countries has led the Scandinavian and Netherlands large WtE Plants to import large quantities of RDF (notably from UK and Italy) to continue their operations.

The transport of high-volume, low-density materials such as waste fuels adds both economic and environmental pressure, contributing to increased fuel consumption and greenhouse gas (GHG) emissions along the entire supply chain.

Environmental concerns also represent a major area of scrutiny. Large WtE facilities function as point sources of emissions, necessitating stringent control and continuous monitoring of pollutants such as NO_X, SO_2, particulate matter, and traces of heavy metals. Although modern flue gas cleaning systems and advanced emission control technologies have improved environmental performance, the concentration of large combustion activities in a single site increases the localized environmental load, including cumulative air pollution and thermal effects. Additionally, the large-scale transportation of secondary fuels contributes to indirect emissions and extends the system's overall environmental footprint.

The social dimension is equally significant. The siting of large WtE plants frequently encounters strong opposition from local communities, often related to concerns about pollution, odor, visual impact, and traffic load associated with the importation of waste from other regions. Public resistance has been documented in several proposed Greek projects, such as the case of Western Macedonia, where municipalities and civil society organizations expressed strong objections to regional waste incineration facilities. Recent unanimous opposition for the centralized scenario has been recorded amongst local authorities. Concentrating large-scale infrastructure in limited areas can thus lead to severe social conflicts that may delay or even prevent implementation [65]. These realities underscore the importance of exploring decentralized or modular alternatives, which can be better aligned with regional waste generation patterns and local acceptance.

In contrast to large, centralized facilities, smaller WtE plants offer several advantages. They can be developed in modular phases, enabling gradual implementation, reduced initial and future (inclusion of carbon capture systems) investment requirements, and shorter permitting and construction periods. This phased approach enhances flexibility, allowing plant design and capacity to adapt to changing waste generation trends, recycling progress, and evolving regulatory frameworks. Smaller-scale systems also lower financial risk by reducing techno-economic risks, distributing investment over time and allowing incremental adjustments in technology and capacity. In several EU countries, including France, Denmark and the Netherlands, this approach has facilitated the progressive integration of new technologies, such as advanced gasification and high-efficiency cogeneration, without locking systems into rigid long-term feedstock commitments.

In summary, although large-scale, centralized WtE facilities are often associated with favorable economies of scale and process optimization potential, their applicability in regions characterized by heterogeneous waste generation profiles and evolving recycling frameworks—such as Greece—should be assessed. Emerging evidence indicates that appropriately scaled, modular WtE configurations can exhibit comparable energy.

6. Conclusions

The purpose of this study was to examine how the spatial organization of RDF-to-energy infrastructure shapes the environmental and economic performance of national waste systems. By explicitly integrating transport geography into a life-cycle perspective, the analysis clarifies an issue that has long been acknowledged in policy discourse but rarely quantified with system-wide evidence: the sustainability of WtE systems is fundamentally contingent on spatial design. This insight links back to the core motivation of the introduction, which emphasized that technological efficiency alone cannot determine the viability of modern waste infrastructures when the logistics surrounding them define most of their environmental footprints.

The findings illuminate a broader conceptual point: waste management cannot be treated as a purely technological problem, and must be considered a spatially embedded service system. When residual material must traverse large territories—particularly in geographically fragmented contexts like Greece—the environmental logic of large, centralized infrastructure becomes misaligned with the spatial realities of waste generation. The results show that the relationship between facility scale and sustainability is not linear; rather, it is mediated by the geography of transport. This reframes how WtE strategies should be evaluated, shifting the focus from maximizing thermal efficiency at a small number of large plants to optimizing the spatial distribution of treatment capacity within a national system.

This repositioning has methodological implications as well. The study demonstrates that incorporating explicit spatial parameters into LCA provides a more realistic approximation of national-level impacts than process-based comparisons alone. It also illustrates how spatially resolved assessments can bridge the gap between technical modeling and policy instruments such as the EU proximity and self-sufficiency principles. In doing so, the results strengthen the argument that environmental assessments of WtE infrastructures must reflect not only technological characteristics but also the territorial configurations within which they operate.

Beyond national application, the analysis contributes to a wider theoretical discussion within waste-systems research: decentralization is not merely a logistical adjustment but a structural strategy that reshapes the flows, risks, and governance of residual waste. A distributed network of WtE facilities can support more adaptive, resilient, and regionally balanced waste systems by reducing dependence on long-distance material flows and enabling modular investments instead of large, irreversible commitments. This reinforces the idea that spatial diversification is not a compromise solution but a legitimate sustainability pathway.

Several avenues emerge for future research. More dynamic modeling frameworks are needed to capture evolving waste compositions, energy-market interactions, and the potential integration of emerging low-carbon technologies. Moreover, coupling spatial LCA with social and economic assessments would provide a fuller understanding of how decentralized WtE infrastructures reshape local acceptance, regional equity, and long-term investment risk. Integrating these perspectives would support the development of planning tools capable of reconciling environmental performance with institutional, financial, and societal realities.

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Abbreviations

The following abbreviations are used in this manuscript:

AD	Anaerobic Digestion
AP	Acidification Potential
BAU	Business as Usual
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CO_2eq	Carbon Dioxide Equivalent
ETS	Emissions Trading System
EP	Eutrophication Potential
FE	Freshwater Eutrophication
FRS	Fossil Resource Scarcity
FU	Functional Unit
GHG	Greenhouse Gas
GWP	Global Warming Potential
HDV	Heavy-Duty Vehicle
IR	Ionizing Radiation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LU	Land Use
MBT	Mechanical–Biological Treatment
ME	Marine Eutrophication
MET	Marine Ecotoxicity
FET	Freshwater Ecotoxicity

TET	Terrestrial Ecotoxicity
MRS	Mineral Resource Scarcity
MU	Management Unit
NMVOC	Non-Methane Volatile Organic Compounds
ODP	Ozone Depletion Potential
OF-HH	Ozone Formation, Human Health
OF-TE	Ozone Formation, Terrestrial Ecosystems
OPEX	Operating Expenditure
PMF	Fine Particulate Matter Formation
POFP	Photochemical Ozone Formation Potential
RDF	Refuse-Derived Fuel
ReCiPe	Life Cycle Impact Assessment Method (ReCiPe 2016)
RRF	Recovery and Recycling Facility
SRF	Solid Recovered Fuel
tkm	ton-kilometer
WC	Water Consumption
WtE	Waste-to-Energy
YPEN	Hellenic Ministry of Environment and Energy

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