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Perspectives of decentralised gasification of residual municipal solid waste

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Abstract

In the European Union (EU), the dominant technology for high-temperature thermal treatment of residual Municipal Solid Waste (i.e., the unsorted waste where source separation is performed) is the moving grate incineration. The process of combustion in this sector has been optimised thanks to the introduction of stringent criteria of operation both in the combustion chamber and in the treatment of the generated off-gas. However, the costs of treatment can be sustainable only if the tariff to be applied for the service is coherent with the average value found in the sector. The literature demonstrates that, under a capacity threshold, the grate system is out of market, thus limiting the implementation of small decentralised plants. This paper discusses the potential benefits of small-scale and decentralised thermo-chemical treatment plants replacing a single large-scale one. In addition, the present article analyses the consequences of the results of a recent survey that zoomed in on the availability of small-scale gasifiers for implementing such a strategy. The results of this analysis show that small-scale gasification is preferable to other technologies (e.g., incineration and pyrolysis) in terms of scale effect and flexibility/modularity. Compared to other thermal treatments, the local environmental impact could be reduced by converting syngas into fuels or chemicals rather than burning it for direct energy recovery. The paper also shows that small-scale gasification is able to respond to different needs in both EU and non-EU countries, like the management of progressively lower amounts of residual waste requiring treatment/management of uncontrolled dump sites.

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1. Introduction

The waste hierarchy in the EU considers energy recovery at a lower level with respect to material recovery in order to integrate it. WtE refers both to anaerobic digestion and to high-temperature thermal processes. The

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Nomenclature

CE	Circular Economy
WtE	Waste-to-Energy
rMSW	Residual Municipal Solid Waste (also called unsorted urban waste)
EU	European Union
RDF	Refuse Derived Fuel
SC	Selective Collection
SF	Slope Factor
SRF	Solid Recovered Fuel

latter are combustion, gasification and pyrolysis. Referring to EU and EU-like contexts, combustion is the most adopted process among the three. In order to be economically sustainable, combustion (incineration) requires to be implemented in large plants. Indeed, to this concern the sector has clearly demonstrated that, in terms of specific cost of treatment (e.g., Euros per 1 ton of waste fed), there is an unfavourable scale effect when the treatment capacity of a moving grate incinerator is under a certain threshold [1,2].

In the EU, the management of rMSW in contexts where CE principles are clearly applied will have to take into account a SC efficiency that can exceed even 80%; that means rMSW is even lower than 20% of the produced and collected MSW [3–6]. Of course, also non-EU countries begin to move towards CE principles ans SC implementation, starting from the recyclable fractions of MSW [7–9].

A question may arise on the fate of the resulting rMSW, as the options available are energy recovery and/or sanitary landfill after pre-treatment. Landfill disposal will be limited by the EU to 10% or below after 2035 [10,11]. Zooming in on the contents of rMSW is compulsory: indeed, if the recyclable materials still present in the rMSW are more than 50%, an ideal rMSW with only non-recyclable materials could comply with the EU target of limiting the share of landfillable MSW to 10%. In reality, we must take into account also the residues from the treatments of the SC streams: e.g., residues generated during composting or in anaerobic digestion plants with post-composting, etc. [12].

The present paper wants to give a contribution to understand the potentiality of an alternative scenario based on two points:

- no longer centralisation of rMSW treatment in large plants;
- introduction of decentralised treatment plants no more based on the process of direct combustion.

The technical and scientific literature make available documentation often oriented to large-scale gasification plants and special waste as feedstock [13–15]. However, scenarios with rMSW as input have been present in the international literature for years as an alternative option to combustion [16–18]. EU-like contexts are interested too in this topic [19,20]. The particularity of the context of the present article is a scenario where small gasification plants are used to manage rMSW collected in small regions, each one to be serviced with a plant. This scenario looks extreme but the future of waste management in EU could be based strongly on the principles of SC maximisation and proximity of treatment, reducing the capacity of each plant to be implemented [21]. Moreover, the evolution of the sector is expected to make available processes suitable to avoid pre-treatment of rMSW before gasification: indeed, if gasification could be performed avoiding RDF/SRF generation, the cost of treatment of rMSW could be reduced. RDF/SRF generation should remain available for strategies oriented to exploit co-combustion in cement kilns, power plants, etc [22,23].

2. Materials and methods

The starting point of the analysis are the results of a survey recently issued in Italy focusing on the viability of a rMSW management based on small gasification plants [24]. This is the most recent survey on small-scale gasification at a commercial scale for rMSW. That work was developed specifically for a small region with high SC efficiency to be serviced.

The potentialities of these technologies are discussed in the present article according to:

- indirect role and effects of SC under a perspective of highly efficient source separation;
- principle of proximity and social acceptance;
- advantages and limits of flexibility given by small-scale capacity plants;
- prevention of local impacts;
- recommendations from an enhanced vision of health impact.

The aforementioned survey [24], the related environmental, geographical and cultural context, the recent literature and the requirements set by the EU legislation in the recent years will serve as the basis for deepening the discussion of the previous five points. The last point will be discussed based on recent literature findings on the potential adverse impacts induced by the heavy metals emitted from thermal WtE plants (e.g., incineration, gasification, pyrolysis). Basic principles of the health risk assessment and the results of previous work by the authors will be taken into account to set up a critical analysis on the potential impacts of WtE plants on the local air quality.

The reference region considered in the present paper is located in northern Italy in Italian Alps. A virtuous SC system is currently active, with an efficiency that reached 76.8% in 2018 [25]. The area is a typical mountainous region characterised by the presence of several valleys and by meteorological phenomena (e.g., frequent episodes of atmospheric stability and thermal inversion) that do not represent ideal situations for the atmospheric dispersion of the air pollutants emitted by anthropic activities. The resident population is about 545,000 inhabitants, mainly distributed at the bottom of the valleys. The local population, like many rural populations living in Alpine climates, make use of wood biomass for heating purposes. This is believed to worsen the local air quality in a geographical context with unfavourable conditions for the dispersion of air pollutants [26]. The concerns of the local population and politics on the implementation of WtE plants in the area are partly motivated by these issues, since additional emission sources would add to the existing ones.

3. Results and discussion

Given the EU criterion that limits the share of rMSW sent to landfills to 10%, the most probable way to comply with such criterion is to perform a high-temperature process with energy recovery (not necessarily combustion). This is what emerged also from the survey recently issued in Italy, focusing on the viability of a rMSW management based on small gasification plants [24]. This is the most recent survey on small gasifiers at a commercial scale for rMSW; the Authors of that section of the overall document (co-authored with an Italian University) belong to a public research centre specialised in thermo-chemical processes, not only aimed at generating energy. Table 1 presents the results of the survey in terms of available small-scale gasification technologies.

Table 1. Small-scale gasification technologies of WtE, Waste-to-Chemicals e Waste-to-H_2 proposed in commercial scale under 100,000 t/y for the conversion of rMSW alone or mixed. Data extracted from PAT [24].

Technology	Process	Products	Capacity (input)
A	Fluidised bed	*Syngas* for electricity generation	19,000–165,000 t/y
B	Fluidised bed	*Syngas* for production of MeOH, EtOH	From 100,000 t/y
C	n/a	*Syngas* for production of H_2, fuels, electricity	Modules from 72 t/d
D	Low temperature fixed bed	*Syngas* for heat/electricity generation	Modules of 15–150 t/d
E	Fluidised/Fixed bed	*Syngas* for heat/electricity generation; MeOH; EtOH	Modules of 150 t/d; plants from 100,000 t/y
F	Pressurised fluidised bed	*Syngas* for generation of H_2, DME, MeOH, jet fuel	Modules of 20,000 t/y pre-treated;
G	Gasification with syngas refining by plasma torch	*Syngas* for production of H_2, fuels, chemicals, electricity SNG	Modules of 67,000 t/y.

A sequential question concerns the reason why gasification is the winning process at a small scale. We can try to give an explanation: the reason could be strictly related to the size of the area to be serviced; indeed, the literature has pointed out that, under around 100,000 t/y of input waste, direct combustion is not economically viable

[1,27,28]; additionally, when compared to pyrolysis, gasification has the advantage of giving only one product of interest (syngas), simplifying the management of the strategy. In addition, it is worth mentioning that the absence of combustion of any solid fuel gives to gasification an advantage in terms of local environmental impact compared to pyrolysis [29].

The principle of proximity in treatment is conventionally applied to rMSW in EU: it is a principle established in the Framework Directive on waste of the European Commission [30]; it implies that waste should generally be managed as near as possible to its area of production, mainly because transporting waste has a significant environmental impact [31–34]. Proximity for EU is quantitatively different from the vision of proximity of the population living near a plant and asking for limiting the arrival of waste of "others". In practice, a reduction in capacity of the plants is a sort of demonstration of attention to this social preoccupation. Not all the technologies present in Table 1 allow for an extreme decentralisation suitable for interpreting proximity according to the vision of the population. However, three technologies seem to be very flexible, allowing for the local treatment of rMSW in small urban areas. It is clear that the scale can reduce not only the total mileage of transport, but also takes into account the local opposition to the arrival of waste from areas far from the one hosting a treatment plant.

Increasing both proximity and SC has the consequence of reducing the capacity of rMSW treatment plants virtually needed, compared to the past. As an example, we can consider the dynamics of the proposals for WtE plants that were made in target area presented in the previous section in the past years. In this region three proposals for thermal treatment plants were drafted in the last two decades, the first two with no success in implementation. Over the years, the situation in this region was as follows:

- The population to be serviced remained practically steady because of the absence of a significant demographic growth.
- The per-capita production of MSW (rMSW + SC) remained quite steady because of a limited development of the economy in the related period.
- The autonomy of the area to be serviced avoided to include external inputs according to the principle of self-sufficiency and no more.
- SC evolved significantly with the consequence of reducing notably the rMSW potentially interesting for WtE options.
- 20 years ago, the first proposal referred to rMSW incinerator with a capacity of 240,000 t/y; 12 years ago, the proposal was calibrated for 103,000 t/y; nowadays the potential input is set around 60,000 t/y [24] for a population of around 545,000 inhabitants (role of tourists excluded); thus, today the expected input for a design is below the threshold that guarantees the economic sustainability of the grate incineration, but is expected to be economically sustainable for a gasification process [24].

However, three opposite strategies are interesting to discuss:

- The first one is the decentralised production of RDF/SRF from rMSW and its treatment in a centralised gasification plant. This option could give higher guarantees in case of chemical conversion of syngas, thanks to the level of homogeneity that can be reached through the production of RDF/SRF. The limit is the scale of the plants to produce RDF/SRF because it cannot be too small for the economic sustainability of the system.
- The second one is the treatment of rMSW in a centralised gasifier with no pretreatment. This option is based on a gasification without pre-treatment. As the input would be rMSW, it must be expected that the characteristics of the syngas would be unsteady, making its chemical conversion more difficult.
- The third one is the treatment of rMSW in a decentralised way in small gasification plants without going through the production of RDF/SRF, if the technology allows it (avoiding the costs of pretreatment). This option maximises the principle of proximity and decreases transport emissions. Of course, if the transfer stations already exist on the territory, with the aim of minimising the cost of transportation thanks to the use of larger trucks, a strategy could be placing a small gasifier in each transfer station.

A schematic representation of these three scenarios is presented in Fig. 1. All these scenarios offer interesting options for advanced rMSW management. However, it must be considered that the opposition to high-temperature processes will always exist, since the zero scenario (do nothing) would change whatever solution is chosen.

Two questions must be analysed in relation to the health impact of small plants, specifically small gasifiers:

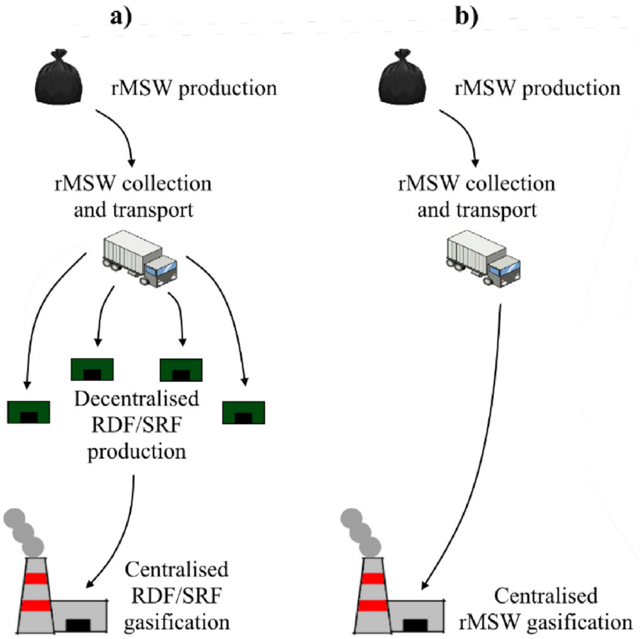

Fig. 1. Schematic representation of the possible strategies involving waste gasification: (a) decentralised RDF/SRF production and centralised gasification, (b) direct rMSW centralised gasification and (c) direct rMSW decentralised gasification.

- At local scale, "small" does not means impacting less than "large"; indeed, several parameters may influence the dispersion of the pollutants released and their impacts on the surroundings. In practise, when designed, even a small plant must be subjected to an optimisation of the design parameters.
- Rethinking the conventional approach could open to rethinking the control of the plant, looking beyond what the regulation in force asks. This concept is explained just below and can be applied to any kind of plant in the waste sector.

A recent work [35] highlighted the potential risk induced by hexavalent chromium (Cr VI) released by rMSW combustion plants. Cr VI has a cancer potency that exceeds those of other relevant heavy metals for rMSW combustion by $>$ 2 orders of magnitude. Fig. 2 presents a comparison among the heavy metals in terms of the so-called slope factors (SFs), relative to the inhalation and ingestion routes of exposure. SFs are defined as the excess cancer risk induced by a chemical per unit of dose received over a lifetime, and is expressed as $[\mathrm{mg}/(\mathrm{kg}_{\mathrm{bw}}\ \mathrm{d})]^{-1}$, where $\mathrm{kg}_{\mathrm{bw}}$ is the average body weight, normally assumed as 70 kg [36–38].

The cancer potency of Cr VI, combined with uncertain data available in the literature on the emissions of Cr VI from rMSW combustion plants, makes Cr VI a key pollutant to control, apparently secondary only to dioxin and dioxin-like polychlorinated biphenyls (dl-PCBs). As a matter of fact, the emissions of dioxin and dl-PCBs have prioritised interventions both on the side of technology development and on the side of the EU environmental legislation. The result is that, nowadays, dioxin and dl-PCBs emission limits from rMSW plants are lower than the emission limit values for heavy metals by more than four orders of magnitude [39]. However, the inhalation SF of Cr VI is only 2.5 orders of magnitude lower than the inhalation SF of dioxin (Fig. 1). This means that, if carcinogenic metals are not adequately controlled at the emission level, the overall cancer risk induced by an rMSW plant might be underestimated.

At present, Cr VI from rMSW combustion is not explicitly regulated by the EU legislation. A cumulative limit value exists for a large group of heavy metals, including total Cr, but no specific reference to Cr VI is made. In the study carried out by Rada et al. [35], a proposal for an emission limit value for Cr VI was made (0.005 mg/N m^3), based on the cancer potency of Cr VI and on the plausible Cr VI content in the heavy metal mixture released at the stack. However, the actual impact of Cr VI cannot be controlled only by limiting its concentration in the exhaust gas, since other parameters play a crucial role. For instance, a plant with a capacity of 20,000 t/y would induce 1/5 of

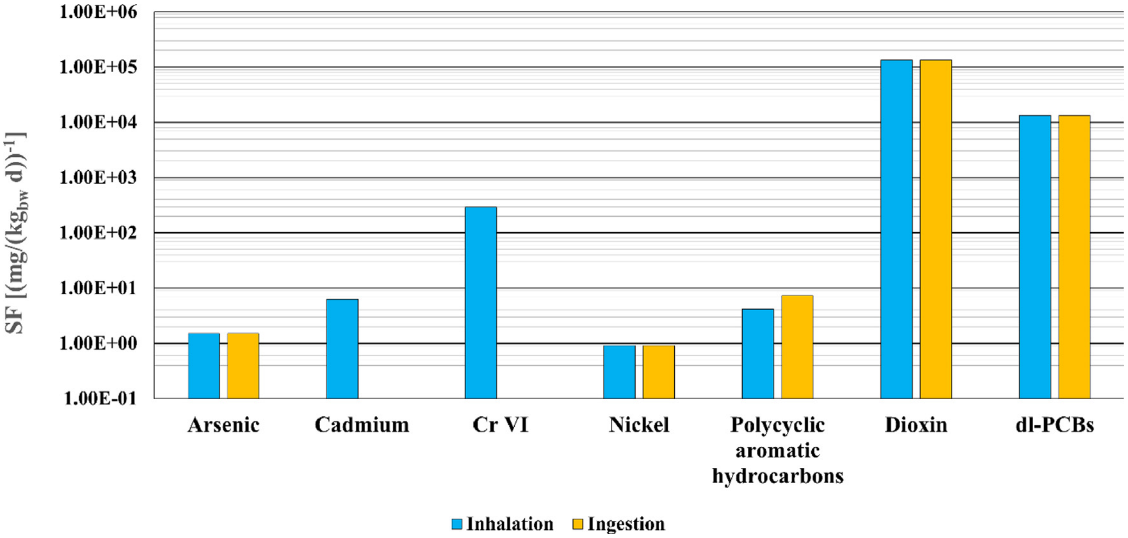

Fig. 2. Comparison between the inhalation and ingestion SFs of the carcinogenic chemicals [38].

the impacts expected by a plant with a capacity of 100,000 t/y only if the following parameters are kept unchanged with respect to the large-scale plant: combustion technology, exhaust-gas velocity and temperature, stack height, meteorological conditions, local morphology, presence of population, local diet. Only under these circumstances, the equation "smaller plant, smaller impact" is valid.

To ensure the compliance with a Cr VI limit value, the air pollution control technologies of rMSW combustion plants may require improvements. The relatively high solubility of Cr VI in water suggests that wet removal processes would be advantageous to reduce Cr VI emissions. However, the trend of the Waste-to-Energy sector is to make use of dry removal technologies, because of their ease of operation and management, and because they do not generate wastewater streams. Dry air pollution control technologies include, for instance, bag filters, electrofilters and cyclones. It is worth mentioning that air pollution control technologies that remove heavy metals are effective on other pollutants as well, like dioxin and dl-PCBs, which are mainly released in particle phase.

Given the importance of Cr VI, it is appropriate to introduce a continuous monitoring of heavy metals concentrations at the stack of an rMSW combustion plant. The monitoring should focus especially on total Cr and cadmium, with additional periodical analyses on Cr speciation. Once Cr VI emissions are estimated, the expected risk in the surroundings of a plant can be calculated through dispersion modelling and exposure assessment. The cancer risk induced by Cr VI could be verified by integrating the exposure assessment procedure with on-field monitoring, thanks to recent developments that contributed to considerably reduce the detection limit of Cr VI concentration in ambient air [40] and make it compatible with health risk assessment. In case Cr speciation were not sustainable from an economic and technical point of view, one could consider a simplified approach based on dispersion modelling, precautionary assumptions on Cr VI content in total Cr and the health risk assessment process:

- the environmental impact assessment procedure should calculate the Cr VI stack concentration that would induce an acceptable cancer risk in the area of the plant;
- as a first approximation, the Cr VI content in total Cr could be assumed as 20%, which is a very precautionary assumption based on the highest Cr VI content (12.7%) reported by Świetlik et al. [39];
- a corresponding total Cr concentration limit value at the stack should be adopted, based on this assumption. This way, Cr VI emissions would be kept under control by the continuous monitoring of total Cr, which would be easier to monitor than Cr VI.

The continuous monitoring of stack concentrations should be adopted also for dioxin and dl-PCBs, whose respective SFs are $1.33 \cdot 10^{-5}$ and $1.33 \cdot 10^{-4}$, for both inhalation and ingestion [38]. Continuous monitoring should be combined with periodical verification of their deposition fluxes to soil, given the important role of food-chain contamination in the long-term exposure to persistent organic pollutants.

The previous considerations are valid for gasification plants based on syngas combustion. In the case of syngas conversion to alternative fuels or chemicals, significantly smaller local impacts are expected due to the absence of a combustion stage. However, at present, the scientific literature lacks in-depth studies on the potential release of pollutants streams into the environment from syngas conversion processes.

In non-EU like contexts, the flexibility of a small-scale gasification could help tackle progressively the use of uncontrolled dump sites. After excavation of the dumped material, small-scale gasification at relatively low temperature could act as a pre-treatment before sorting and recycling. In this case it is not a matter of decentralisation: the advantage could be the possibility to progressively implement the capacity of treatment of waste to be diverted from landfilling. The number of gasification modules could increase in time, specifically with the technology D in Table 1, thanks to the reduced capacity of the unit module. This technology allows for another interesting potential use if we look at the first treatment step: the temperature and duration of the process are expected to efficiently convert volatile solids into syngas (to be exploited for energy purposes) and guarantee the evaporation of moisture, leaving a solid residue suitable for a simplified post separation of non-combustible materials (glass, metals, etc.) after a natural cooling.

The same approach based on flexibility in plant capacity could be used for site remediation activities: old waste dumped in a site could be excavated in order to become the feedstock of one or more small gasifiers before separation of incombustible materials, interesting for recycling, still present in the site. That would allow a significant reduction of volume for final disposal.

A question can arise concerning the compatibility of the decentralisation strategy with the COVID-19 pandemic. A key factor in the management of the COVID-19 emergency is the exploitation of the high-temperature of waste incinerators in order to destroy the surgical masks collected in the territory together with the rMSW [41–43]. In the case of a management based on small-scale gasifiers, the question is if the available processes allow for the destruction of infected material under safe conditions. The answer is positive, as even in the case of relatively low gasification temperature, the environmental conditions in the process chamber (a few hundreds of °C) are adequate for solving the problem.

Finally, in the frame of the commercial proposals for rMSW gasification, it will be interesting to investigate the performances of a technology which is proposing an extremely modular gasification without pre-treatment of the input (a few tons per day per module). Looking at the more flexible technology in Table 1 (case D), literature data on the process and its performance are expected to increase in the near future thanks to incoming research supervised by a public University collaborating with a team of external certified laboratories [44].

It must be underlined that flexibility avoids implementing a rigid MSW management system. Indeed, during the life of a gasification plant (e.g., 15 years) decision makers could change their approach in terms of material recovery valorisation referring to MSW management; this is the case of diapers that, for instance, in Italy should be subjected to SC as a consequence of the vision of the Italian Ministry of Ecological Transition in terms of priorities in material recovery maximisation. Their presence in rMSW is reaching remarkable percentages in rMSW in regions where SC has reached very high results (e.g., 80% of SC). It is clear that the interest for their valorisation is growing thanks to their composition based on plastic and cellulosic materials. But it is also clear that the introduction of their source separation decreases the availability of mass and energy at the inlet of the thermal treatment plant. The adoption of a technology able to be recalibrated thanks to its modularity can help in this case.

4. Conclusions

The present paper investigated the potential role of decentralised WtE plants in contexts where high SC rates are achieved and where the relatively low amount of rMSW may make a conventional combustion plant unfeasible from the economic point of view. Three strategies were compared to understand the potentialities of small gasifiers. The discussion presented in the previous section allows making the following conclusions:

- nowadays, gasification, as opposed to the traditional moving grate technology, can guarantee more flexibility than incineration, thanks to its modularity;

- flexibility is the key when the local context is characterised by low rMSW production (i.e., where incineration is not economically sustainable), when future scenarios are difficult to predict (e.g., SC of diapers), during transitory periods (e.g., landfill or uncontrolled dump site remediation, progressive adaptation to new stricter requirements on waste landfilling) or to implement the concept of proximity in waste treatment, thus reducing transport emissions and public opposition to waste treatments;
- gasification is also preferable to pyrolysis, since only one product (syngas) is formed during the process;
- small combustion plants may also induce lower local impacts, provided that the parameters governing the atmospheric dispersion of the air pollutants emitted are left unchanged with respect to a larger plant for which an environmental impact assessment has been carried out;
- given the potential role of Cr VI emissions, if the WtE approach relies on combustion rather than syngas conversion to other products, decision makers should consider the here proposed strategy to keep Cr VI emissions under control and ensure an acceptable cancer risk in the area;
- local impacts could be considerably reduced when syngas is converted into fuels or chemicals rather than burned for energy purposes.

In conclusion, the present paper shows that gasification represents the preferable WtE technology in terms of flexibility, local environmental impacts and potentials to produce valuable products (e.g., fuels or chemicals). Such advantages, compared to pyrolysis or incineration, make rMSW gasification the suggested option to reduce the amount of waste currently sent to landfills and, meanwhile, make WtE more compatible with geographical contexts that are unfavoured from the point of view of atmospheric dispersion of air pollutants.

The present paper makes a specific reference to the EU context, but the potential flexibility of a strategy based on small plants offers interesting opportunities also in non-EU countries. As a matter of fact, a practical example of application of small-scale gasifiers in non-EU countries was provided in the previous section: the modularity of small-scale gasifiers may help progressively diverting waste from uncontrolled dump sites in contexts where such problem is present. In addition, the first gasification step (i.e., conversion of volatile solids into syngas) would allow for a simplified post-separation of non-combustible materials, thus enabling a new recycling route.

In the future, the management of rMSW in virtuous contexts will have to consider two key aspects:

- SC efficiency can exceed 80%, and thus can limit rMSW to a level lower than 20% of the total MSW produced;
- The principle of proximity in treatment is important not only to reduce transport streams, but also to reduce the local opposition to the arrival of waste from external areas.

High SC and proximity in treatment will give a request of treatment plants with a reduced capacity compared to the past. To this concern, gasification can be considered as a process that is economically sustainable even with smaller potentials than those of combustion plants (specifically, smaller than those based on moving grate technologies, which are the most used in the sector of rMSW treatment).

Finally, the adoption of a strategy based on decentralised gasifiers does not show criticalities during a pandemic. On the contrary, this approach could limit the journeys of the waste trucks that must thermically dispose of waste infected by anti-COVID-19 masks: one of the preferred ways to manage masks from infected domestic users is to send them to an incinerator.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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