Title page

Authors:

Muhammad Nasrullah[a*], Ilaria Schiavi[a,] Elena Reggio[a,] Manuel Lai[a], Carlo Ferraro[b], Simona Tusacciu[a]

Title:

GreenPlasma: a disruptive concept of small-scale end-to-end waste-to-energy system for treating solid waste with plasma pyrolysis technology

Affiliations and addresses of the authors:

[a] IRIS srl, C.so Unione Sovietica 612/21, Turin, Italy
[b] LaserLam srl, Via Papa Giovanni Paolo II 24, Orbassano (TO), Italy

Corresponding author:

*E-mail muhammad.nasrullah@irissrl.org
Mob. +39 338 4789848

Submitted Abstract - accepted

Introduction

This paper presents the concept behind GreenPlasma, a small-scale end-to-end waste-to-energy system for the thermal treatment of solid waste. The core of the system is a pyrolyzer that thermally treats solid waste using plasma technology. The pyrolyzer is complemented with a pre-treatment system of input waste feedstock and a post-treatment system for cleaning and exploitation of syngas. This system aims to treat up to 50 kg of solid waste per day. The system can be used to process different types of waste feedstocks especially marine litter, residual waste, but also waste electric and electronic equipment and clinical waste. Developed from low cost commercial components, the system uses plasma technology-based pyrolysis to extract energy from waste in the form of a syngas, which can be exploited for heat or electricity production, and heat. This energy can be used directly in situ by the community producing the waste treated in the device. As a residue, the device produces an inert material that can be used as partial substitute of aggregates in bitumen- and cement-bound construction. The system has been developed with the aim to provide a low-cost alternative for those communities (mountain villages, islands, new housing developments, boats, ports, large ships, retail parks, hospitals etc) that either pay high costs for collection of waste because of their location or peculiar regulatory obligations, or that would like to become independent in the way they deal with their own residual waste and recover energy off it. This paper presents how the idea was born and developed and the first studies on the mass and energy balance, different sections and components and environmental soundness of the system.

The system has been developed within a project[i] developed with funding from the European Regional Development Fund distributed by the Piemonte Region, Italy and gave rise to a patent application (ongoing) to the EPO (EP 3023693)[ii.] It was also proposed for a feasibility study under the Horizon 2020 SME Instrument Phase 1 funding programme obtaining a Seal of Excellence for having been positively evaluated. The innovation is being taken forward by IRIS from TRL5 to TRL7 with the support of grants from the European Union's Horizon 2020 Research and Innovation programme[iii], in a specific application whereby the system, mounted on a small vessel, is used for treating on board floating marine litter collected during navigation, as part of port and marinas' cleaning operations or collected by booms mounted at rivers estuaries to intercept litter coming from land.

Materials and methods

The idea for a small-scale device able to treat thermally unrecoverable waste was born out of the various waste crises that affected the region around Naples, Italy in the late Noughties. Those crises demonstrated the fragility of a collection and disposal system that, when not properly managed, can give rise to a serious health and safety emergency. If each household or group of dwellings had a device able to treat its own waste, and hence was not relying on a centralised service, the mountains of garbage seen in the streets of Naples would not have arisen. On the back of IRIS's own expertise, the company proved that the same equipment used for arc welding could be successfully used to generate a stable gas plasma between two conductive electrodes: Confining the system in a refractory reactor, temperatures of around 1000°C could be reached at atmospheric pressure, hence obtaining the conditions for the pyrolysis of waste materials with production of a combustible gas (syngas). From this proof of concept, the company developed an automated device encased in a metal, water cooled sleeve and equipped with an electro-mechanic control able to varying the distance between the two electrodes to obtain and maintain an electric arc for the generation of plasma and the treatment of waste inserted into the reactor. This prototype device has since been subject of further design development to transform it into a continuous end-to-end waste-to-energy (WtE) system. The prototype was also used to provide data for obtaining a first estimate of the energy balance and a comparison with current alternative waste management practices (collection and centralised disposal) for a specific mountain location to support the case for its application, and for undertaking a thermo-economic study based on exergy for evaluating the best exploitation scenarios. The pre-treatment section of the WtE system, depending upon the composition and physical nature of input waste feedstock, consists of certain unit operations such as drying, shredding and metal sorting. The post-treatment section consists of gas cleaning processes such as cyclone, scrubbing, filtration, chlorine, sulphur and ammonia removing and gas exploitation setup such as heat exchanger and small-scale gas turbine to produce heat and electricity.

The specific mountain location chosen is Ambornetti, a hamlet in the Municipality of Ostana, near Cuneo, Piemonte (Italy), some 1600m above the sea level. This hamlet is being refurbished to be transformed in a minigrid community hosting tourist accommodations, a restaurant, a spa, a farm and a dairy. The on-site waste treatment device is a fundamental part of the services that this community likely to host up to 80 people a day will require, together with on site generation of electricity (via photovoltaic and biomass CHP). As the second major application, IRIS will implement its system onto a vessel servicing booms mounted at the river’s mouths to collect marine litter flowing from inland into the sea (Saronikos Gulf area, Greece). The system will also to be demonstrated as a port facility in Hirtshals, DK, for treating fishing gear to be disposed of or fished marine litter.

Results and discussions

Considering the working cycles and capability of the device, as developed so far – i.e. the working prototype currently available, it was calculated that the treatment of the above quantity of waste will absorb 25MWh of energy but would provide 21MWh of energy, reaching near self-sufficiency. The pyrolyzer device converts more than 95 wt.% of input waste material into gaseous product and less than 5 wt. % of it into a vitrified solid residue. The overall yield and efficiency of the system can be improved to lower the energy requirements and obtain a fully self-sufficient system. There is an option to couple GreenPlasma system with an anaerobic digester for the estimated 850kg/year of organic waste processing, producing in turn exploitable biogas; this dual system will be able to cover the overall energy requirements of the device

From the point of view of the environmental advantages deriving from the use of the GreenPlasma solution, a comparison could be done with the alternative of the collection of the waste and disposal at a central facility. Considering the current waste collection practices for the Municipality of Ostana, each kg of unsorted waste travels about 40km for its disposal, travelling on a large vehicle that comes up from the town of Pinerolo, where a landfill and mechanical biological treatment facility treats the waste collected from the surrounding Municipalities.

A preliminary thermo-economic study of the WtE system has been performed considering the three main case scenarios of applications for the said system: 1) a stand-alone tourist facility in the mountains, 2) small boat for marine litter disposal and 3) large boat for an on-board waste disposal. The third case scenario was found to be the most feasible in terms of thermo-economic application of the system. In this scenario, the investment cost was found to be less than half as compared with the other two case scenarios.

Conclusion

The device embodies a very disruptive concept: by taking the proximity principle to its extremes, as it makes possible a truly local but still environmentally sound and safe thermal disposal of waste with energy recovery, hence allowing for a novel approach to residual or difficult waste disposal with important social and economic consequences. First of all, local distributed plants are a very manageable alternative to large, central plants that nobody wants on their doorstep (and that, in the EU Circular Economy Action Plan[iii], have an even more limited role in the recovery of waste) and that need “feeding” with waste to work at ideal conditions. Furthermore, with wide adoption, the collection of residual waste could be eventually phased out completely, with further significant savings for the waste collection authorities. Finally, the waste remains truly a responsibility of the waste producer, as it does not get forgotten the instant it is disposed of in the bin: the waste producer needs to deal with it within the boundaries of its own community. This is potentially a strong driver for waste minimisation. The advantages of this disruptive approach to the disposal of residual solid waste are quite clear, and GreenPlasma grants an affordable and environmentally sound technology that can be applied also to other wastes.

i GreenPlasma project description by Mesap, Piemonte's Innovation Cluster for MEchatronics and Systems for Advanced Production: http://mesapiemonte.it/en/green-plasma-2.html#

ii EP 3023693 “Device and system for plasma treatment of solid waste”, published 25th of May 2016, priority date 24th of November 2014, Applicants IRIS srl and LaserLam srl. The patent is to be shortly granted

iii COM (2015) 614 COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS - Closing the loop - An EU action plan for the Circular Economy, http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1453384154337&uri=CELEX:52015DC0614

Paper Abstract

This paper presents the concept behind GreenPlasma, a small-scale end-to-end waste-to-energy system based on plasma pyrolysis technology. The paper describes how the idea was born and developed and describe first studies on the mass and energy balance, different sections and components and environmental soundness of the system. The core of the system is a pyrolyzer treating solid waste using plasma technology, aiming to process up to 50 kg of solid waste per day. The pyrolyzer converts more than 95 wt.% of input marine litter (macro plastics) into the gaseous product and less than 5 wt. % of it is left as vitrified solid residue. The gaseous product (syngas) can be exploited for heat or electricity production, and heat. As residue, the device produces an inert material that can be used as partial substitute of aggregates in bitumen- and cement-bound construction. The system can be used to process different types of waste feedstocks especially marine litter, household residual waste, but also waste electric and electronic equipment and clinical waste. The system has been developed with the aim to provide a low-cost alternative for those communities (mountain villages, islands, new housing developments, boats, ports, large ships, retail parks, hospitals etc) that either pay high costs for collection of waste because of their location or peculiar regulatory obligations, or that would like to become independent in the way they deal with their own residual waste and recover energy off it. The system is being taken forward from TRL5 to TRL7.

Key words Pyrolysis of waste, plasma technology, waste-to-energy, marine litter, household residual waste

1. Introduction

The autumn of 2010 will be remembered in Italy for the highest point of a 15 year-long waste management crisis in Naples, with national and international news showing appalling pictures of mountains of municipal solid waste in streets and beaches for days on end. The collection had stopped as the waste could not be disposed of anywhere in the Region, with the local energy from waste plant working only at 25% capacity and landfills filling up quicker than expected. This situation inspired a couple of young Italian entrepreneurs to consider the feasibility of a disruptive solution, i.e. equipping every household with a system to deal with their own residual waste (i.e.: municipal solid waste not sorted for recycling). The thinking was that if each household had a micro-scale system for dealing with their own waste, this situation would have not arisen.

Indeed, the peculiar situation highlighted one of the major disadvantages of large infrastructures: usually best performing in terms of economics and best suited for providing public services such as water treatment, transport etc, they however rely on a very complex system for their functioning, more so when part of such services might be delivered by different players – e.g. waste collection authorities often not responsible for the disposal infrastructure. A very local disposal option would mean not only independence from large, centralised plants, but also no need for an organised collection, with clear environmental and cost savings. The challenge of a small/ micro scale disposal option would be to be as efficient as large plants.

Such solution would extend the concept of producer responsibility/ manage-it-yourself, already behind the home composter/digester or the sink waste processor, to a fraction of waste less “popular” in terms of public acceptance. The residual municipal waste is also traditionally more difficult to treat and, because of its mixed nature, one of the potentially more impacting waste categories, as its current treatment includes landfilling, thermal treatment in large scale plants and mechanical biological treatment, which still produces a residue destined to landfilling or thermal treatment at Energy from Waste plants even when market and regulatory conditions permit the exploitation of refuse-derived fuel. Further advantages of a home system would be the independence from the quantities of waste produced – while large plants work most efficiently when at design load – and the opportunity to exploit locally the energy generated from the recovery of waste, with efficiencies not far from the large plants.

The two entrepreneurs identified pyrolysis as the thermal treatment that could ensure the best treatment of residual waste and plasma as the technology to try for obtaining such treatment. Their knowledge of plasma as used in arc welding was therefore selected for starting a practical investigation into the feasibility of the solution.

Such investigation started with a proof of concept in the lab that evolved into a working prototype of batch system: this rapid excursion to a Technology Readiness Level of 5 was achieved owing to financing from the European Regional Development Funds[0]. One of the outcomes of such project was a patent application to the

EPO (November 2014), which resulted in a patent award in 2018 [1]. Further financing from the Horizon2020 SME Instrument 1 (Sea Litter Critters [2]) allowed for a study of the market feasibility and of some technical aspects of a specific application of such device, mounted on small autonomous vessels roaming the coast for collecting floating macro marine litter and processing it on board. This same application is being further explored within CLAIM [3], a large H2020 project on solutions to clean marine litter, while further work on the application of the device as a solution for waste management in small communities is being taken forward through self-financing by IRIS srl in the context of the architectural and community renovation of Ambornetti, a mountain hamlet in the west Italian Alps.

1.1. Guiding principles of the design

Since inception, the feasibility study of the localised, home-based end-to-end waste-to-energy solution was driven by the overarching necessity to develop a system destined to non-specialist users and possibly to citizen consumers. As such, the concept to be developed into a device needed to meet the following requirements:

- Very small scale
- Simplicity and safety of operation
- Affordable price
- Use-as-needed working set up

Very small scale: true to the inspiration of the solution, the system is to be used by a very small community of one or more families (e.g. in a block of flats, in a housing development), compatibly with the most cost-efficient scale obtainable. In its version for municipal waste, it would be destined to treat the residual waste only (at least the fraction currently incinerated or landfilled, i.e. some 247 kg out of the 482kg of municipal waste produced per year on average by each European) [4], A 50kg/day capacity would satisfy the treatment needs of about 70 people, or about 24 households composed by 3 people on average– the forecast population of the Ambornetti mountain community.

Simplicity and safety of operation: the system would need to require only very simple steps to operate day by day by the user, with more complex, periodic maintenance tasks left to an expert service. Practically, these requirements have been imagined to translate into a device organised so that the user is able just to put in its black bag of residual waste and get out hot water for sanitary use or heating, with all the treatment, inclusive of pre- and post-. Some simple safety directions would need to accompany the use of the system, e.g. avoiding the introduction of batteries or small electric items: although destined to treat residual waste, it is acknowledged that users might not undertake a full separation of the waste. This does not create any safety issues in the case of paper/card, plastic, metallic, textile or organic components, while items not usually readily collected by kerbside recycling schemes, such as lamps, small electric appliances, batteries could create some hazards. Some system to intercept these items before entering the pyrolyzing chamber had to be defined.

Affordable price: as the device is destined to a single or small group of buyers, its price – and cost, as a consequence - must be contained. The best case scenario from a business point of view – i.e. a quick return of investment for the buyers 2- is the one whereby the home pyrolisation entails a monetary recognition by the waste collection/management authority, either as subsidy or wavering of the refuse collection tariffs, particularly within a Pay As You Throw tariffing scenario: in the latter case, with a PAYT tariff of 1.22€/kg of waste, the Ambornetti community would recover the investment in the small scale plant (about 42000€ price estimate) around year 2.

Use as needed working set up: the plant needs to be flexible in its working, with quick and safe warm up and cool down. These features would ensure that the system could be turned off and on as required without losses of efficiency nor production of toxic emissions. Plasma generated by electric arc ensures high temperatures to be reached very quickly, almost immediately in the area surrounding the arc, where any gas generated in conditions critical for formation of dioxins and furans (basically slow transit around the 400°C temperatures) could be directed for quickly thermally destroying such compounds. A system to store gas, including that produced at critical temperatures, and a gas recirculation for further "cleaning" is implemented.

On the basis of the above, a system was designed and built as first batch prototype for testing the working and the performance mainly of the core reactor. An extensive experimental campaign was useful to assess working parameters and the overall feasibility of the concept, as well as to build up the required experience to design a more robust version of the device and explore potential applications other than residual municipal waste. The design was supported also through the employment of an SME Innovation Associate under the Horizon 2020 INNO-SUP European grant [5].

1.2. Applications

The system had been conceived mainly as a solution for treating residual municipal waste but its peculiarity makes it suitable to a number of applications. IRIS has explored in particular an integration of the system on small vessels for treating on board marine litter collected at sea. A feasibility study [2] was undertaken to explore the market appeal and the technical feasibility of mounting the solution on a completely unmanned, autonomous vessel. Following on from this desktop study, the concept is now being developed for demonstration within project CLAIM (Cleaning marine Litter by developing and Applying Innovative Methods), an EU Horizon 2020 project [3] whose remit is to find new ways of tackling pollution in marine areas, with a specific focus on the Mediterranean and the Baltic Seas Within this project, the system integrated on a special boat will be shown to work for treating floating litter collected by booms mounted at river mouths in the Saronikos gulf, Greece.

1.3. Overview of the solution

The first design activities focused mainly on the reactor. The very first proof of concept used simply a covered ceramic melting pot and a TIG welder to generate an electric arc between two conductive elements. From this very simple set up, the team was able to understand some key elements:

- The best materials for the electrodes are those that do not generate unwanted residues within the reaction chamber: metal electrodes such as tungsten (as used in TIG welding) end up dropping molten material
- Even a simpler construction than that of a TIG welder can be used: TIG welding uses torches that are relatively cheap but highly engineered commercial components, delivering high voltage (peaks of 1000V with currents in the region of 100-200A) with a built-in inert gas shielding system (to avoid oxidation of the weld) and water cooling (for safety of use and long term reliance of the system): lower voltages would be required, hence simpler electronics and simpler controls; inert gas shielding and water cooling are not required throughout the whole treatment process.
- Very high temperatures compatible with a pyrogasification and the production of a combustible gases could be reached with the above arc generation system in a small scale reactor.

From those first considerations, IRIS, who supported LaserLam during the GreenPlasma project [0], designed a first purpose built reactor and specified a suitable power supply. From this initial set up, some more lessons were learned that enabled the team to reach the final specifications of the system to inform an application for a patent granted in March 2018 [1].

2. Materials and methods

The small scale end-to-end waste-to-energy system consists of a pyrolyzer reactor which is complemented with pre-treatment and post-treatment set ups. The pyrolyzer reactor is the core of the system in which waste material is thermally treated at high temperature (1000 °C), atmospheric pressure and in the absence of air/oxygen. The input waste material is first prepared (particle size reduction, sorting, drying) in pre-treatment set up before it is introduced into the reactor. The product gas (syngas) is cleaned and exploited to produce heat or electricity and heat in a post-treatment system. The pyrolyzer aims to process 50 kg of waste material/per day on a twelve hour shift. A simplified diagram of the end-to-end waste-to-energy system is shown in Figure 1. The list of the components of the waste-to-energy system (with the reference to Figure 1) is listed in Table 1.

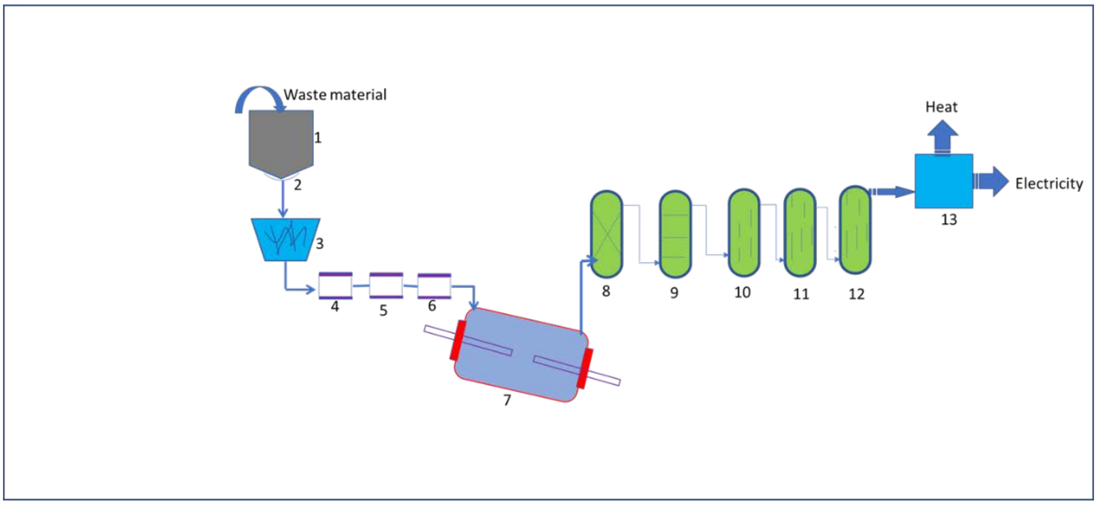

Figure 1: A simplified diagram of the end-to-end waste-to-energy system

Table 1: List of components (reference to Figure 1)

Nr.	Component
1	Input waste feeding hopper
2	Automatic open/close feed rate controller
3	Shredder
4	Magnetic separator
5	Eddy current separator
6	Dryer (if required)
7	Pyrolyzer/Reactor
8	Water scrubber
9	Filter bags
10	Sulphur removal absorption unit
11	Nitrogen removal absorption unit
12	Chlorine removal absorption unit
13	Combined heat and power (CHP) system

2.1. The pyrolyzer

The pyrolyzer reactor is confined in a refractory lining, wrapped with insulation material and encased in a metal, water cooled sleeve. It is equipped with an electro-mechanic control able to vary the distance between two electrodes to obtain and maintain an electric arc for the generation of plasma to produce heat. The waste material is introduced at a given rate from one end of the reactor. The electrically generated plasma arc in the reactor develops quickly very high temperature (>5000 °C) near the electric arc making the thermal waste treatment highly efficient and environmentally friendly by pyrogasifying the material obtaining a combustible gas. The solid residue produced in the reactor is taken out on a continuous/semi-continuous basis from an outlet near the bottom of the reactor. The pyrolysis process runs at around 1000 °C and at atmospheric pressure in the absence of air/oxygen

Geometrically the pyrolyzer is rotating/oscillating around its axis at a defined slope angle. This geometry provides means for better mixing of the material inside the reactor ensuring an efficient heat transfer from the heat source to the waste material in the reactor reducing the residence/material processing time to meet the requirements of desired material processing capacity. In a rotary kiln/reactor different types of particles' motion can develop, but for a good pyrolysis rolling motion of particles is desired assuring mixing of solid bed, which optimizes mass and heat transfer for pyrolysis process. In rolling regime, the bed material may be divided into two regions: a thinner active layer and a thicker one which is stagnant/comparatively stagnant. In rolling motion, inside the active layer a uniform flow of the particles takes place, while particles in the stagnant region are brought upward by the rotating wall, until they enter the active layer and start rolling, in which solid particles are considered like a granular substance [6, 7].

1.1. Pre-treatment and post-treatment setups

Depending upon the composition and moisture content the input waste material is prepared in a pre-treatment section of the process before it is fed to the pyrolyzer. Based on the physical nature (composition and moisture content, mainly), the pre-treatment setup may consist of a shredder to reduce the input waste's particle size (< 15 mm), metal sorting units (magnetic and eddy-current separators), and drying unit (for feedstocks having high moisture content > 25 wt. %). The use of magnetic separator and eddy-current separator in the process configuration (Figure 1) may be after shredding unit or before shredding unit depending on the process requirements based on the composition of input waste feedstock. The pre-treatment provides a well-prepared material with the desired values of parameters (in terms of particle size, moisture content and composition) to be pyrolysed in the very next step of the system i.e. pyrolyzer reactor.

The product gas (syngas) cleaning and exploitation for electricity and heat production is performed in the post-treatment section of the system. This post-treatment involves various operations/processes;

- The product gas is passed through a filter in which small solid particulates and liquid oil droplets in the gas are filtered
- Water quenching avoiding the formation of dioxins and furans and removing further dust, soot and ash
- Filter bags removing the fly ash and fine solid particles
- Absorption unit to remove sulphur/sulphur containing compounds
- Absorption unit for the removal of nitrogen/nitrogen containing compounds
- Absorption unit to remove chlorine/chlorine containing compounds
- Exploitation of the clean/high calorific syngas in a combined heat and power (CHP) system to produce heat or electricity and heat depending on the requirements

The effective post-treatment of product gas (syngas) ensures the gas is cleaned to a maximum possible extent having high calorific value providing high yield of electricity and heat as a process product.

2.2. Experimental work

An experimental campaign was run on the existing pyrolyzer which is a fixed reactor. The objective of this experimental work was to obtain the data for optimisation of the process parameters to be utilized for the newly designed pyrolyzer reactor (described in Section 2.1.). The data related with optimization of process parameters include optimum values for process temperature, residence/processing time of material, erosion rate of electrodes, feed rate of waste material and power requirement for the process. The experiments are performed in the range of 800 °C – 1000 °C of process temperature, atmospheric pressure and in the absence of air/oxygen. The waste material used for the experiments is marine litter (macro plastic), which is re-produced sample (mixture of different types of plastic) of marine litter [8]. The amount of marine litter used for testing in the experiments for one batch is 50 grams, dry and with particle size of 10-15 mm.

The process temperature in the reactor is measured by a thermocouple (type B) inserted from one of the axial reactor's cover. Power to the reactor for generating plasma arc is provided by an external power supply. The electrodes erosion rate is calculated from the difference in their weights and dimensions (before and after the test) over the total test run processing time. Residence/material processing time is calculated by the time taken to complete the material's thermal treatment. Amount (mass) of solid residue left in the reactor after the test is weighed to determine solid residue content for the process. Material conversion is calculated from the weight difference between input waste material and the solid residue left at the end of test. The flow rate of gas (syngas) produced in the reactor as a result of thermal treatment of waste material is measured by a gas flowmeter.

3. Results and discussions

3.1. Preliminary mass and energy balance of the pyrolyzer reactor

The preliminary mass and energy balance is calculated based on the results obtained from experimental work performed on the existing pyrolyzer fixed reactor. The reactor is found to convert 85-90 wt. % of input waste material into gaseous product and the rest of it into a vitrified solid residue. In the newly-designed rotating/oscillating reactor more than 95 wt. % of input marine litter is expected to be converted into the gaseous product, as with proper mixing the mass and heat transfer to the material will improve significantly in the reactor ensuring the maximum possible material conversion into the gaseous products.

The energy balance's calculations procedure for a rotary kiln biomass and waste pyrolysis reported in the literature [9] is followed here for calculating the energy balance of the process. The energy balance of the reactor is calculated based on the overall energy required by the pyrolysis process of marine litter. The overall energy required by the process is classified into three sections;

- Energy consumed to pyrolyse the marine litter
- Energy consumed in raising the temperature of material to 800 °C – 1000 °C
- Energy consumed in heat losses from the reactor to the surroundings

The energy balance for the reactor is calculated by using Equation (1).

$$E_t = E_p + E_T + E_l \quad (1)$$

Where,

E_t is the total energy required for the process
E_p is the energy consumed for pyrolysis of material
E_T* is the energy consumed in raising the material's temperature
E_l is the energy consumed in losses

* In the process the input plastic waste material is rapidly heated up to 800 °C. As a result of it the plastic material is converted (nearly completely) into volatile matter (mixture of gases) and water vapors. The temperature of the gases and water vapors is raised to 1000 °C. The input waste feed is assumed to contain 20 wt. % of moisture content in the energy balance.

Energy consumed in raising the material's temperature includes the raise of temperature for marine litter material and gases and water vapors produced as a result of pyrolysis. E_p, E_T and E_l were converted into their respective power (electricity) values. The theoretically calculated overall power required for the process for treating 50 kg/eight hours of marine litter is 5.2 kW for the process to take place at 1000 °C. With 80 % of power transforming electrodes efficiency, the power requirement value gets to 6.5 kW respectively. These values of power requirements for the pyrolysis process are based on the theoretical calculations and necessarily required to be verified/testified with the experimental/actual values, which is to be done with the newly-designed pyrolysis reactor.

3.2. Kinetics of plastic pyrolysis

In order to process the desired amount of plastic waste material with the specific sizing of pyrolyzer reactor and to know about the required material processing time in the reactor, it is important to have the kinetics study of plastic pyrolysis. Plastic pyrolysis is a complex process in which long polymer chains are broken into shorter ones [10]. Pyrolysis of plastics follow a complex route and may not be described in terms of one or certain chemical reactions; mainly, it involves thermal cracking of material. Generally, in this thermal cracking with temperature increasing, plastics undergo three main thermal transitions: glass transition, melting, and decomposition. The required residence time for maximum conversion of plastic into gaseous products from the overall reaction kinetics can be calculated by using the following Equations (2), (3) and (4) for a first order reaction.

$$\frac{-dW}{dt} = kW \quad (2)$$

Where,

-dW/dt	decrease in weight of material with time
k	reaction rate constant
W	weight of material

Integrating and replacing X_p, the degree of conversion (the weight percentage of initial solid that is successfully converted into the product) with decrease in weight of material in Eq. (2).

$$-\ln(1 - X_p) = kt \qquad (3)$$

Where X_p is the mass fraction of material's conversion in the reaction k can be calculated from the Arrhenius equation given as Eq. (4):

$$k = Ae^{-E_a/_{RT}} \qquad (4)$$

Where:

k	reaction rate constant
A	Pre-exponential factors
E_a	Activation energy
R	Universal gas constant
T	Temperature

The experimental values of Pre-exponential factor (A) and activation energy (E_a) for polyethylene (PE) and polypropylene (PP) taken from literature [11] are given in Table 2.

Table 2: Experimental values of A and E_a for plastic pyrolysis [11]

Plastic type	A (s-1)	Ea (kJ/mol)
PE	$7.2\text{x}10^{13}$	259
PP	$8.6\text{x } 10^{11}$	224

The time required to pyrolyse PE and PP with 99 wt.% conversion calculated based by using Eq. (2), (3) and (4) at 700 °C is 5 seconds and 5.65 seconds respectively and at 800 °C is 0.26 seconds and 0.43 seconds respectively. This is the theoretically calculated time for almost complete conversion of plastics (PE and PP), which necessarily required to be verified with the experimental/actual values, which is to be done with the newly-designed pyrolyzer reactor.

3.3. Environmental benefits of the process

As mentioned above the application of this GreenPlasma end-to-end waste-to-energy system is Ambornetti, a hamlet in the Municipality of Ostana, near Cuneo, Piemonte (Italy), some 1600m above the sea level. This hamlet is being refurbished to be transformed in a minigrid community hosting tourist accommodations, a restaurant, a farm and a dairy. From the point of view of the environmental advantages deriving from the use of the GreenPlasma waste-to-energy solution, a comparison can be made with the alternative of the collection of the waste and disposal at a central facility. Considering the current waste collection practices for the Municipality of Ostana, each kg of unsorted waste travels about 40km for its disposal, travelling on a large vehicle that comes up from the town of Pinerolo, where a landfill and mechanical biological treatment facility treats the waste collected from the surrounding Municipalities.

Considering the case scenario of the GreenPlasma end-to-end waste-to-energy system application for unsorted household residual waste thermal treatment on the mentioned mountainous location in Italy. For this a waste collection truck travels 80 km (40 km from waste treatment facility to the mentioned location to collect the waste plus 40 km back to the waste treatment facility) to collect one tonne of waste material form the mentioned location. On average a waste collection truck consumes about 25 litres of diesel to travel 80 km for one tonne of waste collection. As given [12] one litre diesel consumption produces 2.64 kg of CO_2, implying that 25 litres diesel consumption produces 66 kg of CO_2 for the collection of one tonne of waste material. It was calculated that the treatment of the waste will require 25MWh of energy and provide 21MWh of energy. An estimated amount of waste which will not be transported to the waste treatment facility would be around 15 tonnes. So, this will save around 1 tonne of CO_2 production from transportation. As reported [13] carbon dioxide emission factor for solid recovered fuel produced from municipal solid waste (energy waste collected from household) is 40 tonne/terajoule of energy and for natural gas is reported [14] 56.1 tonne/ terajoule. At the moment, in Italy mainly power is being produced from fossil fuels dominated by natural gas. So, the production of 21 MWh of energy from the said waste will produce 3 tonnes of CO_2. In case the required energy of 25 MWh is being produced from natural gas which will produce 5 tonnes of CO_2. S, according to this calculation the estimated CO_2 balance is of 1 tonne. The overall yield and efficiency of the system can be improved to lower the energy requirements and obtain a fully self-sufficient system as there is an option to couple the system with an anaerobic digester for the estimated 850kg/year of organic waste processing, producing in turn exploitable biogas; this dual system will be able to cover the overall energy requirements of the device from renewable energy instead of from fossil fuel. This scenario will turn the CO_2 balance completely beneficial.

3.4. Preliminary study on thermo-economics of the process

As a preliminary study the exploitation of the syngas is accessed in a microturbine and internal combustion engine (ICE) for a combined heat and power (CHP) system.

- For the microturbine option of the total input energy (power required for the process and energy of input waste material) 60 % is obtained in the form of heat, 15 % in the form of electricity and the rest 25 % is consumed in losses (process losses).

- For the internal combustion engine (ICE) option of the total input energy (power required for the process and energy of input waste material) 52 % is obtained in the form of heat, 18 % in the form of electricity and the rest 30 % is consumed in losses (process losses).

A preliminary thermo-economic study of the GreenPlasma end-to-end waste-to-energy system has been performed considering the three main case scenarios of applications for the said system:

1) a stand-alone tourist facility in the mountains
2) small boat for marine litter disposal
3) large boat for on-board waste disposal

The evaluation of thermo-economic study for the said three scenarios was based on the investment cost for manufacturing the waste-to-energy system and operational cost and revenue generation from heat and electricity as process product and cost saving from not paying to some external waste management authority.

The third case scenario i.e., large boat for on-board waste disposal found to be the most feasible in terms of thermo-economic application of the system. In this scenario, the investment cost was found to be less than half as compared with the other two case scenarios.

The system has been developed with the aim to provide a low-cost alternative for the mentioned community so that the people living there become independent in the way they deal with their own household residual waste and recover energy from it. This is expected to provide a significant social and importantly the environmental benefits as mentioned above.

4. Conclusions

The device embodies a very disruptive concept: by taking the proximity principle to its extremes, as it makes possible a truly local but still environmentally sound and safe thermal disposal of waste with energy recovery, hence allowing for a novel approach to marine litter and residual or difficult waste disposal with important social and economic consequences. First of all, local distributed plants are a very manageable alternative to large, central plants that nobody wants on their door step and that need “feeding” with waste to work at ideal conditions. Furthermore, with wide adoption, the collection of residual waste could be eventually phased out completely, with further significant savings for the waste collection authorities. Finally, the waste remains truly a responsibility of the waste producer, as it does not get forgotten the instant it is disposed of in the bin: the waste producer needs to deal with it within the boundaries of its own community. This is potentially a strong driver for waste minimisation. The advantages of this disruptive approach to the disposal of residual solid waste are quite clear, and the end-to-end waste-to-energy system grants an affordable and environmentally sound technology that can be applied also to other wastes.

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6. References

[0] GreenPlasma project, "Nuovo processo Green, autocontrollato, per il microtrattamento, mediante Plasma, di acque industriali e rifiuti solidi "a km zero", project number FA211-414C, funded by Regione Piemonte POR FESR 2007-2014

[1] System for plasma treatment of solid waste EP 3023693 B1, 2018. https://data.epo.org/publication-server/rest/v1.0/publication-dates/20180321/patents/EP3023693NWB1/document.pdf

[2] Sea Litter Critters, project funded by the Horizon2020 SME Instrument programme (Phase 1) with grant agreement 717863. https://cordis.europa.eu/project/rcn/200326_en.html

[3] CLAIM, project funded by Horizon 2020 Grant Agreement no: 77458 https://www.facebook.com/pg/CLAIM.H2020/about/?ref=page_internal

[4] EUROSTAT, Municipal waste statistics. Data for 2016, extracted in April 2018: http://ec.europa.eu/eurostat/statistics-explained/index.php?title=Municipal_waste_statistics

[5] FormulaGP - Recruitment plan for a skilled associate to help developing the patent pending IRIS GreenPlasma device, project funded by Horizon2020 Grant Agreement 739802 https://cordis.europa.eu/project/rcn/210959_en.html

[6] Francesco Fantozzi et al., 2007, ''Rotary kiln slow pyrolysis for syngas and char production from biomass and waste – part 1: working envelop of the reactor'', Journal of Engineering for Gas Turbines and Power, 129, pp. 901 – 907.

[7] Saeman, W. C., 1951, "Passage of Solids Through Rotary Kilns—Factors Affecting Time of Passage," Chem. Eng. Prog., 47, pp. 508–514.

[8] https://www.ospar.org/work-areas/eiha/marine-litter (assessed on 27.04.2018).

[9] Simone Colantoni, Pietro Bartocci, Umberto Desideri, 2007, 'Rotary Kiln Slow Pyrolysis for Syngas and Char Production From Biomas sand Waste—PartII: Introducing Product Yields in the Energy Balance'', Journal of Engineering for Gas Turbinesand Power, Vol. 129, OCTOBER 2007.

[10] Dorota Karolina Adelajda Ligenzowska, Plastic Pyrolysis Using Montmorillonite-Based Catalysts. Master Thesis, 2015. Available at: https://fenix.tecnico.ulisboa.pt/downloadFile/1970719973966058/Thesis%20.pdf (accessed on 08.05.2018).

[11] R. W. J. Westerhout et al., 1997, '' Kinetics of the Low-Temperature Pyrolysis of Polyethene, Polypropylene, and Polystyrene Modeling, Experimental Determination, and Comparison with Literature Models and Data'' Ind. Eng. Chem. Res., 36, pp. 1955-1964.

[12] http://ecoscore.be/en/info/ecoscore/co2 (accessed on 03.05.2018).

[13] Muhammad Nasrullah, Pasi Vainikka, Janne Hannula, Markku Hurme and Janne Kärki 2015, 'Mass, energy and material balances of SRF production process. Part 3: Solid recovered fuel produced from municipal solid waste'', Waste Manag Res. 2015 Feb;33(2):146-56.

[14] A.K. van Harmelen, TNO report ''CO_2 emission factors for fuels in the Netherlands'', April 2002 Available at:

https://www.rvo.nl/sites/default/files/2013/10/Harmelen%202002%20(EN)%20CO2%20Emissionfactors%20for%20fuels%20in%20the%20Netherlands.pdf (accessed on 04.05.2018)