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Article

An Innovative and Alternative Waste Collection Recycling Program Based on Source Separation of Municipal Solid Wastes (MSW) and Operating with Mobile Green Points (MGPs)

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Abstract: Recently, among European Union (EU) member states, but also globally, there have been available and successful recycling and treatment practices of Municipal Solid Wastes (MSW). Greece has currently implemented low recycling levels, 21%, of the annually produced MSW, compared to the EU regulations. In 2021 the prefectural authorities of Attica Region launched a pilot program of rewarding recycling with source Separation called "THE GREEN CITY". This program consists of 60 mobile green points (MGPs) that serve at a unified citizen awareness and MSW collection at 7-streams network throughout the prefecture of Attica. In this study, the whole design analysis of "THE GREEN CITY" pilot recycling program contained estimations and calculations of (a) the distances of all waste collection remote itineraries (basic analysis); (b) the annual fuel cost of the MGPs for the realization of all waste collection remote itineraries (financial-based analysis); and (c) the annual carbon dioxide (CO_2) emissions into the atmosphere from the IVECO MGPs during the coverage of all waste collection remote itineraries (environmental-based analysis). Then a research synthesis of all these analyses revealed and evaluated the pilot recycling program's real capabilities and limitations in alignment with: (a) its ultimate goal to help Greece achieve the setting target of Directive 2018/851 for at least 55% by weight recycling and reuse of the total annually generated Greek MSW by 2025 and (b) the MGPs proven ability to support environmental sustainability in densely populated prefectures such as Attica.

Keywords: mobile green points; "THE GREEN CITY" recycling program; source separation; fuel cost; carbon dioxide emissions

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1. Introduction

Recently, there has been a high research interest in developing an integrated management of environment (IME) based on the principles of carbon capture and storage (CCS) and the MSW management. In such a way, the mechanical and the biological treatment of MSW produces a compost, from controlled temperature and moisture aerobic conditions, that enables the MSW decomposition in the presence of microorganisms and small invertebrates. This MSW treatment can be characterized as an environment-friendly waste disposal technique, supporting a low-cost source of adsorbent for CO_2 capture [1].

Another MSW treatment is the segregation of household waste by source separation. Subsequently, the waste collection is the responsibility of municipal authorities and certain public agencies. In such a way, the source separation supports a closed loop model of waste, in which raw materials and disposable matter can undergo recycling and a second round of use as consumable products [2–4], while simultaneously achieving the quantitative reduction of MSW disposed in landfills [5–8]. Besides, the review article of Karimi et al. [9] also supported that biomass, biochar, etc., could be proven promising resources of developing MSW management resources, especially in response to the exponential population expansion. Furthermore, Shah et al. [10] linked the accruing MSW globally as the result of evolving industrialization and economic growth, while simultaneously increasing the waste generation of Organization for Economic Cooperation and Development (OECD) economies. As a result, technological advancements (research and development, R&D) constitute a significant factor of waste generation reduction. Indeed, reduction coupled with reduction of the collected MSW could be proven beneficial to environmental protection and to the local or national economy, being particularly achievable when recyclable materials are generated after biological treatment of organic/food wastes [3,4,11].

2. Literature Review

The research focus of this study is the recyclable types of waste, such as paper and cardboard, plastics, metals and glass. These types of MSW are commonly collected at the existing collection points in the prefecture of Attica, which is the area the proposed pilot program of MSW collection was applied. The functionality of jointly treating waste materials for energy purposes has been investigated in recent literature. In such a study, a functional unit was applied for the management of municipal organic waste (food waste and garden waste) under the system boundary of "cradle to grave", which is shown in Figure 1. This is a life cycle assessment system accounted credits and environmental burdens of by-products or organic waste residuals by deploying datasets relevant to the "allocation at the point of substitution" (APOS) model. This holistic system boundary also integrates the life cycle processes of collection, transportation, treatment and by-product utilization. The most common forms of such a utilization are that of ash disposal, energy recovery and land application of compost (Figure 1) [12].

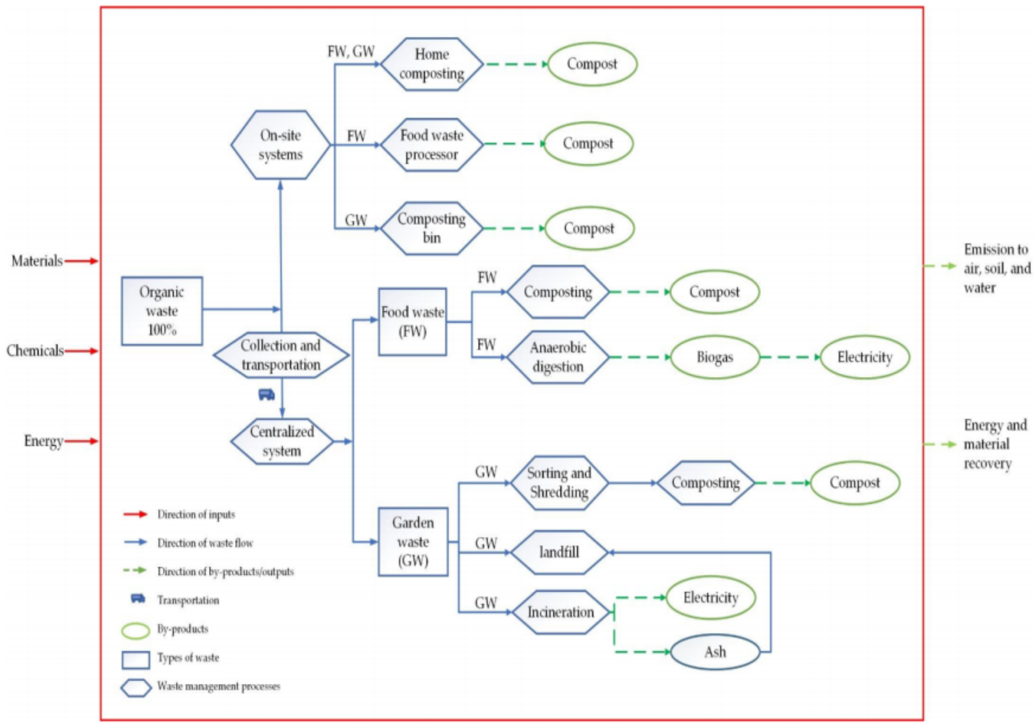

Figure 1. System boundary of the municipal organic waste management systems. Source: Rotthong et al., p. 5 [12].

Municipal solid waste (MSW) is commonly referred to as the unwanted or useless solid materials originating from joint residential, industrial and commercial activities at the built environment [1,13]. The reported annual MSW production was 2.01 billion metric tons in 2018, but it is expected to increase within the next 3 decades (in 2050) to around 3.40 billion metric tons annually. It is also noteworthy that about 13.5% of today's waste is recycled, and 5.5% is composted, while a large portion of 40% of waste generated worldwide is not properly managed. Besides, there is reported a large fluctuation of waste generated among developed and developing countries, since there are rich countries, including the United States, Canada and the European Union members, that have 16% of the global population but are responsible for more than 34% of the world's waste. In this context, there is an imperative need of actions and initiatives to be undertaken in order to manage and control such accruing MSW in the future. In response, the scope of this study is the development of a new and smart waste management strategy aimed at reducing the destructive effects of this huge amount of solid wastes. In particular, while a large number of research activities have focused on the development of new waste management strategies centered on treatment techniques for solid wastes, these strategies have shown operational constraints, such as the employment of extremely high temperatures, dumping on the land or extended storing/disposing sites in which the application of biological processes can treat the wastes and produce compost, being among the most popular strategies [1].

Therefore, the scope of our study is to introduce a novel strategy of MSW that focuses on the initial steps of MSW treatment, which are the collection and the transportation of MSW, while the other processes of MSW management, such as the physical, chemical or biological treatment of MSW, are out of the scope of this study. These two investigated steps are considered to be of primary importance for the MSW treatment, while the environmental impact of daily generating quantities of waste in Attica, which is a city of 3,000,000 inhabitants, is also considered. Subsequently, the study proposed a feasible alternative method of collecting and transporting MSW in large cities (as Athens is) and densely populated areas (in general). In such a way this study should offer a realistic and plausible future solution of improving the existing planning and facilities of MSW collection and transportation, being beneficial especially in cases when waste generation increases beyond the treatment capacity of existing waste management facilities, or period MSW overload at seasonal summer-winter holidays visitors in the Region of Attica (as a popular visiting destination). Of special environmental concern, MSW types in Attica are the bulky flows of waste from electrical and electronic equipment (WEEE), metal wastes and construction, demolition and excavation waste (CDEW). There is an abundant bibliography of studies on waste reuse or recycling MSW and raw materials savings, some of which proposed the incorporation of MSW fractions with other types of urban disposable materials, such construction materials, which could contribute to the implementation of a circular economy approach and could simultaneously alleviate the problem represented by MSW. Actually, the exact recycling and management of the aforementioned MSW types are considered waste treatment processes out of the scope of our study, but they have been extensively studied elsewhere [12–14].

3. MSW Concerns and Recycling Perspectives

3.1. International Overview

In a global context, it is noteworthy that MSW is a major contributor to the construction industry, counting 3000 million tons of natural resources annually and counting 34% of GHGs emissions globally. It can also be signified that a portion of at least one-third of the MSW produced globally is not managed in an environmentally sound manner. Another problematic utility of MSW is its conventional use as an energy source through incineration, entailing the generation of acid gases, polychlorinated dioxins and other persistent organic pollutants of environmental degradation and social opposition. The European Environment Agency (EEA), among others, proposed specific measures of controlling waste generation, mainly based on the principles of circular economy and the fostering of hydrogen and biofuel solutions and technologies for greener and healthier cities [13,15]. In this organizational context of MSW recycling and reusing, there are EU Directives obligating the household-wastes separate collection of (a) discarded textiles and hazardous household products (up to 1 January 2025) and (b) biological wastes' collection and treatment at the source (up to 31 December 2023) [15].

Examples of particular interest in worldwide MSW reuse are that of construction materials, having plastics incorporated as substitutes for sand in concrete and pavements production; paper as a hygrothermal and lighting regulator in buildings; and glass reuse as fine aggregate in concrete mixtures, while favoring a circular economy approach to reduce their landfilling practices, especially at the high flows of MSW generated in Latin America and the Caribbean [13].

3.2. The Case of Greece

In Greece, the most common way of MSW management, 77.7% of all MSW, is disposal in legal, or sparsely observed illegal, landfills. The second method choice is MSW recovery-recycling and composting, 21% of all MSW, while the third choice is the treatment for energy recovery purposes, 1.3% of all MSW [16]. From 2015 on, recycling in Greece has been enhanced, being followed by the nation's recovery from the economic crisis. However, there is a low pace adaptation with the EU recycling rates, since the recycling rate in Greece, only in late 2019, reached the average recycling rate of the EU in 1996, as it is shown in Figure 2 [16].

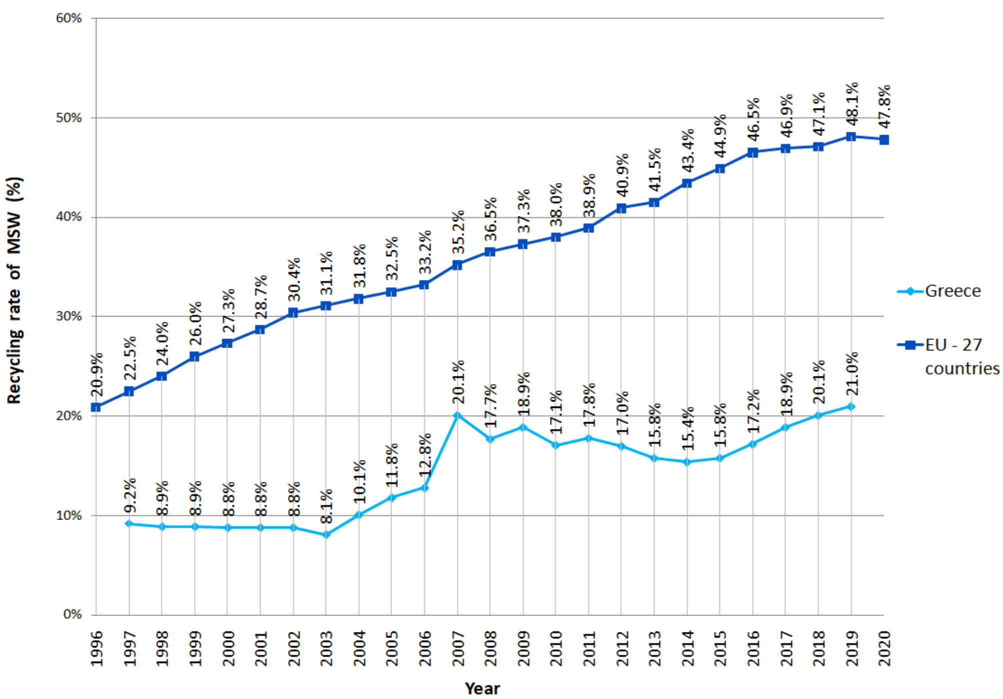

Figure 2. Trend of MSW recycling rates in Greece (light blue) and in the EU of 27 countries (dark blue), respectively, period 1996–2020. Source: Adapted from [16].

3.2.1. Operational Overview of the Pilot Program

The pilot program is called "THE GREEN CITY", and it is structured in alignment with the mobile green points (MGP) at selected areas of Attica, Greece. This is a rewarding program, and it is based on collecting various recycled materials and products in collaboration with the "Specialist Integrated Association of the Prefecture of Attica" (EDSNA, in Greek) in collaborating with private contractors, citizens and private companies. Subsequently, the "THE GREEN CITY" operation has been contracted by the EDSNA and a private recycling company [17].

The main types of recyclable MSW collected at the MGPs included [17]: paper, cardboard, transparent plastic bottles for liquids and food (PET), non-transparent plastic containers (PP, PS, HDPE, LDPE, PE and PVC), metals, aluminum, glass, edible oils, clothing and textiles.

The operation of this pilot program requires a daily mobilization of 30 MGP for each one of the municipalities participating, having three central spots of each one municipality (including schools, outdoor parking, supermarkets, parks). The MGPs are self-propelled vehicles of the prefecture of Attica that are driven by two employees, the driver and the environmental awareness specialist. The collecting and storing capacity of MGPs is 1.2 tons of clean recyclable materials per day, while organic wastes are excluded. The vehicles are 6.5–8.0 m long, making it easy to move and park within the densely populated municipalities. The MGPs collected and stored clean recyclable MSW at four large/big bags of 1 m^3 volume each, as well as machinery to compress paper and cardboard packing the MSW. Moreover, an internet connection is the place at which the collected materials are weighted and the gathered electronic points of "THE GREEN CITY" are rewarded (Figure 3).

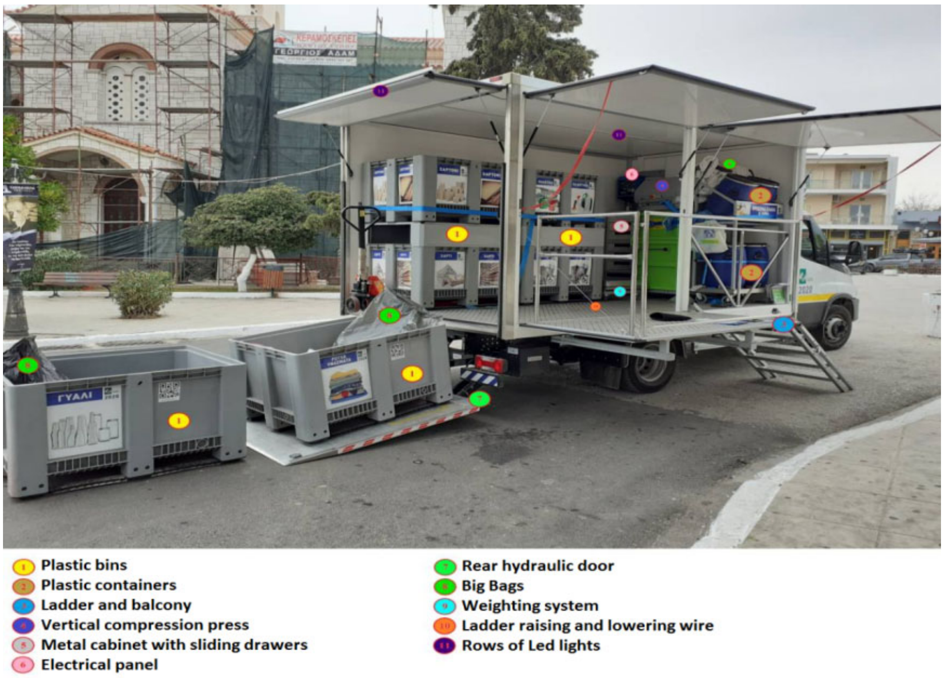

Figure 3. MGP basic equipment in full deployment. Source: Adapted from [14].

This pilot program covers more than 60 municipalities of the prefecture of Attica with over 3 million inhabitants. In particular this pilot program involves the collaboration with 62 of the 66 municipalities of the prefecture of Attica, as is shown in Figure 4. The four non-included municipalities of Attica are that of Athens, Piraeus, Hydra and Fyli. The time of modular installation of MGPs at each spot point of the cooperating municipalities is 1.0–2.5 hon weekdays (Monday–Friday), and the time plan of the "THE GREEN CITY" operation is that of working hours (9:30–15.40). A typical day of MGPs is the selection and the installment to those locations where information about the program tasks can be provided at public and private ownership (mainly businesses) [14].

Figure 4. Attica areas which are served (green color) and which are not served (white color) by the "THE GREEN CITY" recycling program. Adapted from [14].

3.2.2. MGPs Spatial Planning of the "THE GREEN CITY" Pilot Rewarding Program

The total public awareness and waste collection network of the MGPsin Attica have been geographically divided into eight main networks of remote sub-areas of Attica (Figure 5: Western, Eastern, Northeastern, Saronic and Kythera). They also concern the West-, East-, North- and South- suburbs of the Attica terrain [14]. In Figure 5, the spatial distribution of 562 MGPs is shown, in which a unified network of public awareness and waste collection has been developed. In particular, a portion of 312 (green pin) spots, i.e., 56%, is installed at recreation areas and parks; 95 (blue pin) spots, i.e., 17%, are installed at service hubs or educational hubs; 73 (yellow pin) spots, i.e., 13%, are installed at large-scale infrastructures; 59 (red pin) spots, i.e., 10%, are installed in commercial areas; and 17 (purple pin) spots, i.e., 3%, are installed at food-related shops like restaurants and cafes. Lastly, 6 (white pin) spots, i.e., 1%, are deactivated—inactive spots [14].

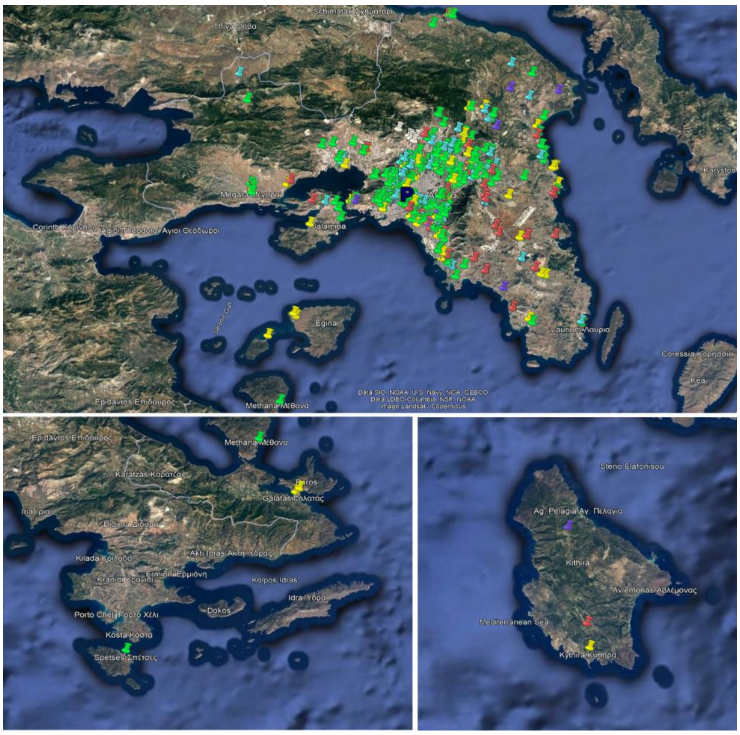

Figure 5. The network of public awareness and waste collection (all MGPs-spotted) of the pilot program. Adapted from [14].

4. Methodology

4.1. Methodology of Calculating Remote-Route Distances

This study calculated the distance in each of the routes that were carried out in Western, Eastern and Northeastern Attica (Figure 6). In these remote areas, the MGPs of “THE GREEN CITY” recycling program travel the longest distances in terms of time and kilometers from their central depot at Tavrou 50, which is their daily point of departure towards their final destination (daily municipal service). However, this study did not count the remote routes of the Saronic Gulf and Kythera, which both belong to the prefecture of Attica, since most of them are served by sea transport (Figure 6).

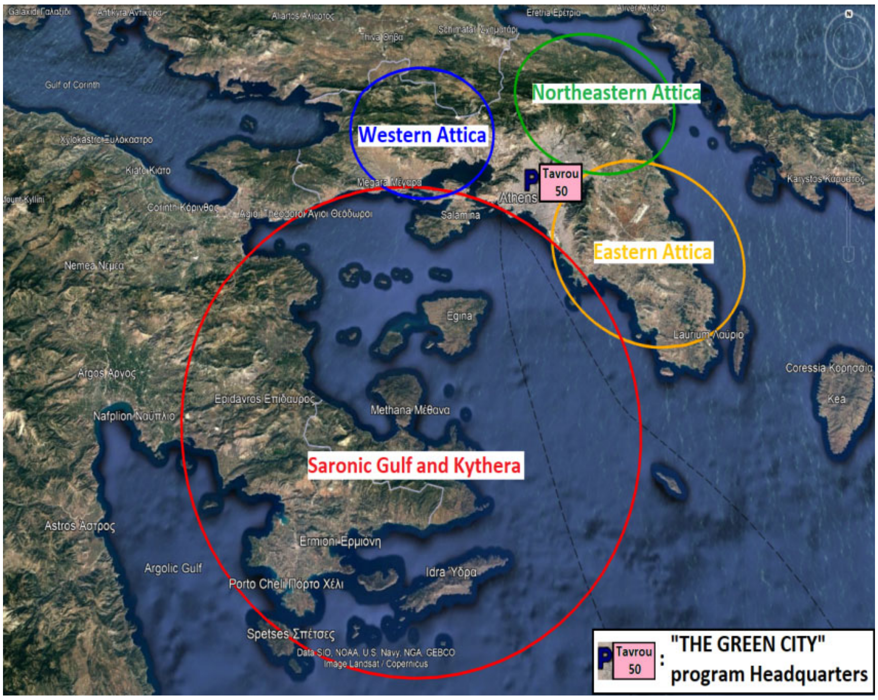

Figure 6. Map pointing out the remote areas of the prefecture of Attica, Google Earth Pro 2022. Source: Adapted from [18].

Initially, the Google Maps application was deployed to calculate the daily kilometer and time distances of each route of “THE GREEN CITY” recycling program at the remote subareas of Attica. Practically, each distance starts from the headquarters and central depot address of “THE GREEN CITY” recycling program at Tavrou 50, which is located in the municipality of Tavros-Moschato (Athens Metropolitan Area),and ends up at the designated service points for citizens and businesses (by the MGPs) in the territory of each served municipality in Attica. Finally, each of these distances was multiplied by the number “2”, i.e., ×2, in order to derive the round trip total time and kilometer distance that was traveled by each MGP of “THE GREEN CITY” program to each remote municipality in the Attica Prefecture.

The remote municipality of Megara is a typical example of calculating the time and kilometer distance by using the Google Maps application as it is presented below (Figure 7).

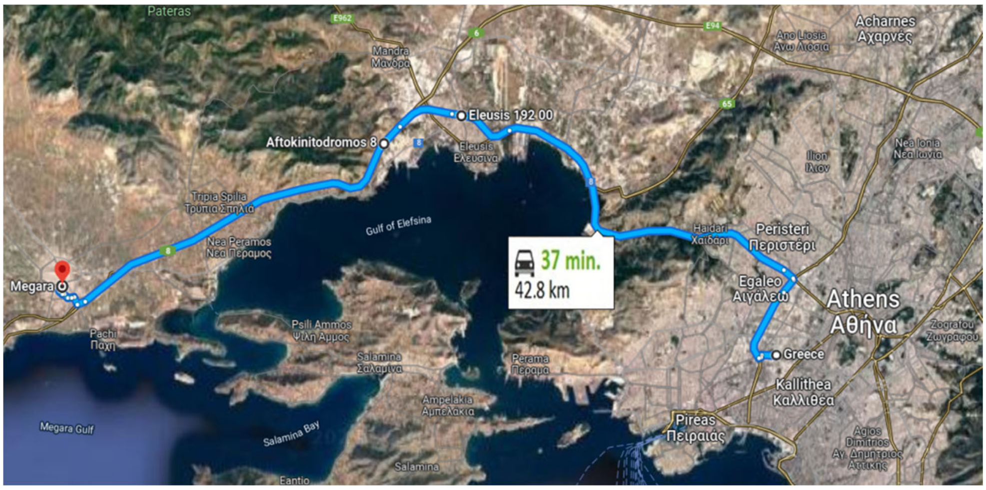

Figure 7. Time and kilometer distance from the headquarters of "THE GREEN CITY" program to the remote municipality of Megara, Google Earth Pro 2022. Source: Adapted from [18].

Actually, an MGP needs to spend 37 min and to cover 42.8 km from its central depot to the designated service points of Megara in order to serve the city's increasing recycling needs, according to the Google Maps application. Therefore, the following calculations are applied:

$$37 \times 2 = 74 \text{ min round trip, from the MGP depot to Megara}$$

and

$$42.8 \times 2 = 85.6 \text{ km round trip, from the MGP depot to Megara}$$

Likewise, each distance of the other remote and serviced routes of "THE GREEN CITY" recycling program in Western Attica (Figure 8 and Table 1), in Eastern Attica (Figure 9 and Table 1) and in Northeastern Attica (Figure 10 and Table 1) was calculated by using the same tool and method, respectively.

Figure 8. Time and kilometer distances of "THE GREEN CITY" program in Western Attica, Google Maps 2022 (horizontal view) [18]. Source: Authors' own study.

Table 1. Time and kilometer distances of "THE GREEN CITY" program in Western Attica, in Eastern Attica and in Northeastern Attica.

Western Attica		
Destination	**Time (min)**	**Distance (km)**
Megara	37	42.8
	74	85.6
Mandra-Eidyllia	73	69.2
	146	138.4
Elefsina	35	26.6
	70	53.2
Aspropyrgos	27	19.4
	54	38.8
Total	172	158
	344	316
Eastern Attica		
Destination	**Time (min)**	**Distance (km)**
Pallini	34	32
	68	64
Rafina-Pikermi	39	41.3
	78	82.6
Paiania	29	34.3
	58	68.6
Kropia	47	51.4
	94	102.8
Spata-Artemida	44	45.5
	88	91
Markopoulo	43	49.7
	86	99.4
Saronikos	63	65.9
	126	131.8
Lavreotiki	52	69.4
	104	138.8
Total	351	389.5
	702	779
Northeastern Attica		
Destination	**Time (min)**	**Distance (km)**
Oropos	51	56.2
	102	112.4
Marathon	74	68.4
	148	136.8
Dionysos	35	32.2
	70	64.4
Penteli	39	30.4
	78	60.8
Total	199	187.2
	398	374.4
	One Way Trip	
	Round Trip	

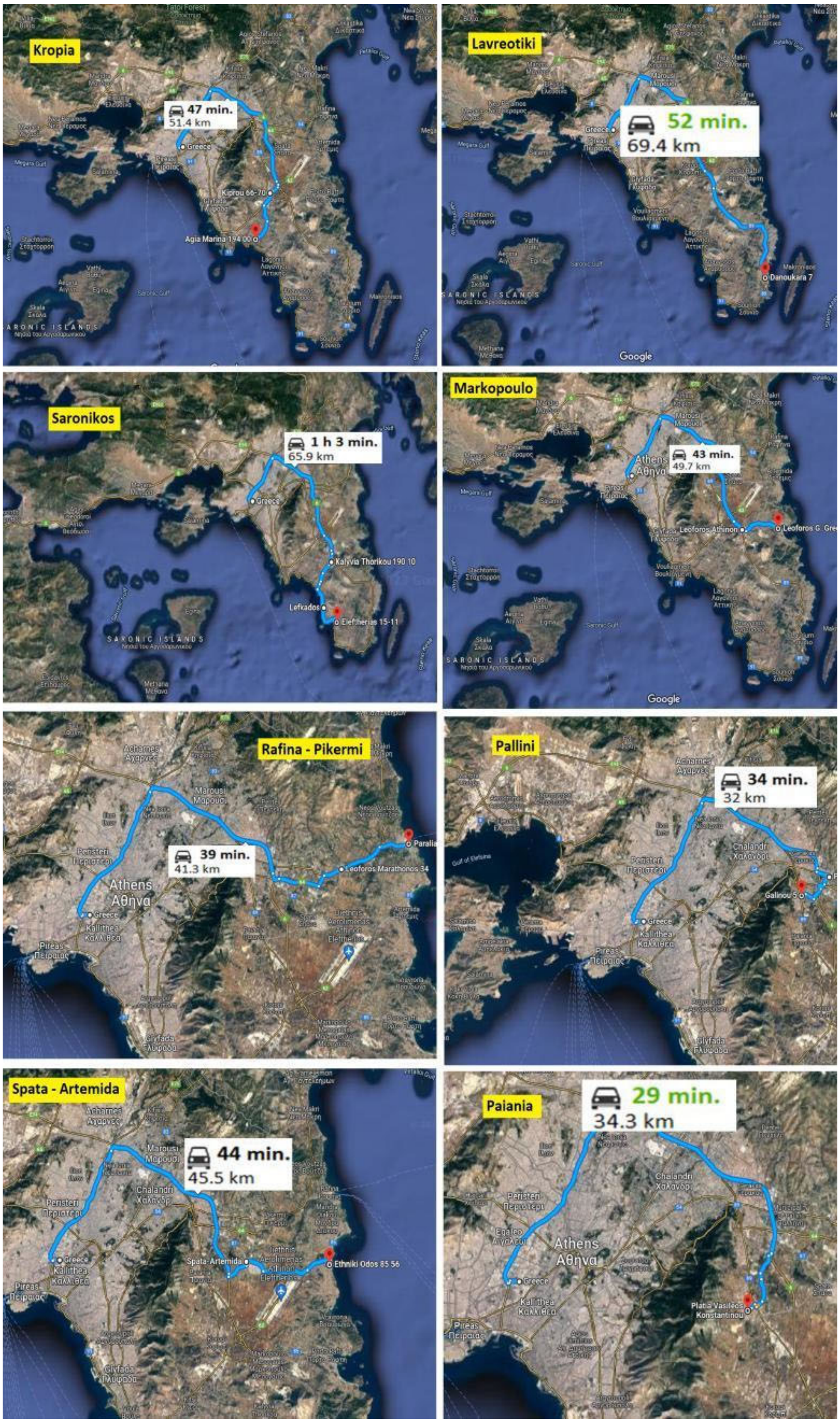

Figure 9. Time and kilometer distances of "THE GREEN CITY" program in Eastern Attica, Google Maps 2022 (horizontal view) [18]. Source: Authors' own study.

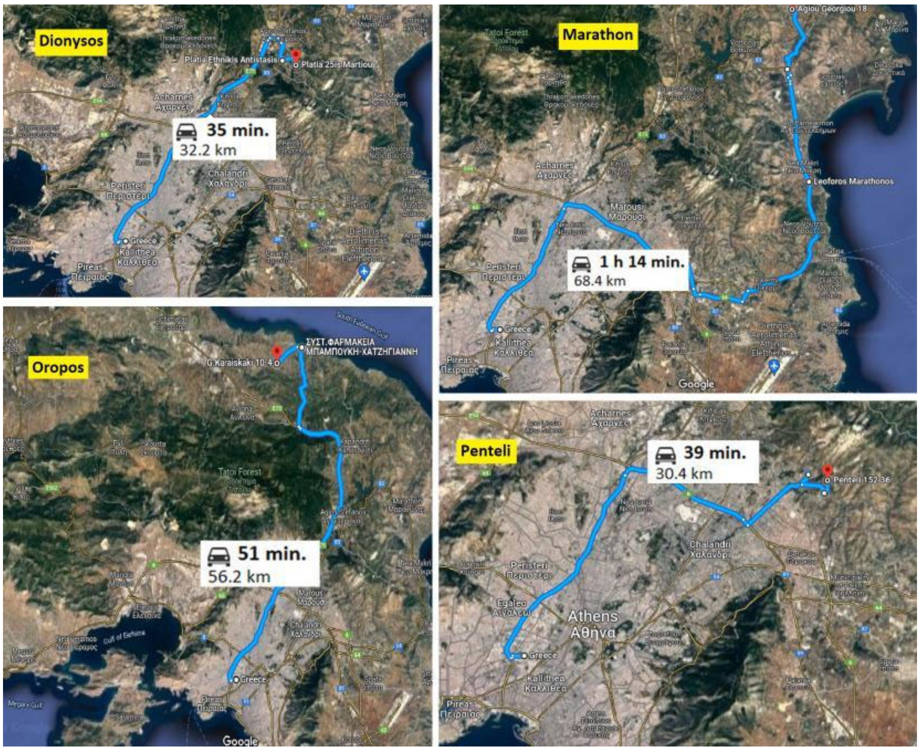

Figure 10. Time and kilometer distances of "THE GREEN CITY" program in Northeastern Attica, Google Maps 2022 (horizontal view) [18]. Source: Authors' own study.

4.2. Methodology of Calculating the Annual Fuel Cost for the MGPs

The MGPs are small trucks–vans manufactured by the IVECO automobile manufacturer with the trade name IVECO DAILY 35S18, and they can transport up to 1.2 tons of recyclable materials per day [17]. These vehicles run on diesel fuel. According to the official reports of the European Environment Agency (EEA) for the year 2020, an IVECO DAILY 35S18 van with its basic equipment weighs approximately 2.7 tons as confirmed by the worldwide harmonized light vehicles test procedure (WLTP, a testing procedure used to find out the real-world fuel economy and CO_2 emissions of a vehicle) test mass. Besides, if the extra weight of the daily collected recyclable materials by an MGP is added, then the truck's total weight can reach 3.9 tons per full load. Therefore, EEA reports that the specific CO_2 emissions (WLTP) of an IVECO DAILY 35S18 reach A1 = 309 g CO_2/km when it only carries its basic equipment, while they approach A2 = 425g CO_2/km when an IVECO MGP is filled with collected clean recyclable materials [17,19].

At the same time, the United States Environmental Protection Agency (EPA) calculated that the consumption of 1 gallon of diesel fuel by vehicle engines produces approximately 10,180 g of CO_2, which is equivalent to B = 2687.52 g of CO_2 per liter of diesel [20].

The General Secretariat of Commerce and Consumer Protection of the Greek Ministry of Development and Investment reported (on 11 November 2022) that the average refinery price in Greece was C = EUR 1859 per liter of diesel. It is noteworthy that this price includes an additional value-added tax that charges fuel consumers with an additional rate of 24% of the actual commodity value. Based on that pricing value (dating at 11 November 2022), the average selling price of diesel in Greece was determined as follows [21]:

$$C = €1499 \text{ per liter} + 1499 \times 24/100 = €1859/\text{L of diesel}$$

$$(\text{diesel net price}) + (\text{value-added tax, } 24\%) = (\text{Final Greek retail diesel price})$$

Taking into account the aforementioned values, the following calculations are derived:

D1 = A1 × (1/B) = 309 g CO_2/km × (1 L of diesel/2687.52 g CO_2) = 0.115 L of diesel/km, which are consumed when the IVECO MGPs are traveling empty.

D2 = A2 × (1/B) = 425 g CO_2/km × (1 L of diesel/2687.52 g CO_2) = 0.158 L of diesel/km, which are consumed when the IVECO MGPs are traveling with full cargo (of collected recyclable materials).

Subsequently:

P1 = D1 × C = 0.115 L of diesel/km × 1.859 €/L of diesel = 0.21 €/km, which is the fuel price when the IVECO MGPs are traveling empty.

P2= D2 × C = 0.158 L of Diesel/km × 1.859 €/L of Diesel = 0.29 €/km, which is the fuel price when the IVECO MGP are traveling full cargo (of collected recyclable materials).

Afterwards, assuming that for each serviced route of "THE GREEN CITY" recycling program in the remote municipalities of West, East and Northeast Attica, the MGPs (as small trucks–vans being autonomous-driven by the driver) travel their transition distance emptily loaded, and their return-back distance from their route destination to their depot with a full load. According to this assumption, the MGPs have shown different fuel consumption profiles during the transition to their daily service and operation destination and when returningback to their headquarters. Additionally, it was assumed that each of the remote routes in Western, Eastern and Northeastern Attica takes place once a week, thus, four times a month. Therefore, in this context the following data are applied for the Western Attica itineraries:

L1 = (Xwg × P1) × 4 = (158 km × 0.21 €/km) × 4 weeks = €132.72 total monthly fuel cost to travel the transit distance of all remote routes in Western Attica, where:

Xwg = Xwr: Total transit distance of all MGP routes in Western Attica (Figure 8).

P1: Fuel consumption of an empty movingIVECO MGP.

L2 = (Xwr × P2) × 4 = (158 km × 0.29 €/km) × 4 weeks = €183.28 total monthly fuel cost to travel the return distance of all remote routes in Western Attica, where:

Xwr = Xwg: The total return distance of all MGP routes in Western Attica (Figure 8).

P2: Fuel consumption of a fully loaded (with collected recyclable materials) moving IVECO MGP.

Moreover:

LTw = (L1 + L2) × 12 = (€132.72 + €183.28) × 12 months = €3792 total annual fuel cost for handling all the remote routes of Western Attica by the MGPs.

For Eastern Attica itineraries the following data are applied:

L3 = (Xeg × P1) × 4 = (389.5 km × 0.21 €/km) × 4 weeks = €327.18 total monthly fuel cost to travel the transit distance of all remote routes in Eastern Attica, where:

Xeg = Xer: Total transit distance of all MGP routes in Eastern Attica (Figure 9).

P1: Fuel consumption of an empty moving IVECO MGP.

L4 = (Xer × P2) × 4 = (389.5 km × 0.29 €/km) × 4 weeks = €451.82 total monthly fuel cost to travel the return distance of all remote routes in Eastern Attica, where:

Xer = Xeg: Total return distance of all MGP routes in Eastern Attica (Figure 9).

P2: Fuel consumption of a fully loaded (with collected recyclable materials) moving IVECO MGP.

Similarly, for Eastern Attica the calculations were derived as follows:

LTe = (L3 + L4) × 12 = (327.18 € + 451.82 €) × 12 months = €9348 total annual fuel cost for handling all the remote routes of Eastern Attica by the MGPs.

Besides, for the Northeastern Attica itineraries, the following data are applied:

L5 = (Xneg × P1) × 4 = (187.2 km × 0.21 €/km) × 4 weeks = €157.25 total monthly fuel cost to travel the transit distance of all remote routes in Northeastern Attica, where:

Xneg = Xner: Total transit distance of all MGP routes in Northeastern Attica (Figure 10).

P1: Fuel consumption of an empty moving IVECO MGP.

L6 = (Xner × P2) × 4 = (187.2 km × 0.29 €/km) × 4 weeks = €217.15 total monthly fuel cost to travel the return distance of all remote routes in Northeastern Attica, where:

Xner = Xneg: Total return distance of all MGP routes in Northeastern Attica (Figure 10).

P2: Fuel consumption of a fully loaded (with collected recyclable materials) moving IVECO MGP Similarly:

LTne = (L5 + L6) × 12 = (157.25 € + 217.15 €) × 12 months = €4492.8 total annual fuel cost for handling all the remote routes of Northeastern Attica by MGPs.

So the total annual fuel cost of all remoteroutes of Western, Eastern and Northeastern Attica combined is:

LT = LTw + LTe + LTne = €3792 + €9348 + €4492.8 = 17,632.8 €/year

4.3. Methodology of Calculating the Annual CO_2 Emissions into the Atmosphere from the MGPs

In the previous subsection it was mentioned that the EEA estimated the specific CO_2 emissions (WLTP) of an IVECO DAILY 35S18 to A_1 = 309 g CO_2/km when it only carries its basic equipment/net weight and to A_2 = 425 g CO_2/km when an IVECO MGP is fully loaded (with collected recyclable materials) [19]. Therefore, for the calculation of CO_2 emissions that are released from the MGPs into the atmosphere, the following calculations can be made, taking into account all the (aforementioned) assumptions which were adopted in Section 4.2 [19]. Specifically, for the Western Attica itineraries, the following data are applied:

E_1 = (Xwg × A_1) × 4 = (158 km × 309 g CO_2/km) × 4 weeks = 195,288 g CO_2 total monthly emissions that are released into the atmosphere during the transition distance of all remote routes in Western Attica, where:

Xwg = Xwr: Total transition distance of all MGP routes in Western Attica (Figure 8).

A_1: Specific CO_2 emissions (WLTP) of an IVECO MGP when it only carries its basic equipment/net weight.

E_2 = (Xwr × A_2) × 4 = (158 km × 425 g CO_2/km) × 4 weeks = 268,600 g CO_2 total monthly emissions that are released into the atmosphere during the return distance of all remote routes in Western Attica, where:

Xwr = Xwg: Total return distance of all MGP routes in Western Attica (Figure 8).

A_2: Specific CO_2 emissions (WLTP) of an IVECO MGP when it is fully loaded (with collected recyclable materials).

Subsequently:

ETw = (E_1 + E_2) × 12 = (195,288 g CO_2 + 268,600 g CO_2) × 12 months = 5,566,656 g CO_2 or 5567 tons of CO_2 total annual emissions that are released into atmosphere during the completion of all remote routes of Western Attica by the MGPs.

Similarly for the Eastern Attica itineraries, the following data are applied:

E_3 = (Xeg × A_1) × 4 = (389.5 km × 309 g CO_2/km) × 4 weeks = 481,422 g CO_2 total monthly emissions that are released into the atmosphere during the transition distance of all remote routes in Eastern Attica, where:

Xeg = Xer: Total transition distance of all MGP routes in Eastern Attica (Figure 9).

A1: Specific CO_2 emissions (WLTP) of an IVECO MGP when it only carries its basic equipment/net weight.

E_4 = (Xer × A_2) × 4 = (389.5 km × 425 g CO_2/km) × 4 weeks = 662,150 g CO_2 total monthly emissions that are released into the atmosphere during the return distance of all remote routes in Eastern Attica, where:

Xer = Xeg: Total return distance of all MGP routes in Eastern Attica (Figure 9).

A_2: Specific CO_2 emissions (WLTP) of an IVECO MGP when it is fully loaded (with collected recyclable materials).

Moreover:

ETe = (E_3 + E_4) × 12 = (481,422 g CO_2 + 662,150 g CO_2) × 12 months = 13,722,864 g CO_2 or 13,723 tons of CO_2 total annual emissions that are released into the atmosphere during the completion of all remote routes of Eastern Attica by the MGPs.

For the Northeastern Attica itineraries, the following data are applied:

E_5 = (Xneg × A_1) × 4 = (187.2 km × 309 g CO_2/km) × 4 weeks = 231,379.2 g CO_2 total monthly emissions that are released into the atmosphere during the transition distance of all remote routes in Northeastern Attica, where:

Xneg = Xner: Total transition distance of all MGP routes in Northeastern Attica (Figure 10).

A_1: Specific CO_2 emissions (WLTP) of an IVECO MGP when it only carries its basic equipment /net weight.

E_6 = (Xner × A_2) × 4 = (187.2 km × 425 g CO_2/km) × 4 weeks = 318,240 g CO_2 total monthly emissions that are released into atmosphere during the return distance of all remote routes in Northeastern Attica, where:

Xner = Xneg: Total return distance of all MGP routes in Northeastern Attica (Figure 10).

A_2: Specific CO_2 emissions (WLTP) of an IVECO MGP when it is fully loaded (with collected recyclable materials).

So:

ETne = (E_5 + E_6) × 12 = (231,379.2 g CO_2 + 318,240 g CO_2) × 12 months = 6,595,430.4 g CO_2 or 6595 tons of CO_2 total annual emissions that are released into the atmosphere during the completion of all remote routes of Northeastern Attica by the MGPs.

Therefore, the total annual emissions of CO_2 that are released into the atmosphere during the completion of all remote routes of Western, Eastern and Northeastern Attica combined are:

ET = ETw + ETe + ETne = 5,566,656 g CO_2 + 13,722,864 g CO_2 + 6,595,430.4 g CO_2 = 25,884,950.4 g CO_2/year or 25,885 tons of CO_2.

5. Results and Discussion

5.1. The Greek Context

Based on the aforementioned results and regarding the financial perspective, the total annual fuel cost of all remoteroutes of Western, Eastern and Northeastern Attica combined is LT = EUR 17,632.8/year. From the environmental perspective, the total annual CO_2 emissions that are released into the atmosphere during the completion of all remoteroutes of Western, Eastern and Northeastern Attica combined are ET = 25,884,950.4 g CO_2/year or 25,885 tons of CO_2, contributing to air pollution and to climate change, respectively. Actually, this kind of joint co-evaluation of financial and environmental dimensions, which are referred to MSW management, is consistent with a plethora of relevant studies that have been focused on the public views and attitudes regarding this important issue, as well as with the socioeconomic and environmental co-evaluation of green energy investments [22–25]. Besides, according to Table 1, it can be denoted that by selecting the lowest values in time (in minutes) and distance (in km) per sub-region of Attica (Western, Eastern, Northeastern) and per type of routes (one-way, round trip), the following percentage profile is exported (Table 2).

Table 2. Profile of differences in time and distance, per type of trip, accordingly.

Dimension	Time (min)		ΔT (in %) One Way (or Round Trip)	Distance (km)		Δx (in %) One Way (or Round Trip)
Type of Routes	**One Way**	**Round Trip**	**Time-Based**	**One Way**	**Round Trip**	**Distance-Based**
Western Attica (basis of comparison)	172	344	0	158	316	0
Northeastern Attica	199	398	+15.70	187.2	374.4	+18.48
Eastern Attica	351	702	+104.07	389.5	779	+146.52

Table 2 revealed that, as far as time and distances of MGPs are increasing per sub-periphery, then an increase was reported at both the "one way" and the "round trip" types of routes studied. However, a proportional increase of the "time" and "distance" increase between the sub-peripheries ("distance" differences were higher than that of "time" differences) was not reported. Such a differentiated trend can be attributed to differentiated geographical morphologies of truck routes, to varied land inclination slopes, as well as to provisions of safety conditions while driving such bulky vehicles at each one sub-periphery.

Therefore, there should be more careful driving behavior on behalf of the MGPs workers while driving them at empty vs. full loads/cargo. Such a careful driving behavior is of utmost importance, especially for round trip routes—where full-loaded trucks are traveling large distances—compared to the one-way routes, respectively.

Within the last decade of reporting, the "THE GREEN CITY" pilot recycling program of the Attica Region sustained the following organizational and operation challenges: financial, technical and logistics, environmental, social, weather and climate, geographical and spatial, administrative, communication and advertising. At the same time, "THE GREEN CITY" recycling program is running smoothly at the prefecture of Attica, having no frequent or lasting interruptions reported. Moreover, the collected quantities of clean recyclable solid waste (7 streams of household waste) are steady increasing in the 62 cooperating municipalities of Attica. By mid-2022, the registered number of citizens in "THE GREEN CITY" recycling program was 70,000, and the collected amount of clean recyclable MSW was 400 tons. In this context, the pilot program expects the MGPs consolidation and network expansion with more municipalities and citizens in the future, targeting at least 100,000 members and the collection of 700 tons of MSP for further sorting and recycling processes. It is also noticeable that the majority of the MGPs of temporary installation and operation for the MGPs, i.e., 56% of the total and unified network of the program, are located next to recreational and green areas. However, it should be stressed that near-commercial parking sites require additional special permits from neighboring private businesses and shops, together with municipal or regional permits needed.

The novelty of our study lies in its capability to provide useful information on integrating different types of MSW systems among different stakeholders, such as researchers, central and local/public and private ownership, and policymakers. The results of this study could effectively describe and express other alternative MSW management systems of local scale across the world, with similar conditions. They can also be combined with other results and evaluations that are referred to solid waste management in order to export an holistic sustainability performance for each alternative MSW management system, program or investment, such as "THE GREEN CITY" one for the Greek case of Attica Prefecture. Furthermore, the results coming from this research can guide developing countries worldwide which have similar climate and population conditions as well as similar MSW compositions with those of Greece to make initial/preliminary/proactive decisions towards the directions of sustainable development, waste management, natural resources protection, air pollution, water pollution, ground pollution, energy management orientation and energy conservation without too many experimentations. However, if a similar program with "THE GREEN CITY" recycling program is going to be implemented in another country, it will possibly need additional adaptive measures and designing changes, but at least it will not be initiated or designed from scratch. In such a perspective, a more comprehensive assessment of each country's future MSW management system should take into consideration the following factors: updating waste fraction and component of each waste type; taking into account other impact categories such as land transformation and particulate matter formation; recording the amount of waste and energy losses during waste collection or commingled disposal with other types of waste, including more feasible as well as more effective treatment technologies and by-product utilization strategies; and lastly, evaluating the life cycle of a MSW management system (alternative or conventional). So, this study in consistency with other similar studies can be a good first step in evaluating currently implemented MSW recycling and treatment programs/systems and in leading to integrated designs that can improve existing and future decision-making on MSW recycling and treatment [12], offering also a wider spectrum of benefits in environmental [26–29] and energy management [30].

5.2. The International Context of Challenges and Opportunities

Although there are many studies focused on deploying strategies of MSW management, there are also certain restrictions that are worth mentioning. Indeed, from a technological perspective, some applications of MSW incineration ashes to construction materials are the following: The aluminum in the ashes used can form cracks due to the aluminum hydroxide that makes the disposable material extra-porous, while also mortar properties and worsen the strength of ash-mixed concrete containing little SiO_2 while producing a porous texture. Therefore there is porosity reduction by using lower proportions of fine aggregate ashes or cement (less than 30% substitution). Moreover, when vitrification is used to solidify the coexisting heavy metals, then a leaching over time reduction it is anticipated [13]. Another critical constraint of MSW management it is the direct or embodied energy use in a highly unsustainable manner. Focusing on the construction section it can be stressed out that the manufacture of concrete alone generates 8% of the total CO_2 emissions associated with buildings and construction, being mainly attributed to the calcination process during cement production. Another crucial issue is that this energy is currently and mostly provided by non-renewable sources, making their use as a certainly unsustainability factor [13].

MSW management reflects particular interests of regional impact of the planet. In this respect there are EU countries employing waste prevention programs primary aiming at reducing, recycling and reusing landfilling MSW. Once the MSW reaches these sites, it is incinerated for electrical power and other purposes. Moreover, there also concurring economic and fiscal incentives offered to citizens but, while environmental programs of materials' recycling have been emerged in EU and abroad, they do not always consider the reduction of virgin materials through their substitution with other sources of inputs, such as MSW. To this context OECD surveyed the waste reduction in a measurable way among its member-states through environmental performance reviews and supported incentive national programs to regulate the generation, management and reduction of waste as well as the rational use of energy [13,31].

It is certainly challenging the proper disposal of MSW for society, considering the limited waste absorption and recovery capacity of the biosphere, without compromising the environmental sustainability and the negatively impacting natural resources. Therefore, the fast emerging economic development and the rapid urban growth also represent great challenges for governments, society, and the environment, notably concerning the resulting MSW volumes. In this context infrastructure blossom implies that the regional development of large projects from both the government and private sectors it is underway. For this the reduction of their own waste generation in cities they should consider options that favor MSW incorporation into value chains that benefit other sectors, such as construction, collaborative economy, circular economy, energy poverty and energy safety [32–34]. To this end, it is important the MSW evaluation performance of MSW-modified materials to be coupled with evaluations of the leachate produced (especially in plastic-addition cases), economic benefits, and life-cycle analyses. It is also crucial that circular economy actions to be inclusive and compatible with the specific social needs of each location and country, in order to ensure a justice-oriented transition. In such a way the economic benefit of waste collectors must be measured by incorporating them into a productive value chain at their local community, while adopting realistic policies and laws that motivate all stakeholders to incorporate more ecological practices in their production processes, and assuring practices to quantify the natural resources' recovery being prevalent almost all over the globe, but predominately and primary in global South [13].

6. Conclusions

Based on the national plan of Greece that the recycling rate of MSW in 2022 can exceed 25% by weight annually, or even approaches 30%, this promising target indicates the decisive role of increasing social awareness of recycling appreciation and the environmental sensitivity among citizens. To this end many conventional recycling programs as well as the alternative recycling program of "THE GREEN CITY" proposed at this study, they can decisively contribute to the realistic MSW treatment of current and future generated (and steadily increasing) MSW quantities in a plausible manner, while increasing the national recycling rates of clean and organic MSW.

However, all these alternative recycling programs have costs, too. In our pilot program, for example, "THE GREEN CITY" recycling program spends annually EUR 17,632.8 in fuel demands for the completion of all remote itineraries in Western, Eastern and Northeastern Attica (by the MGPs), while emitting almost 25,885 tons of CO_2 annually directly to the atmosphere during these served itineraries. Consequently, it is very important for a current or a future recycling program to take into account the three pillars of sustainability (financial, social and environmental) during its operation and to be constantly improved mainly in the fields of environmental protection, natural resources protection, environmental pollution, integrated waste management, energy conservation, climate change mitigation and climate change resistance.

Finally, the specific recycling program requires vigilance, active participation and sharing responsibilities from state bodies, municipalities, regions, private-owned recycling companies as well as conscious and informed participation and motivation by citizens in order for the setting national recycling goals of Directive 2018/851 in alignment with the national Law 4819/2021 (Government Gazette 129 /A/23-7-2021) for the 55% by weight recycling and reuse of MSW in Greece by 2025 to be, firstly, envisaged and, subsequently, achieved.

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