Sustainable vacuum waste collection systems in areas of difficult access.

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Abstract

Waste collection is the activity of transporting solid waste from the point of production (residential, industrial commercial, institutional) to the point of treatment or disposal. Today, the most common way of waste collection is by road from each individual’s house or collecting point (community bins). Whilst other services and utilities such as sewage, water, drainage and even modern day telecommunications have wisely been designed to be out of sight in the underground infrastructure, solid waste collection has commonly remained unchanged since the 19th century.

Furthermore, traditional municipal waste handling in historical city centres is often made difficult by:

- Old infrastructures;
- Narrow, crooked streets that are not suitable for large waste collection vehicles;
- Little space for rubbish bins, making at source separation difficult;
- High volumes of tourists make traditional bins less accessible by waste operatives, which often conflicts with the objectives of keeping areas associated with tourism clean and hygienic.

In these circumstances, underground vacuum waste collection arise as a revolutionary solution, even in remote areas. This waste management model lets integrate waste collection into the infrastructure of a building, a residential development a district or even entire towns, by transporting waste using vacuum technology through an underground network of pipes. The result, among other positive elements, is an average reduction in CO_2 emissions above 90% compared with traditional collection models by truck.

Keywords

accessibility, smart cities, underground infrastructure, vacuum systems, waste collection.

Introduction

In 2010, 50.6% of the world population lived in urban regions and it is projected that by 2050 urban dwellers will likely account for 86% and 67% of the population in the more and less developed regions, respectively [1]. Urbanisation is, thus an irreversible phenomenon that creates the need to expand existing residential areas, consuming, at the same time, neighbouring “green areas”. This trend collides head-on with the model of sustainable development that the new EU policies aim to implement.

In these circumstances, the subsoil arises as a practically unexploited resource with the potential to alleviate the problems associated with the lack of free areas in modern cities. The use of subsoil has several potential advantages apart from the release of space on the surface. The development of new green fields and residential areas; better traffic mobility; the preservation of “sensitive” areas, such as historical city centres and archaeological sites; the reduction of travel distances, as well as considerable energy and time savings; or the reduction of environmental impacts of some activities (noise, odours, risk threats) are only some of these advantages [2].

According with Sterling et al. [3], in order to maximise the efficiency of underground infrastructures a careful strategic planning is required which will consider life-cycle cost-benefits and the selection of projects that offer the highest contribution to urban sustainability rather than a short-term fix to an individual need.

Waste management is one of the major issues in urban engineering. The annual generation of municipal waste in the EU-27 reached 477 kg per person in 2015 [4]. The daily waste production per capita ranges from 0.48 to 2.16 kg, with people in highly developed countries producing more waste. In the coming years, both the increase of global population and the growth in developing countries is expected to create a boost in the municipal waste production. Only for the case of urban food waste its production is expected to increase by around 45% until 2025 [5]. Thus, cities will be facing new challenges to efficient address the management of solid waste.

Among waste management activities, collection is the most important and costly aspect of the urban waste cycle because of the labour intensity of the work and the massive use of trucks in the collection process. According Beliën *et al.*, [6], the collection activity accounts for approximately 80% of all costs associated with waste disposal. Environmental costs associated with traditional collection models are also important. The amount of carbon emissions created by heavily polluting waste collection vehicles has to be seriously considered in this sense [7-8]. It is true that the trend today in some developed countries is to change from fossil fuel powered vehicles to eco-vehicles (those using alternative energy sources other than fossil fuel), but this trend is not generalised around the word.

The situation in remote areas is even worst. Difficult access when climatic conditions are adverse or remoteness of centralised municipal treatment systems are factors that make remote areas a real municipal waste treatment challenge. Special attention has to be paid to islands, also fitting in the category of remote areas. Waste generation in the islands has grown significantly in the last years because of touristic activity. The restrictive characteristics of the territory greatly impede, in these cases, the execution of works related to waste collection, transportation, storage, treatment and disposal activities and entail high management costs, due to the need to transfer waste to the continent [9].

Underground vacuum waste collection (UVWC) systems for the collection and transportation of municipal waste has been more broadly introduced in urban areas during the last decade as an alternative to traditional waste management systems. Underground waste facilities are developed as permanent infrastructure. Using airflow, waste is transported under the streets to a waste collection point, a recycling centre or a treatment facility. This development counts on multiple advantages in both, the logistic of waste management and the environmental protection. Powered on electricity, this model is an efficient alternative to waste vehicles since it is less polluting, each collection cycle is quicker and more cost effective and even areas of difficult access can receive the service. Furthermore, this technology improves recycling rates up to 50% by making source separation as simple and profitable as possible for the user.

This paper aims at presenting the solutions offered by underground vacuum collection systems to different typologies of communities, including those considered as remote. Furthermore, through selected case studies the applicability of this technology is analysed.

Underground waste infrastructure: pros and cons

The main difference of UVWC systems with respect to typical waste collection models is that the waste containers are positioned underground, thus, they are developed as a permanent infrastructure (Figure 1). Waste is introduced in these containers through selective collection points or inlet chutes for various waste fractions and then, at preselected time intervals, their automated transport takes place by vacuum suction through an underground pipe infrastructure, towards a central station. There the waste streams are sorted and disposed in large containers for further processing. The piping system can follow the path of already existing utility tunnels, reducing in this way the costs associated with the system deployment.

Figure 1. Underground vacuum waste collection system. Source: www.envacgroup.com

Littering and hygienic problems are kept to a minimum with UVWC systems as the container overload is decreased and odour issues are better controlled, while at the same time a smooth operation of the system can be achieved 24 hours, 365 days a year, even at difficult situations either as a result of severe weather conditions or external events (e.g. strikes, protests, traffic congestion, etc.) [2]. Also a reduced number of waste collection trips is required, a fact that positively influences operating cost, traffic congestion, minimises CO_2 emissions from the garbage trucks and presents potential space savings [10]. The reasons for the introduction of UVWC in urban areas are also that these systems can be efficient and hygienic. On the other hand, according to Punkkinen et al. [11], a UVWC system could be less sustainable at global scale than a traditional door to door waste collection due to its high electricity consumption and the manufacture of system components. The origin of the electricity, in this case, can play a decisive role in the sustainable balance of the whole process. Table 1 gathers the major pros of this waste collection modality, as well as the main cons.

Table 1. Pros and cons of the UVWC systems.

Pros	Cons
Release space in the surface and improve aesthetics.	Pipe blockages can occur.
Reduced operation and maintenance costs	High investment cost required in the initial phase.

leading to cost savings in the long run.	
Ability to properly collect the main waste streams.	Unsuitable for the management of large items and liquid waste. Difficulties when handling cardboard and glass waste.
Able to manage high volumes of waste. Ideal for high populated areas.	Not recommended for low populated areas due to economic reasons.
High adaptability to varying topography, including slopes, climatic conditions and space limitations.	Modifications after installation are costly.
Avoid the usage of garbage trucks in the collection area.	Truck usage is still needed for transportation after the collection station.
Better working conditions.	Qualified workforce is required.
Noise, odour and hygienic problems are minimised.	
Superior protection against vandalisms.	
Adaptation to Smart Cities.	

The way waste collection is organised affects which waste fractions and how much waste is generated and recovered by household source-separation. Since inlets of the pneumatic waste collection systems are prepared to integrate all types of sensors, households can be encouraged to source separate their waste fractions, for example by using individual electronic ID cards to open these inlets and following policies of ”produce less, pay less”.

Oh et al. [12] assessed the difference in per capita generation of household waste according to the different waste collection methods in Korea. Observations on household waste show that there were considerable differences according to waste collection methods. The value of generation of food waste indicates that a person in a city using UVWC produces 40% less of the food waste (109.58 g/day), on average, compared with that of a truck system (173.10 g/day). The value of generation of general waste in a city with an UVWC system showed 147.73 g/day), which is 80% than that with trucks delivered (185 g/day).

Sensorization in UVWC collection systems can provide reliable and timely information for the requirements defined by the Smart Cities. Gathered data (e.g. number of openings by user, volume and weight deposited in each opening, quality of the separation, etc.) would allow to know the social behaviour to establish and plan, in a simple and operative way, the collection processes and information policies.

The information transmitted by the sensors has two main objectives: to know what happens in the area under study and to provide an efficient and immediate response. Pneumatic waste allows adjusting the processes of collection to the data that receives through the sensors immediately. All this makes possible that waste collection is more efficient. Obviously, traditional collection cannot follow the same practices. Trucks containers collection cannot be established depending on the filling of each container, the overflows detected or any other incident that may occurred [13].

In the case of remote areas, the application of UVWC systems will depend mainly on the existing population density, as it can be deduced from the Table 1. It is not the same a rural area with a high dispersion of the population than a rural area or island highly populated due, for example, to touristic reasons. In the first case these systems are unsuitable due not only to logistic (e.g. long walking distance to the nearest collection point), but also economic (e.g. high return on investment period). In the second case, the installation of a UVWC system can solve many of the problems associated with waste management in remote areas, as seasonality or low levels of selective collection, among others [14].

Comparative cost assessment

The UVWC systems suppose, in general, reduced operating costs for waste handling compared to traditional systems [2]. Although a greater initial investment is required [15], the more economical operation of the system can actually compensate this disadvantage in the long term [16].

The value of the surface space releases with the underground system could potentially have a significant impact on the cost analysis. If the land recovered from traditional waste collection can be put to a valuable use, the pneumatic system could be lower cost than the door-to-door system.

An underground collection system is at a cost disadvantage compared to traditional door-to-door collection when the target area is small, sparsely populated or with low waste production, even six times more expensive according to Teerioja et al. [15]. On the other hand, the economic comparison is positive for underground systems in bigger installations, higher population densities and higher trend to generate waste. Also the installation of UVWC in new residential areas has a better economic performance than in old areas. The main reasons for this are that the installation of a pneumatic system is easier in new construction sites, lowering its cost, and also that the saved space from waste collection activities can be easily put to efficient alternatives, as new apartments or parking space.

An important part of the economic benefits of UVWC structures are latent and are associated with social and environmental externalities, as urban revival, time savings, limited disturbance in the city´s man-made and natural environment, or environmental protection,. This latent cost/benefits has been proof to be the pivotal point in an evaluation process that can render an underground project not only feasible but also favourable [10]. In some cases such benefits can also be expressed in monetary terms, either by the more efficient utilisation of the use by itself, or by the more efficient utilisation of the system as a whole. When considering such issues under the whole life cycle of the project, underground facilities in general, and UVWC systems in particular, can become the number one priority for infrastructure development.

Several studies carried out in different parts of the world confirm the costs advantages of UVWC systems compared with traditional waste collection modalities [2, 3, 7, 11, 12]. Table 2 shows the results of one of these studies. It can be seen that while the two systems, traditional and underground, are very similar in the CAPEX required, the OPEX associated with underground systems is much more advantageous for the final user, with the cost being three times lower in this case.

Table 2. Costs comparative over 30 years among traditional and underground waste collection systems for a development of 10,000 dwellings in 2017. Source: ENVAC.

Capital Expenditure (CAPEX)	Underground system	Traditional system (EUROBIN)	Comments
Capital costs	13,600,000 €[1]	3,060,000 €[2]	[1]Design, piping, inlets deployment, equipment in collection station [2]Trucks replaced every 15 years, 1,700 bins x 300 €/bin replaced every 5 years
Waste housing cost	620,000 €[1]	12,750,000 €[2]	[1]Building to host 1,700 bins x 2.5 m^2/bin x 3,000 €/m^2 [2]Building for collection station
Excavation works	1,360,000 €	0 €	Trenching
Total CAPEX	15,580,000 €	15,810,000 €	
CAPEX per dwelling	1,558 €	1,581 €	
CAPEX per dwelling and year	52 €	52.7 €	
Operational Expenditure (OPEX)	**Underground system**	**Traditional system (EUROBIN)**	**Comments**
Maintenance	115,300 €	36,000 €	Replacements and cleaning
Energy	12,900 €	0 €	
Personnel collection costs	0 €	160,000 €[2]	[2]1,700 bins require 8 full time staff , salary 20,000 €/y
Waste collection costs (fee)	100,000 €[1]	500,000 €[2]	[1]10 €/dwelling/year [2]50 €/dwelling/year
Total OPEX per year	228,200 €	696,000 €	
OPEX per dwelling and year	22,8 €	69,6 €	

Törnblom [17] compared the economic performance of a conventional collection system and a stationary vacuum system for the development of a new housing project comprising near 3,000 dwellings. The annual operating cost of this project using vacuum collection was approximately 3 times lower compared to the manual handling of surface containers (43 €/flat vs 130 €/flat). On the other hand, investment costs resulted 1.6 times higher (2,254 €/flat vs 1,406 €/flat). Considering a 30 year´s depreciation period with 6% cost of capital, the global annual cost per dwelling resulted 232 € for manual waste handling and 206 € for the stationary vacuum system.

There also some studies with negative results for the UVWC system. Teerioja et al. [15] compared pneumatic versus door-to-door waste collection in an existing urban area of 0.2 km^2, with a population density of 20,000 citizens per km^2 and an annual generation of municipal waste of 2,000 t. In this case, the pneumatic system was estimated to be 6 times more expensive that the traditional system in use in that moment, being the investment cost the dominant factor. However, the derived result was favourable to UVWC for higher population densities, higher propensities to generate waste or considering a new residential area instead an old one.

Analysis of selected case studies

Until now, there are close to a thousand systems in operation all over the world, mainly in Europe, China, South East Asia, and the U.S., with this figure continuously growing. Some representative examples are concentrated in Spain:

Case study 1: Barcelona (Spain)

Barcelona is the forefront of pneumatic waste collections systems utilisation, having a consistent planning policy in this issue, aiming at a complete integration of such systems in the city. The city has 8 system running plus 2 mobile, serving or collecting the waste of 141.000 inhabitants. The Municipality is taking advantage that they are revamping some areas or districts to introduce novel waste collection technologies on them.

Barcelona decided to install a pneumatic system in the neighbourhood called “22@” which is a consolidated area that the Municipality was going to revamp. The area is comprised 12,6 million square metres with 12,600 dwellings and 4,225 inhabitants.

Besides the benefits of the system and the good service that offer to the citizens, the Municipality wanted to change the manual collection system with huge bins of 3,200 litres for a pneumatic system, in order to eliminate the heavy trucks driving through the area every day and, in this way, reduce the CO_2 emissions. To do so, a 3 fractions system was designed: 1,300 t/year of rest and 1,381 t/year of recyclable (organic to be collected from the dwellings and paper and cardboard from the offices).

After the change, an environmental study was implemented. The study consisted on analysing the reduction of CO_2 tons by comparing the number of kilometres that the trucks are doing daily to collect the manual bins with the fewer kilometres that the system needs to send the containers of the central station to the final location. The results are showing in the Table 3.

Table 3. Traditional vs vacuum waste collection figures in “22@” Barcelona (Spain). Source: ENVAC.

	Traditional waste collection	Vacuum collection
Collection points	230	644
Number of collections per week	7	12.6
Average waste amount per transport (t)	6.8	664
Energy housekeeping	Less electrical energy but more fossil vehicle fuel	More electrical energy but less fossil vehicle fuel
Material housekeeping in life cycle perspective	More plastic but less steel and aluminium	Less plastic but more steel and aluminium
Technical life spam for important components		
Buildings (y)	30	30
Storage bins (y)	7	-
Vehicles (y)	7	10
Inlets	-	10
Pipe system	-	30
Garbage trucks figures		
Operation (km/y)	23,560	117
Working time (h/y)	2,685	65
Fuel consumption (l)	38,800	76
CO_2 emissions (t)	109	0.2

According Table 3, vacuum collection saves in the case of the neighbourhood “22@” in Barcelona 99.8% of in situ CO_2 emissions. Also increases in the recycling rates were reported.

Case study 2: León (Spain)

The city of León has installed a vacuum city for the historical part of the city where narrow streets made it difficult for conventional waste collection vehicles to access the area. Furthermore, traditional collection deteriorated the heritage roads and buildings.

Previously to the vacuum system implementation a wide-ranging survey and planning programme were followed, which established how the system could be installed whilst preserving the area´s historical infrastructure and architecture.

The 3.8 km long pipe network transports around 20 tonnes per week of different fractions of waste that end in a terminal station located on the outskirts of the city.

Nowadays the system is serving the historical district and a new neighbourhood called “La Lastra” where the central station is located. This area is 30% constructed and there is some new building under construction.

In 2016, the system managed a total of 62 t of packaging and 819 t of rest fraction with a consumption of 225 kW per ton of waste collected. Within both areas the estimation of the local CO_2 emissions saving is 98.4%. The total cost of the project in operation since 2001 amounted to 5.2 M€, while maintenance costs are estimated to be today around 300,000 € per year.

Case study 3: Balearic and Canary Islands (Spain)

With one system installed in Tenerife and two in Palma de Mallorca, these territories are pioneer in the introduction of underground waste collection systems in remote areas. Waste generation in the Spanish islands is very high due to the tourism. The Balearic Islands, for example, is the Spanish autonomous community with the highest rate of waste generation per capita year after year (631 kg were generated per inhabitant in 2014), while the Canary Islands ranks in the second place (with a production of 605 kg) [18].

One of the facilities in Palma de Mallorca provides service to 11,000 houses generating 36 t per day of urban waste. This installation is located in the heart of the historical centre. Located 100 m from the sea, the plant is completely underground allowing to collect 2 different fractions (organic and rest). The plant is equipped with a double set cyclone-compactor that prepare the waste for transportation until the final treatment. The system is characterised by a very complex network of 12 km of pipes that run through narrow streets where it is impossible to enter with conventional trucks, and inlet chutes strategically placed according to the existing historical elements.

Design of a UVWC for a remote area: the case of Naxos Island (Greece)

The municipality of Naxos is responsible to establish and implement a waste management plan and include provisions for the collection, storage, shipment, usage and disposal of the waste generated in the municipality. Practically, in the municipality many different schemes for waste management are in place. The waste collection is done by municipality-owned trucks with cranes to empty the containers, while the bins for mixed waste are emptied to larger garbage trucks. These containers are not placed by every property, but in locations designated by the municipality for common use. Some particularities arise in the case of recycling bins that are mainly distributed in Chora, the town of the island, and the area of the central and south west coast, where most tourists are staying or visiting. As a result, the villages in the northern, central and eastern areas of the island are not supplied with these bins. That results to larger volumes of mixed wastes that end up in the landfills. Also, a door-to-door scheme is adopted, but only for the businesses located in the front face of the port and the first narrow street of the castle. This choice causes a lot of problems to the rest of the businesses that are located also in the main roads of the town, as they have to transfer big volumes of waste for long distances to locations that are easily filled [19].

Integrating a pneumatic collection system into existing infrastructure is technologically challenging. The potential application of vacuum collection systems in remote areas is under study in the LIFE PAVEtheWAySTE project. The case of Naxos Island, more specifically Naxos Town (Chora), is being analysed. The purpose of this section is to provide a description, cost estimate and justification for the installation of a solid waste pneumatic tube collection system in the city of Naxos. The system would provide this city with the most advanced waste collection technology, with minimum operating costs but with an unbeatable level of service for the citizen.

Narrow streets with steep slopes characterise the structure of this medieval and touristic city, making municipal waste management a daily dare for local authorities. Underground collection arises here as an interesting option considering its potential advantages. The lack of garbage bags in the streets and the lack of containers, connected with the elimination of the annoying garbage truck, would make this touristic area a much more pleasant place to live and to visit.

The project includes the deployment of inlet points in the street. During the operation, the waste is temporally stored in the chutes that connect the disposal door with the waste valve. The waste valve is opened by an electronic signal sent from the collection station. Bags fall into the pipe by gravity and then, they are transported (sucked) to the collection station at 20 m/s. The bags arrive at the terminal and the diverter valve sorts the bags into different containers depending upon the type of waste stream collected. The waste is separated from the air by a cyclone and waste bags are pushed into the container where they are compacted. Once the container is full, it is replaced by an empty container. Finally the full container is loaded on to a standard truck and is transported to the disposal destination.

The pneumatic waste collection system tries to give an ecological and quality distinction in the studied area. With the system, the fractions rest, recyclables, and organic will be collected in the same inlet point, getting the sorted collection closer to the users, favouring the recycling. The proposed pipe networks will be connected with the corresponding collection stations located in the parking next to the port of Naxos.

The surface of the action area is approximately 1.1 km^2. The action area is formed by houses, commerce, offices, hotels and tertiary uses. It is essential the identification of the waste generation volume produced (current and foreseen) and that the system will collect every day. For its setting, it is necessary to interpolate the data coming from the buildable square meters and the use typology of it. Other possibility is to make a field study and to locate the dwellings and the number and type of the commerce in the action area. As result, the value of equivalent dwellings is obtain, value to which a daily production value of waste is applied.

The current and foreseen waste production in the area under study is gathered in Table 4.

Table 4. Municipal production in Naxos Chora.

		Biowaste production (t)	Recyclables production (t)			Rest waste (t)
Year	Waste production (t)	~40% of waste	Total ~48.5% of waste	Packaging ~25.95% of waste	Non-packaging ~22.55% of waste	
2015	5,528	2,211	2,681	1,434	1,247	636
2016	5,583	2,233	2,708	1,449	1,259	642
2017	5,639	2,256	2,735	1,463	1,272	648
2018	5,696	2,278	2,762	1,478	1,284	655
2019	5,752	2,301	2,790	1,493	1,297	662
2020	5,810	2,324	2,818	1,508	1,310	668
2021	5,868	2,347	2,846	1,523	1,323	675
2022	5,927	2,371	2,879	1,538	1,336	682
2023	5,986	2,394	2,903	1,553	1,350	688
2024	6,046	2,418	2,932	1,569	1,363	695
2025	6,106	2,443	2,962	1,585	1,377	702

It has been calculated the foreseen production of waste in the total area of Naxos Chora by the year 2025 as 6,106 t of total waste. Considering that the glass and bulky cardboard fractions are not collected through the pneumatic waste collection system, the amount of waste to be collected then is 5,312 tons per year (87%), with a peak in summer months up to 22.14 tons per day to be collected. In order to give a good service even in high season, the system has been design using this figure as reference, i.e. 8,081 tons per year. This is a huge quantity to be handled by only one pneumatic system so it has been proposed to have a double system in the area. Each single system will handle around the half of the waste production.

For simpler calculation the waste production is transformed into equivalent dwellings. Every dwelling produces 2.13 kg a day of waste. So each system will serve to approx. 5,250 equivalent dwellings, and a total of 10,500.

Figure 2 shows the proposed development of the UVWC system in Naxos Chora that includes 2 terminals, 2 independent pipe networks and a total of 50 disposal point, each one composed by 4-6 inlet chutes (for selective collection). The discharge gates will be open free for home users at this stage, with a volume of 45 l. The stores will have a restricted opening hatch with volume of 100 l.

For the execution of the pipe networks it will be necessary to do digging workings, construction of lodging wells of the inspection openings and construction of chambers for the sectioning valves. One of the preliminary conditions to take into account in the layout of the pipe network is that it must be the straightest possible trying to reduce costs of installation, energy consumption and erosion in the pipe. The collection points are strategically placed in order to cover the whole area and facilitate the users´ needs. Both pipe networks will have a total length of 6,000 meters, 498 mm of internal diameter and with an average depth of 2.5 meters below ground level. The depth of the pipe network could be variable due to the pneumatic waste collection system allows the reverse-slope collection. The maximum slope admitted in this design is approximately 20%.

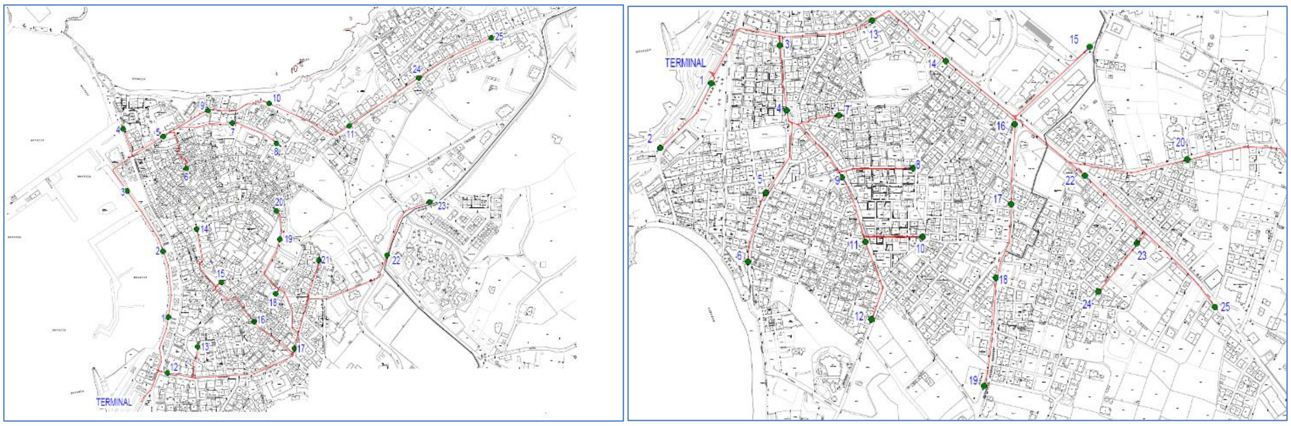

Figure 1. Proposed underground waste collection network for Naxos Chora.

The mechanical elements of the system will have to be activated by automatic-pneumatic mechanisms. To do so, it is necessary a parallel network signal cable and pneumatic tube that will run in conduits of minimum section of 60 mm. Each pair of signal cable and pneumatic tube will run through one of these conduits. The installation will have a nominal voltage not exceeding 50 V in a.c. or 75 V in d.c.

Each collection station (there are 2 in this design) will occupy an area of 48 m x 22 m. They will be equipped with compactors for waste preparation and systems for air treatment, among other components.

The capital expenditure estimation of the proposed UVWC system is presented in Table 5. It includes the development of the pipe networks (trenching, construction, pipe materials, etc.), the setting up of the inlets in the collection points (inlet chutes, excavation, etc.) and the development of the terminals (building construction, electromechanical installations, etc.). The UVWC system is assumed to have a working life of about 30 years, so the annual amortisation of the system (excluded cost of capital) will be around 342,000 €, that is 32.6 € per dwelling and year.

Table 5. Estimated capital expenditure for the UVWC in Naxos.

Concept	Cost (Million €)
Terminal T1	1.279
Outdoor inlets T1	2.524
Pipe network T1	1.372
Terminal T2	1.226
Outdoor inlets T2	2.542
Pipe network T2	1.318
Total	10.261

The capital expenditure for the conventional collection system already existing extended to 10,000 dwellings can be estimated as the cost required for the purchase of 4 garbage trucks (130,000 € each and lifetime 15 years) as well as for 500 waste bins 300 € each and lifetime 5 years) and the terminal for waste storage (1,500,000 €). In this case, the annual amortisation of the system (excluded cost of capital) would be around 115,000 €, this is 3 times less than the UVWC system.

The operational costs for the UVWC system include the cost required for the maintenance of the electromechanical installations and the inlets, the electricity costs and personnel costs. An estimation has been carried out considering current Greek prices in accordance to Nakou et al. [16] that is presented in Table 6. According to this author the operational costs for the conventional system in Greece are around 75 € per ton of collected waste in a study involving 6,500 users with an annual waste production of 5,840 t, the double than the estimations for the UVWC system in Naxos (37,5 €/t).

Table 6. Estimated annual operational expenditure for the UVWC in Naxos.

Concept	Cost (€)	Comments
Personnel costs	162,000	5 full-time workers
Electricity costs	50,400	370,000 kWh
Maintenance costs	90,600	Preventive maintenance

		works and spare parts
Total	303,000	
Final cost/tonne	37,5	
Final cost/dwelling	30,3	

According to these figures, the sum of investment and operational costs favours again the underground waste collection concept over a traditional one for a hypothetic deployment in a remote area as it is Naxos island. On the other hand, apart from the reduction in noise and the improvement of the aesthetics of the city, the pollutant emissions generated by the transport trucks would be prevented, with the consequent upgrade in the city´s air quality. Table 7 gathers an estimation of the emissions potentially avoided in Naxos with the implementation of an UVWC system, considering an annual saving of 55,000 km. Especially relevant is the case of CO_2 emissions, with a decrease of almost 58 t/y with respect to the conventional waste collection.

Table 7. Estimated annual emissions savings in Naxos with the UVWC alternative.

Pollutant	Emissions EURO 10 trucks – slow driving [20] (kg/ 1,000 km)	Total emissions avoided (kg)
SO_2	0.64	35
NOx	8.83	486
Particulates	0.18	9
CO	2.34	128
NMVOC	0.75	41
CO_2	1.054	57,943
CH_4	0,02	1
N_2O	0,01	0.5

Future trends

Main actors in the waste sector agree that the current lifestyle, with rising waste volumes and increasing population awareness about environmental problems, demands new requirements that traditional waste management schemes are unable to meet at a reasonable cost. This is the reason why it is expected that underground waste collection will progressively increase both, in densely populated areas with traditional waste systems already installed and in new urban projects where these infrastructures can be introduced from the beginning of the project.

For remote areas, the implementation of underground collection schemes seems a sensible strategy in the case of touristic destinations. Tourism-related activities, such as the hospitality sector, catering and leisure result in an equivalent population much higher than included in the traditional census. The waste management of tourism activities has certain characteristics that must be taken into account to carry out efficient management of waste; especially when there is significant seasonality. In this sense, UVWC systems are very versatile. They can operate in a broad range of waste production by just changing the frequency of the programmed number of collections per day. On the other hand, compression systems located in the central station enable minimised transportation costs (e.g. to the mainland in the case of islands), and thus contribute significantly to making municipal waste management in remote areas sustainable.

Another trend in the waste management sector is the implementation of novel policies, as the pay-as-you-throw concept or the source separation principle. In this sense, UVWC systems, with multi inlet configurations and smart openings of the inlets by using ID cards, can assist in achieving the targets for waste recycling. Rewarding citizens recycling efforts and thus, removing from waste policies the unfair flat-rate tax model, is a successful practice due to the good acceptation by the population. Furthermore, an increased and improved source separation reduces the overall management costs, as the sorting stage can be reduced to a great extent, less contamination of recyclables is achieved and, both, higher recycling rates and increased revenues are succeeded.

Conclusions

The development of new approaches for the management of municipal waste is becoming a mandatory requirement for modern cities, and mainly for those with aspirations to be considered “smart cities”. Especially for the case of historical city centres or places of high touristic attraction where the traditional handling of the waste is difficult due to limitations in accessing the road infrastructure and to the scheduling of operations, the management of waste through underground collection schemes can provide extremely efficient results.

Decisions involving comparisons among waste collection models should not only refer to the well-defined lifecycle costs of the different modalities, but must take into account the various advantages offered by the underground alternative, particularly the environmental benefits. Lower cost solutions with a significant environmental footprint can be in a disadvantageous position in financial point of view when most costly solutions offer significant environmental gains.

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