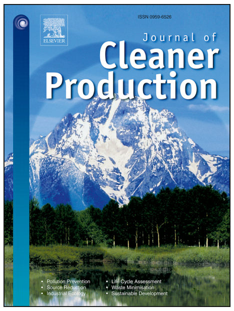

Assessment of carbon emissions' effects on the investments in conventional and innovative waste-to-energy treatments

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Writing – original draft	√	√	√	√	√
Writing – review and editing	√	√	X	X	√
Visualization	X	X	√	√	X
Supervision	√	√	√	√	X
Project administration	NA	NA	NA	NA	NA
Funding acquisition	NA	√	NA	NA	NA

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All persons who have made substantial contributions to the work reported in the manuscript.

Best wishes,

Prof. Francesco Facchini (on behalf of all manuscripts' Authors)

Assessment of carbon emissions' effects on the investments in conventional and innovative Waste-to-Energy treatments

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Abstract: In the current scenario of transition to a Europe-wide circular economy (CE), the Waste-to-Energy (WtE) treatments represent a smart solution to generate renewable energy, reduce landfills and ensure sustainable waste management. The costs and environmental impacts of existing WtE treatments are very different for each available technology. In many cases, their identification is affected by a set of variable boundary conditions strongly dependent on local municipal requirements. In light of these considerations, the paper aims to compare the investment in three different WtE treatments (i.e., incineration, gasification, and *flameless* oxy-combustion) to identify the best solution to support the current transitional phase towards a CE condition. An overall yearly cost analysis was developed by varying local municipal requirements, including investment, operating, and carbon emissions costs. The overall yearly cost and the revenues, due to energy sales and tipping fees, allowed to evaluate the profitability of the investment in the plant lifetime to identify the best WtE treatment. The investment profitability was evaluated by adopting the Net Present Value (NPV) method by estimating the cash flow statement over the entire plant lifetime. The performance of the three WtE treatments, classified as "conventional" (i.e., gasification and incineration) and "innovative" (i.e., flameless oxy-combustion), were compared in a case study concerning Southern Italy's Metropolitan City of Bari. The applied methodology showed, in this case, that gasification, at the moment, has to be deemed as the most sustainable treatment for MSW management. Moreover, the study proved a high dependence between the carbon price and the profitability of the investment and, thus, in the next future the innovative oxy-combustion technology will gain an advantage over all the other technologies, when carbon price will be higher than 44 €/tonnes$_{CO2}$.

Keywords: Circular economy, Economic and Environmental assessment, Municipal solid waste; Waste to Energy, gasification, incineration, smart city.

List of abbreviations

Notation	Meaning	Unit of measurement
$r_{t_{fee}}$	Revenue from tipping fee payment	[€]
c_{cons}	Consumables cost	[€/tonne]
c_{em}	CO_2 emissions cost	[€/tonne$_{MSW}$]
C_{ext}	Investment cost for plant size extension	[€/year]
C_{inv}	Annual investment cost	[€/year]
c_{lab}	Labour cost	[€/tonne$_{MSW}$]
C_m	Maintenance cost	[€/year]
c_{SbP}	Solid by-product disposal cost	[€/tonne]
p_{cons}	Consumables price	[€/tonne]
p_e	Price of the market for selling electricity	[€/MWh]
p_{em}	Price due to CO_2 emissions	[€/tonne$_{CO2}$]
p_{SbP}	Price for disposing of solid by-products	[€/tonne]
q_{cons}	Amount of consumables required to treat 1t of MSW	[tonnes]
q_e	Amount of electricity produced by treating 1t of MSW	[MWh/tonne$_{MSW}$]
q_{em}	Amount of CO_2 emitted to the air by treating one tonne of MSW	[tonnes$_{CO2}$/ tonne$_{MSW}$]
Q_{std}	Plant standard size	[tonne$_{MSW}$/y]
r_e	Revenue from electricity sale	[€]
t_{fee}	Tipping fee	[€/tonne$_{MSW}$]
CCF	Cumulative Cash Flow	[-]
CDCF	Cumulative Discounted Cash Flow	[-]
CE	Circular Economy	[-]
CF	Cash Flow	[-]
DCF	Discounted Cash Flow	[-]
k	Scale coefficient	[-]
LCA	Life Cycle Assessment	[-]
LHV	Low Heating Value	[-]
MSW	Municipal Solid Waste	[-]
VLSFO	Very Low Sulfur Fuel Oil	[-]
WFD	Waste Framework Directive	[-]
WtE	Waste-to-energy	[-]

1. Introduction

The current increase in MSW production is a direct consequence of population growth (at a yearly rate of 2.035% [1]), which is accelerating phenomena such as industrialization, urbanization, and economic development [1] [2]. The global production of MSW, equal to 2.01 billion tonnes in 2016, will grow to 2.56 billion in 2030 and will reach a level of 3.4 billion in 2050. As far as concern the correlation between MSW production and economic development, in 2016, about 34% (683 million tonnes) of the globally produced MSW was generated by high-income countries (i.e., countries with a gross national income per capita of

12,476 $/year or more), despite the same countries being populated by only the 16% of the global population (Figure 1) [2].

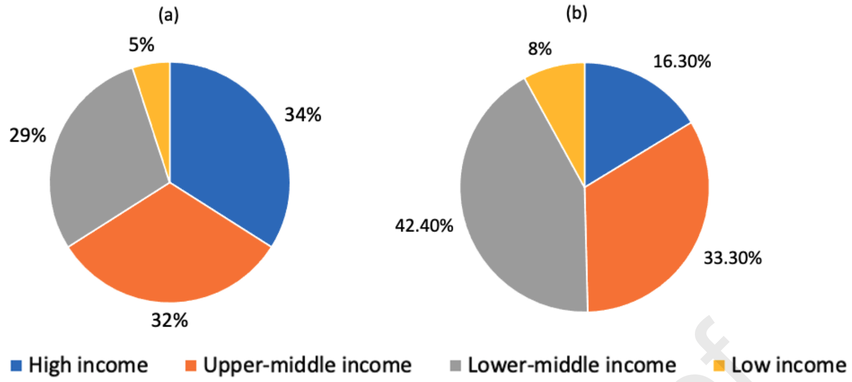

Figure 1. (a) Share of MSW produced globally in 2016 per income category. Adapted from [2]. (b) Share of the global population in 2016 per income category. Adapted from [3]

MSW management shows criticalities both from an economic and an environmental perspective. MSW, indeed, represents one of the most significant sources of pollution at either a global, regional, or local scale [4]. To this concern, in 2016, the MSW management practices generated 5% of the globally emitted 1.6 billion tonnes of CO_{2eq} [2]. Furthermore, at a local and regional scale, the MSW management (e.g., collection, transport, treatment, and disposal) is generally operated in proximity to the urban centres, representing a significant pollution source, very close to citizenship.

From an economic point of view, MSW management is an expensive service for municipalities; in high-income countries, it accounts for 4% of the municipal budget, and of this expenditure, operating costs represent about 70% [3]. Therefore, identifying a solution to manage the increasing amount of MSW produced, accounting for both economic and environmental issues, is a worldwide highly perceived need.

The EU-27 countries are significantly involved in this issue since most of them are included in the high-income category (Figure 1). Several legislative measures have been enacted in the EU to promote sustainable MSW management. The most impactful is the Waste Framework Directive (WFD) 2008/98/EC [5], which can be considered the cornerstone of the European waste policy and regulation. The WFD introduced a waste hierarchy describing, in descending order of priority, the actions to be implemented to manage waste in an environmentally sustainable way, optimising resource efficiency and minimising the environmental consequences of waste management (Figure 2) [6].

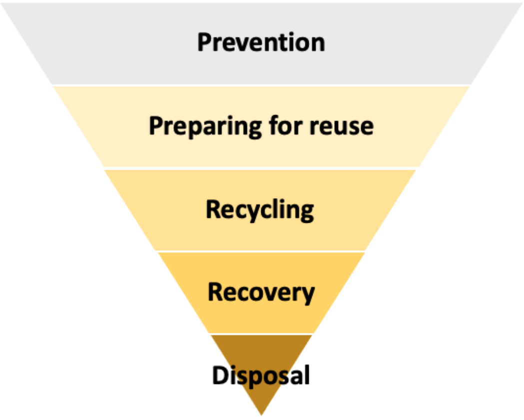

Figure 2. Waste hierarchy pyramid. Adapted from [6]

According to the WFD, sustainable waste management can be ensured by minimising the generation of waste and hazardous substances, avoiding disposal practices and maximising the amount of recycled material [7]. The waste hierarchy identified is a crucial strategy for the transition of the EU economy towards a Circular Economy (CE), allowing MSW management to achieve the best environmental performance [8]. According to CE's definition, MSW production should be minimized, maintaining resources as long as possible within the economic cycle [9]. To foster the achievement of a CE condition, a European target on recycling and landfilling rates of at least 65% and 10%, respectively, must be achieved within 2030 [10]. Currently, the percentage of landfilled and recycled MSW still remains equal to 23% and 48%, respectively, values far short of the target [11]. According to Chen *et al.* [4], despite the improvements achieved, a continuation of the current waste management trend is insufficient to reduce the pressure generated by MSW management and achieve a CE. In light of these considerations, identifying sustainable solutions for MSW management to support and accelerate the transition towards the achievement of the goals set at the EU level is necessary.

Among the actions included in the waste hierarchy (Figure 2), [6]a noticeable category of recovery options is the so-called Waste-to-Energy (WtE), including the treatments to convert MSW into electricity. Although these options are at a lower level (i.e., less preferable) than prevention, reuse and recycling in the waste hierarchy, it can be stated that they are essential to ensure sustainable MSW management and to support the CE transition [12]. WtE treatments, indeed, allow, in this transitional phase, to treat MSW that is not recycled and, simultaneously, to reduce the landfilling rate, consistent with the EU targets and a CE perspective. Once the goals are achieved, these treatments can still be helpful in treating not recyclable materials or perishable waste, avoiding WtE plants' overcapacities. Consistently with these aspects, in the last years, an ever-increasing amount of waste has been processed by adopting WtE treatments [6]. A secondary benefit related to the adoption of the WtE treatment concerns the energy demand of last years. It is estimated that, at the end of this century, the energy demand will be about six times the current one [13] and reach 17 billion tonnes of oil equivalent [14]. In this context, the depletion of fossil fuel reserves and the environmental problems associated with the use of non-renewable sources cannot be neglected [15]. Kumar and S. R. Samadder [13] estimated that around 1.3 tonnCO_{2eq} are avoided, using 1 tonne of MSW for electricity generation. Nevertheless, in EU countries, there is still a strong dependence on fossil fuels for primary energy production. Nowadays, about 70% of direct energy comes from fossil sources (Figure 3) [16].

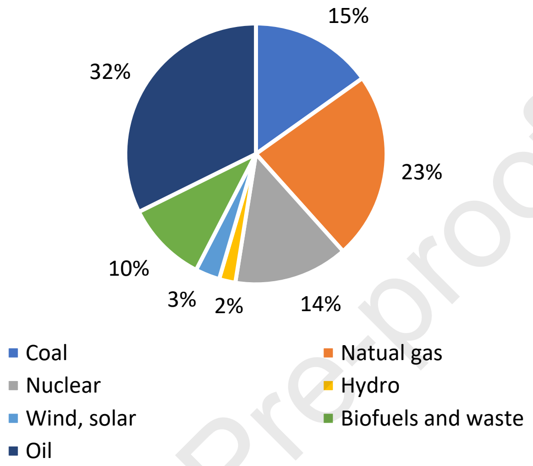

Figure 3. Share of total primary energy supply in 2018 in EU countries per source. Adapted from [16]

Evaluating the potentiality of the existing WtE treatments helps to assess their capability to support and accelerate the current CE transition. Consistently with the above considerations, the following research questions (RQ) have arisen:

RQ1. What are the key drivers to be investigated to assess the economic convenience of WtE treatments?

RQ2. How do the local municipal requirements influence the effectiveness of existing WtE treatments from an economic perspective?

RQ3. Which WtE treatments are available on the market, and what is their potential to support the transition towards a CE?

The present research work's purpose consists of comparing the investment in three different WtE treatments to identify the best solution to support the current transitional phase towards a CE condition. To this end, an overall yearly cost analysis was developed by varying local municipal requirements, including investment, operating, and carbon emissions costs. The overall yearly cost and the revenues, due to energy sales and tipping fees, allowed to evaluate the profitability of the investment in the plant lifetime to identify the most sustainable WtE treatment. Specifically, the investigated alternatives were incineration, gasification and flameless oxy-combustion treatments. The first one is the most widespread, and it is the oldest in technological terms. The second one is considered the most efficient in terms of recovered energy.

The third one is the newest; there are only a few applications at the lab scale, generally adopted for treating low-ranking fuels, coal slurry and industrial wastes [17].

A sensitivity analysis was performed to identify the most significant key drivers affecting the convenience of each considered option. The preliminary assessment allowed to identify the most sustainable WtE treatment for MSW management to support the transition phase when applied to the case study of southern Italy's the Metropolitan City of Bari.

2. Literature review

Wei Lu et al. [18] analysed incineration as a possible alternative for MSW management and proved its validity despite being an outdated technology. According to the authors, the choice of technology for MSW incineration depends on economic and environmental issues. Generally, the green aspects are affected by the high variability of MSW composition and the lack of reliable control systems. A Life Cycle Assessment (LCA) to evaluate the impact of refuse-derived fuel within the incineration process of the MSW instead of the coal was carried out by Havukainen et al. [19]. The results led to reduce the impact of the main environmental categories (i.e., global warming potential, acidification potential and eutrophication). Panepinto and Zanetti [20] adopted a multi-step approach for the economic and environmental evaluation of an incineration plant in Italy. They considered the capacity of the incinerator plant and possible connections with a district heating network for the use of the heat power produced. At a global and local level, an environmental balance and a cost analysis were carried out to evaluate the efficiency of a plant, including heat and electricity cogeneration. In this case, if, on the one hand, the installation of a cogeneration plant in a heating district minimises the environmental impacts, on the other hand, the configuration that provides only the electricity generation is more convenient from an economic perspective.

Similarly, in [21], an LCA was developed to evaluate the environmental impact generated by an incineration plant, including energy recovery in different operating conditions. The research shows that investing in technical improvements is convenient and, therefore, increases the electrical conversion efficiency in the case of a high-size plant. One of the recommended improvements consists of replacing the typical refractory bricks with phase-change material-based bricks in the reactor [22]. It is also shown that the recovery of the bottom ashes helps decrease indices' values in different impact categories [21]. Beylot et al. [23] analysed an LCA related to MSW incineration in France. The study identified a negative indicator for seven of the nine impact categories. In particular, the most significant benefit comes from the cogeneration of heat and electricity as well as from the selective catalytic reduction for NOx abatement. In 2015, subsystems of the plant were modelled, adopting short-term stochastic planning to manage the energy produced by cogeneration [24]. It is noted that short-term stochastic planning increases net revenues and thermal efficiency instead of determinist short-term planning. In [25], the potential benefits in economic and environmental terms of an MSW management strategy based on the incineration and recycling of MSW for a Brazilian location were assessed. The technique consists in recycling 20% of the collected and selected waste and sending the remaining share to incineration. The results showed the potential of the adopted strategy from economic and environmental perspectives. A similar approach, based on the incineration treatment simulation models, was developed in [26] and [27].

Pyrolysis is another MSW treatment recently developed. It is described and detailed in [28], while Wang et al. [29] investigated the environmental feasibility of pyrolysis as an alternative for sustainable MSW management in North Carolina. The environmental impacts of the pyrolysis process were compared with the impact of incineration, anaerobic digestion and landfill. The results proved that fast pyrolysis is the best alternative from an environmental point of view while landfilling is the worst. In [30], the pyrolysis was compared with incineration, gasification and plasma treatment adopting multi-criteria decision-making methods. Li et al. [31] investigated catalytic pyrolysis. They established that if, on the one hand, the use of a catalyst allows a reduction of emissions due to the process, on the other hand, the refrigeration significantly increases the operating treatment costs.

Similarly, the performance of catalytic pyrolysis, if compared with thermal pyrolysis, is proved in [32], [33]. Wang et al. [34] investigated the potential of pyrolysis, combined with thermal or catalytic cracking, to produce syngas under certain operating conditions. In [35], the effects of moisture content and CaO on the product's composition derived from pyrolysis and syngas' Low Heating Value (LHV) were investigated. Song et al. [36] proposed the addition of iron ore and iron oxide to the treatment as an alternative to improve the efficiency and environmental impact due to the pyrolysis of MSW. According to the authors, iron ore and iron dioxide act as waste pyrolysis catalysts; they improve the efficiency and effectiveness of performance treatment.

In the last few years, an increasing interest can be observed in the MSW gasification treatment, which is a valid alternative to other technologies either from a social, economic, and environmental point of view [37]. Hameed *et al*. [38] proved the effectiveness of MSW gasification in reducing pollution and maximising the recovery of energy and material. In [39], the effectiveness of the MSW co-gasification with switchgrass was evaluated by considering LHV, the syngas' yield, and the gasifier and tar temperature. Cai et al. [40] investigated the refuse-derived fuels and straw mixtures' co-gasification performance. They identified a positive impact of the synergistic effects on the system’s performance at low equivalent ratios (0.1-0.2) and high temperatures (800-900°C). Arena et al. [41] reported a technical analysis of the gasification of a recovered solid fuel obtained from MSW sorting. The report confirmed that adopting the syngas for energy applications was effective. From an economic point of view, the investment can be considered sustainable only if an incentive rate for the energy produced is provided. Kardani et al. [42] modelled the MSW gasification in a fluidised bed gasifier to predict treatment features, such as gas and product LHV, as well as syngas yield. Xu et al. [43] developed a thermodynamic model referring to a real case of MSW gasification. The model allowed to compare the composition of the produced gas using different gasifying agents to identify the best for the treatment's environmental performance improvement. A numerical model to compare different gasifying agents was developed in [44]. In [45], a system based on MSW gasification was proposed to simulate the production of electricity, hydrogen and methanol.

Similarly, the performance of a WtE multigeneration system was investigated in [46]. In [47], a biomass-driven cogeneration system was analysed, and the MSW gasification was evaluated. In [48], a thermodynamic model was developed to evaluate the feasibility of MSW gasification in Portugal[49]. The optimal operating temperature of the treatment was identified at 900°C for an equivalent ratio of 0.25. The same approach evaluated the economic convenience of gasifier installation in Brazilian municipalities. The results showed a positive scale-up with increasing the population served, given by reducing the specific costs and increasing the plant's potential [50].

Although in previous works, a comparison has already been conducted between different alternatives for producing energy from MSW[51], [52][53], [54], this research work introduces three main novelties. The first consists of evaluating a new unconventional technology without direct emissions, combining the recovery from MSW with the reuse of CO_2 in total compliance with a CE perspective. The second consist of CO_2 emissions estimating in the overall yearly cost analysis. The third consists of proposing and testing a new approach to provide a preliminary evaluation of the profitability of an investment in WtE treatment by adopting a more simplified assessment if compared to existing methodologies [49], [50][51], [52]. Therefore, the targets achieved in the present work can be considered a starting point for further analysis in more complex scenarios.

3. Materials and Methods

3.1 WtE treatments configuration

The configurations considered for incineration and gasification treatments are shown in Figures 4 and 5, respectively. Although CO2 recovery is also possible in the case of incineration, the most common configurations of the described plants don't include CCS facilities since the treatment required to extract CO_2 is not economically sustainable due to low CO_2 concentration and the high presence of contaminant agents. On the contrary, in the case of flameless oxy-combustion, the oxidizing of all combustible material allows obtaining (at zero cost) high concentrations of pure CO_2.

Consistent with this consideration, the CO_2 liquefaction process is considered in the plant configuration of the most common flame plants.

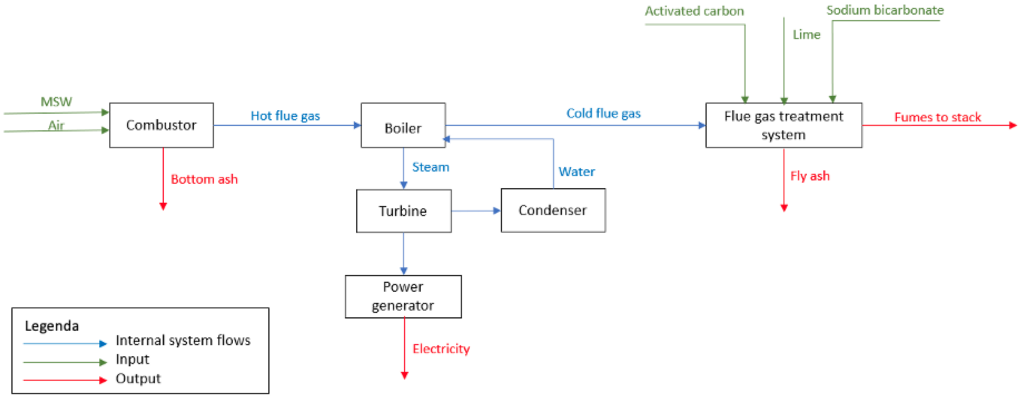

Figure 4. MSW incineration plant configuration

In the incineration treatment (fig. 4), the stored MSW are burnt into the combustor with excess air. Two main by-products are generated from the combustion, one solid and one gaseous. The solid by-product consists of unburned products (so-called bottom ash) collected at the bottom of the reactor and then disposed of outside the system. The gaseous by-product consists of flue gas at a temperature of 1000-1100°C. It is used to warm up the water in a boiler for steam generation, which is part of a steam cycle of electricity production. The combustion fumes are conveyed to the flue gas in reactors and bag filters, where specific additives (i.e., activated carbon, lime and sodium bicarbonate) are added for dust abatement. Finally, the purified exhausts are conveyed to the stack and released into the atmosphere.

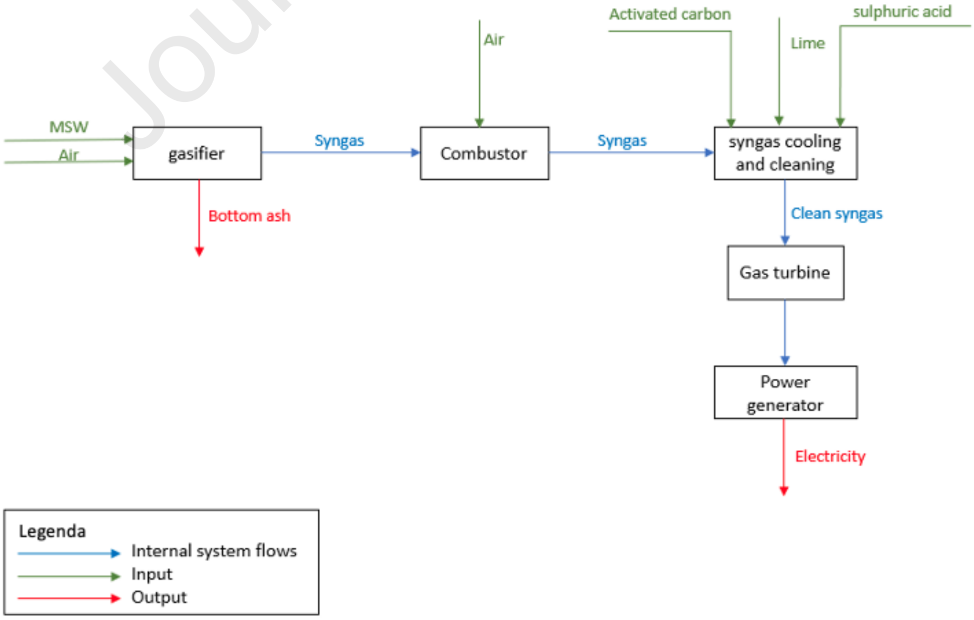

Figure 5. MSW gasification plant configuration

In the gasification treatment (fig. 4), the MSW is firstly shredded and undergoes a metal removal process. Then it is fed into a gasifier for degradation at about 900°C, with a sub-stoichiometric percentage of an oxidising agent (e.g., air). Solid slag and a gaseous product, the so-called syngas, are produced by the reaction in the gasifier. The syngas is burnt in a combustor with air and conveyed to a cleaning system. In the case of the plant configuration considered in the present work, the purified syngas is used as fuel by a gas turbine for electricity generation.

As shown in fig. 6, the technical oxygen of medium purity (88-94%), the mass of MSW pre-ground mixed in aqueous solution (i.e., slurry), and the auxiliary fuel (i.e., methane and Very Low Sulfur Fuel Oil (VLSFO)), enter the combustor. The flameless oxy-combustion is favoured by the combustion chamber's low pressure and high temperature (around 1300-1500°C) conditions. The MSW oxidation reactions produce two main types of by-products: solid and gaseous. The solid output consists of vitrified slag produced by the unburnt material treated with cold water jets in the molten state. The resultant materials are inert pearls with a glassy structure, so-called vitreous slag (VS), incorporating dangerous substances (not risky to human health and the environment [53]). The treated VS is potentially adoptable as an additive in concrete mixtures, cement raw materials, building materials, fluxes, and as a sintering additive [54]. The gaseous output consists of hot exhausts (around 1300-1500°C) and steam. If mixed in the fumes quencher with the cold fumes recovered from the blower and cooled at a temperature of 700-800°C, they can be used to produce electricity by a steam turbine.

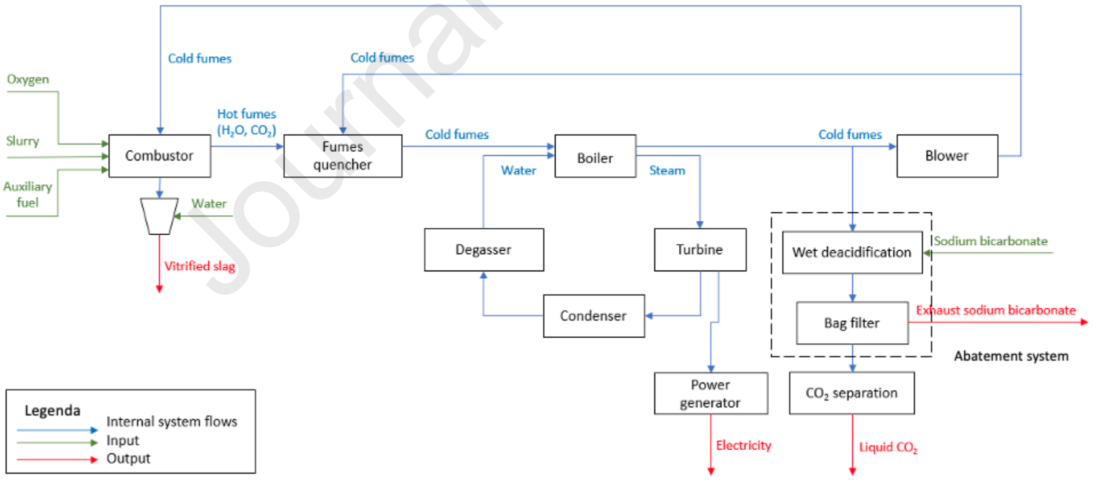

Figure 6. MSW flameless oxy-combustion plant configuration

Cold fumes (at a temperature of 200-250°C) in the output of the boiler are conveyed to an abatement system, including wet deacidification and a bag filter. The dedusted fumes, mainly CO_2, are then treated through a CO_2 separator and recovered as liquid CO_2 for industrial scopes. It is noteworthy that, for the case in fig. 6, a zero CO_2 emission process is accomplished. In this WtE treatment, the adoption of technical oxygen as an oxidizer allows almost all combustible material to be transformed into H_2O and CO_2. This reaction eliminates the concentration of pollutants in the flue gas [55].

Consequently, the obtained flue gas, with a high percentage of CO_2[56], is generally purified, and the CO_2 is liquefied [57]. This treatment allows the sale of the CO_2 extracted, generating a gain. According to the assumptions of this work (described in the next section), this kind of revenue is neglected in the economic evaluation.

3.2 Assumptions and boundaries systems

The proposed cost and investment analysis considers the environmental aspects as an operational cost to acquire emission rights through carbon pricing [58]. Consistent with this approach, the analysis doesn't consider the indirect emissions due to the procurement, extraction and transport of raw and auxiliary materials (fig. 7).

Similarly, the evaluations of indirect emissions, as well as the impact on public health due to energy supply, slag disposal, filtering systems recovery, etc., are out of the boundary of the system considered.

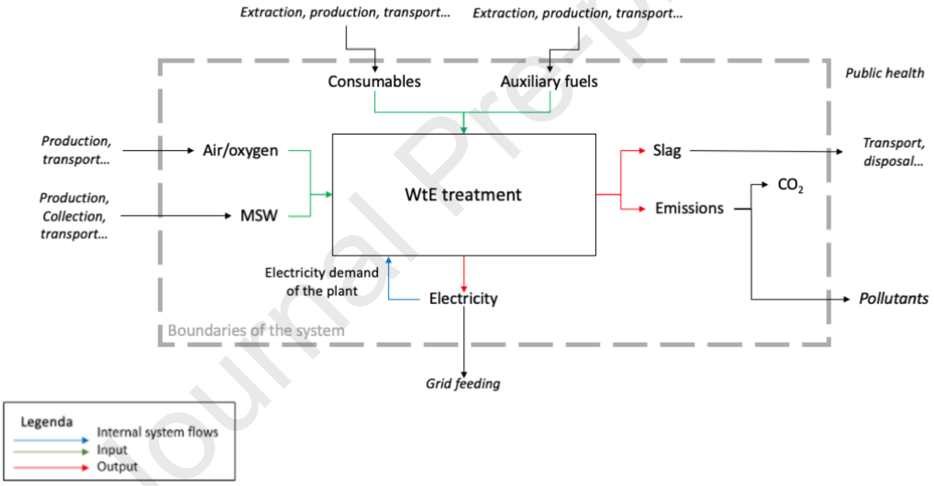

Figure 7. Systems' boundaries

Concerning the pollutants in the flue gases, It was considered only CO_2 emissions. Consistent with this assumption, it can be observed that in the WtE plants considered, the concentration of other pollutants and particulate matter is strongly reduced by adopting flue gas filtering and purification systems [59], [60], as shown in plant configurations (Figures 4-6).

As far as concerns the revenues from the CO_2 sale in the case of the flameless oxy-combustion plant, considering the amount of CO_2 produced, the related prices and the processing and storage costs required to handle the CO2, the expected profit is negligible if compared to the profit generated from electricity sales (directly fed into the grid). Consistent with this consideration, only the revenues from the sale of electricity have been included in the economic assessment.

Therefore, the approach proposed assumes a green-field investment on a stand-alone plant that provides to the decision-maker responsible for the installation and management of the WtE plant a preliminary evaluation on the profitability of the investment in the plant lifetime by varying local municipal requirements, including investment, operating, and carbon emissions costs.

3.3 WtE cost and investment analysis

The cost and investment analysis of the three proposed technologies consists of defining an overall yearly cost ($C_{tot}(q)$) including economic (i.e., investment, operation and maintenance costs) and carbon emissions costs. The MSW annual capacity to be treated (q [tonnes$_{\text{MSW}}$/year]) depends on local municipal requirements. To this concern, a standard size (Q_{std} [tonnes$_{\text{MSW}}$/year]) was set for each investigated WtE treatment. In other words, the Q_{std}-parameter defines the maximum annual capacity to treat MSW of a specific plant. The MSW annual capacity assumed is $Q_{std} = 1E5$ [tonnes$_{\text{MSW}}$/year] for all WtE treatments [61] [62]. In case the yearly amount of MSW to be treated exceeds the given Q_{std}, a significant investment is needed to face the installation of a new thermal utility (C_{ext}). The effect due to possible economies of scale was quantified by assuming a scaling k-coefficient equal to 0.6 [61].

Table 1 summarises the main items' costs with the corresponding notations.

Table 1. List of cost items included in the total cost function

Cost item	Description	Cost type	Notation
Annual investment cost	Investment costs due to acquisition, construction and installation of industrial systems (greenfield project).	Fixed [€/year]	C_{inv}
Investment cost for plant size extension	Investment cost due to thermal facilities acquisition to increase the plant's annual capacity.	Fixed [€/year]	C_{ext}
Maintenance cost	Annual cost for the plant maintenance.	Fixed [€/year]	C_m
Consumables	Cost of additive materials required by the MSW treatments (e.g., oxygen, ammonia, auxiliary fuel, etc.).	Variable [€/tonne$_{\text{MSW}}$]	c_{cons}
Labour	Labour costs to manage the plant operations.	Variable [€/tonne$_{\text{MSW}}$]	c_{lab}
Solid by-product disposal	Cost due to disposal of solid by-products produced by MSW treatments (e.g. slag, ash, baking soda, etc.)	Variable [€/tonne$_{\text{MSW}}$]	c_{SbP}
CO_2 emissions	Cost due to CO_2 emitted (i.e., carbon tax).	Variable [€/tonne$_{\text{MSW}}$]	c_{em}

Fixed costs were evaluated considering the equipment depreciation period, assuming a given available capacity per year. Variable costs were assessed considering the materials needed to treat each tonne of MSW.

Assuming the items cost shown in table 1, the WtE treatment $C_{tot}(q)$ ([€/year]) as a function of the annual capacity of the MSW (q) to be treated, is calculated by eq. 1.

$$C_{tot}(q) = \alpha + \beta\big((n-1)\cdot Q_{std}\big) + C_{ext}(n-1)\sum_{i=1}^{n-1} k^i + \beta(q-(n-1)\cdot Q_{std}) \quad (1)$$

with n ($n \in \mathbb{N}$; $n \geq 1$) that identifies the upper integer of the ratio between the MSW annual capacity and the maximum MSW annual capacity to be treated for a specific plant (eq. 2)

$$n = \left\lceil \frac{q}{Q_{std}} \right\rceil \; s.t. \; q > 0; \quad (2)$$

where α and β depend on equations 3 and 4

$$\alpha = C_{inv} + C_m \;\; [\text{€/year}] \quad (3)$$

$$\beta = c_{cons} + c_{lab} + c_{SbP} + c_{em} \;\; [\text{€/tonne}_{\text{MSW}}] \quad (4)$$

Given C_{inv} and C_m, the other costs are estimated according to equations 5-7.

$$c_{cons} = q_{cons} p_{cons} \;\; [\text{€/tonne}_{\text{MSW}}] \quad (5)$$

$$c_{SbP} = q_{SbP} p_{SbP} \;\; [\text{€/tonne}_{\text{MSW}}] \quad (6)$$

$$c_{em} = q_{em} p_{em} \;\; [\text{€/tonne}_{\text{MSW}}] \quad (7)$$

where q_{cons}, q_{SbP}, q_{em}, identify the amount of consumables, solid by-products, and CO_2 emissions, respectively, produced or needed to treat each MSW tonne . Similarly, p_{cons} and p_{SbP} identify the price of consumables and solid by-products disposal. The p_{em}-parameter represents the economic value assigned to the local carbon tax.

As an extended time period (i.e., twenty years) is considered, and a greenfield investment condition was assumed, the method of the Net Present Value (NPV)(eq. 8), was adopted to assess the investment profitability of each WtE treatment. In this case, considering the plant's entire lifetime, the NPV leads to identifying the investment's capability in WtE treatments to generate money-market liquidity.

$$NPV = \sum_{t=0}^{N} \frac{CF_t}{(1+r)^t} \; [\text{€}] \quad (8)$$

Where:

$t = 0,1,\dots,N$ [year] is the lifetime of the WtE plant.

CF_t [€/year] is the cash flow generated at year *t* by choosing a WtE alternative.

r [%] is the discount rate, i.e., the return value foregone by choosing a WtE alternative.

Similarly, the pay-back period time (PBPT) of the investment, corresponding to the time at which the investment starts to generate monetary liquidity, with regard to the entire investment period, was estimated as follows (eq. 9):

$$PBPT = t \in \{0,1,\dots,N\} \ni \; | \; \sum_{t=0}^{N} \frac{CF_t}{(1+r)^t} = 0 \quad (9)$$

For all the considered WtE treatments, the initial investment outlay was assumed to be fully realised at t=0. The corresponding yearly costs were estimated according to equation 1.

As far as concerned, the revenues generated by the WtE plants, the incomes from electricity sales (paid by the electricity supplier), and the tipping fee (paid by the municipality to treat MSW) were estimated according to equations 10 and 11.

$$r_e = q_e \cdot p_e \cdot q \; [€/year] \quad (10)$$

$$r_{t_{fee}} = t_{fee} \cdot q \; [€/year] \quad (11)$$

where q_e is the amount of electricity generated per each processed MSW tonne, and t_{fee} is the price paid by the municipality to treat one tonne of MSW.

4. Case study: the Metropolitan City of Bari, Italy

Consistent with the purpose of the present research work, three alternative MSW treatments were compared to identify the most cost-effective solution for the case of the metropolitan city of Bari, located in the southern part of Italy.

4.1 Background of the case study

The Metropolitan City of Bari is located in the Apulia region in Southern Italy. In 2019, it had a population of 1.3 million inhabitants. MSW production for the same year was around 580,000 tonnes, with a per capita production of 463 [kg_{MSW}/(in*year)] [63]. The MSW production from 2011 to 2019 in this area decreased, from 650,000 to 580,000 tonne/year, showing a reduction of about 10% (fig. 8).

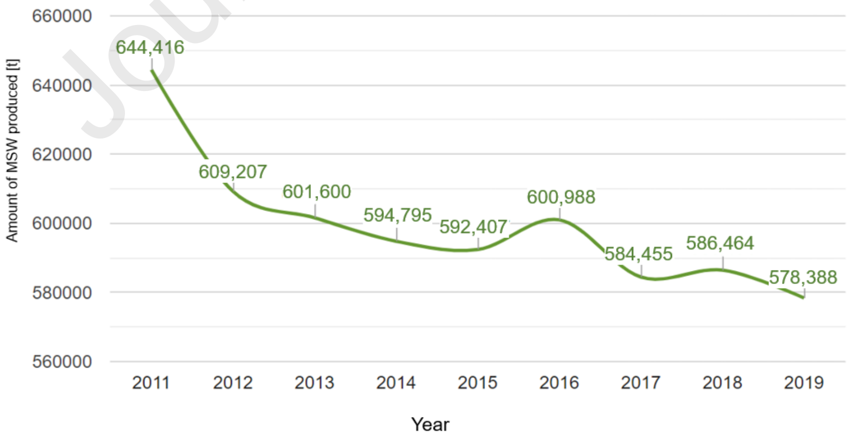

Figure 8. Production of yearly MSW for the Metropolitan City of Bari. Adapted from [63]

Considering the target on the percentage of separate collection and recycling of MSW set by the Legislative Decree no. 152/2006 issued by the Italian Government [64], the Metropolitan City of Bari would ensure a percentage of separate collection of 65% within 2012, December 31st. In 2019, the rate of separate collection for the province of Bari was 57.85% [65] (figure 9), which means about 10% less than the expected target. In 2012, about 20% of the separate collection was achieved.

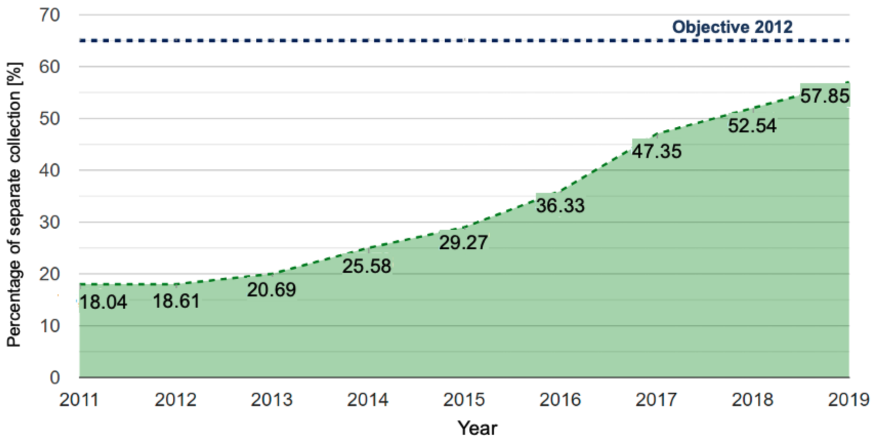

Figure 9. Actual annual separate collection percentage data for the Metropolitan City of Bari. Adapted from [65]

Consistently with Directive 2008/98 of the European Commission, a local target of 55% of waste recycling within 2025 was set [10]. A share of 47% [67] was currently achieved [65], which is a value far from the objectives set at the European level. Therefore, the amount of MSW that should be treated by adopting a WtE solution in the Metropolitan city of Bari is 53% of the total MSW produced, i.e., 306,546 tonnes/year.

4.2 Numerical assessment for cost and investment analysis

The most cost-effective WtE treatment to manage the MSW produced in the Metropolitan City of Bari was identified by the methodology of Section 3. The cost items corresponding to each of the three WtE alternatives were assumed according to data available in the scientific literature (Tables 2 and 3). In the case of most innovative technology (i.e., flameless oxy-combustion), the investment estimation was identified, assuming an investment cost of 7.69 M€ per each MWe net produced [57], considering that a plant allows treating 1E5 [tonnesMSW/year] of MSW, produces 10 Mwe [66]. Although, in this research, the flameless oxy-combustion is considered the most innovative technology, this kind of treatment is largely adopted to produce electricity and heat from coal and low-ranking fuel [67]. Therefore, no further costs due to technology immaturity have been considered. The investment costs for incineration and gasification plants can vary significantly from country to country. Therefore, the average values of the ranges given in [61] have been considered. The investment costs were estimated considering a useful plant life of twenty years and an interest rate of 3.5%.

Table 2. Yearly investment cost due to acquisition, construction and installation of industrial systems (greenfield project) and labour costs to manage the plant operations

Cost		Incineration	Gasification	Flameless oxy-combustion
C_{inv}	M€/year	4.3 [61]	4.95 [61]	5.2 [57]
c_{lab}	€/tonne$_{\text{MSW}}$	8 [68]		

According to [68], the annual cost for the plant maintenance (C_m) and the investment costs for plant size extension (C_{ext}) were identified to be used in equations 12 and 13.

$$C_m = 0.025 \cdot C_{inv} \quad (12)$$

$$C_{ext} = 0.55 \cdot C_{inv} \quad (13)$$

Table 3. Amount of consumable, solid by-products, emissions and electricity required/produced to treat 1 ton of MSW

Amount required		Incineration	Gasification	Flameless oxy-combustion
q_{cons}	[tonnes]	0.01 [69]	0.03 [69]	0.04 (CH_4) 0.01 (VLSFO) 0.5625 (O_2)
q_{SbP}	[tonnes]	0.2 [70]	0.14 [70]	0.25
q_{em}	[tonnes_{CO2}]	0.95 [69]	0.69 [71]	0 [55], [57]
q_e	[MWh]	0.544 [70]	0.685 [70]	0.70 [66]

Table 4 identifies the economic parameters to be used in equations 5-7. Their values allowed to identify the overall cost ($C_{tot}(q)$) coming from the treatment of one tonne of MSW for each WtE alternative technology. In the case of flameless oxy-combustion, the amount of consumables and solid by-products were assumed in accordance with available experimental data.

Table 4. The economic value of the parameters considered for the total cost assessment

Parameter		Incineration	Gasification	Flameless oxy-combustion
p_{cons}	[€/tonne]	800 [72]	800 [72]	300 (CH_4) 400 (VLSFO) 47 (O_2)
p_{SbP}	[€/tonne]	120		
p_{em}	[€/tonne_{CO2}]	42 [58]		

The variable costs associated with one tonne of MSW have been reported in figure 10 for the three WtE alternatives.

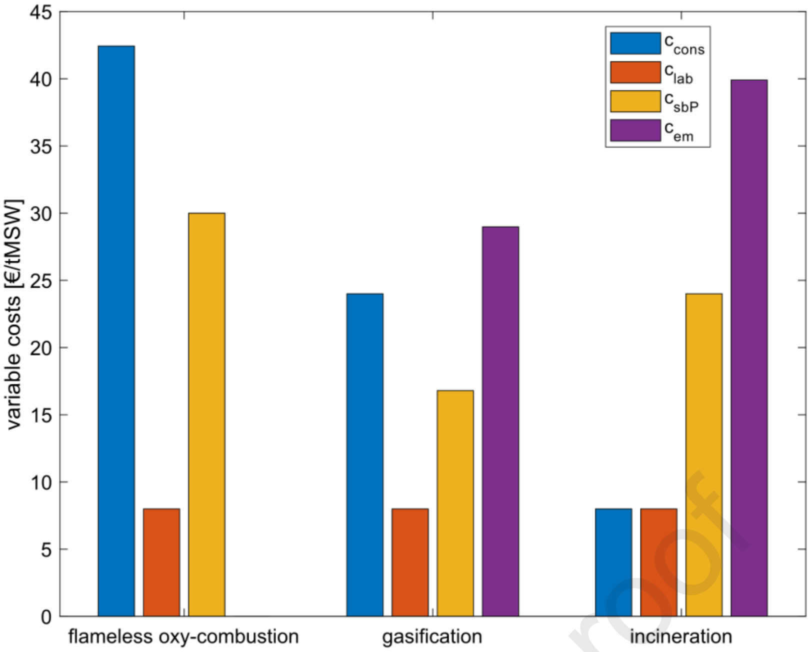

Figure 10. Values of the variable costs for the three considered WtE alternative technologies

The values assumed in the case study to estimate the NPV in three WtE treatments are summarized in table 5. The evaluation of the investment over a period of twenty years, i.e., a period equal to the useful lifetime of the plants, was assumed. Although each plant could be used for a longer period, including cost due to extraordinary maintenance or revamping activities. Moreover, the time horizon identified depends on the current MSWs management strategies that may be subjected to changes in the long period.

Table 5. Input parameters to investment evaluation

Parameter	Unit	Value
q	[tonne_{MSW}/year]	306,546
N	[year]	20
r	[%]	10%
p_e	[€/MWh]	84 [72]
t_{fee}	[€/tonne_{MSW}]	83 [73]
Income taxes	[%]	35%

The cash flow statements for the incineration, gasification and flameless oxy-combustion treatment are shown in Appendix B (Table B.1, B.2 and B.3). For each period considered, the value of CF_t, cumulated cash flow (CCF), discounted cash flow (DCF) and cumulated discounted cash flow (CDCF) are provided. According to the performed analysis, the NPV identified for the gasification is equal to 21.7 M€, higher than 19.3 M€ for the flameless oxy-combustion and higher than 66.8 M€ for the incineration.

Although the most cost-effective treatment is incineration, looking at the highest NPV value, gasification is the most profitable both from an economical and environmental perspective. This result mainly depends on plant investment and revenue values. Therefore, it is possible to conclude that gasification is the most sustainable solution for the MSW management for the Metropolitan City of Bari, between the WtE alternatives.

5.3 Results and discussions

The overall yearly cost of the three WtE treatments depending on the MSW annual capacity to be treated (q) is shown below (fig. 11). In case no waste is treated, total costs of about 4,410 k€/year, 5,070 k€/year, and 5,200 k€/year were estimated for the incineration, gasification, and flameless oxy-combustion, respectively. The total cost increases, according to a step function consistent with (eq. 1), when the treated MSW increase. If the MSW to be treated matches the maximum annual capacity of the plants (i.e., 400,000 tonnes/year), a cost of about 39.070 M€/year, 39.279 M€/year, 40.735 M€/year was estimated for the incineration, gasification, and flameless oxy-combustion, respectively. An average increase of 714% of the overall cost was estimated compared to the zero-waste treatment condition.

The lowest costs due to plant extension were identified for incineration. They are lower than 13.2% and 20.9% compared to gasification and flameless oxy-combustion. The effect due to scale economies highlights a non-linear reduction of plant extension cost with increasing MSW to be treated.

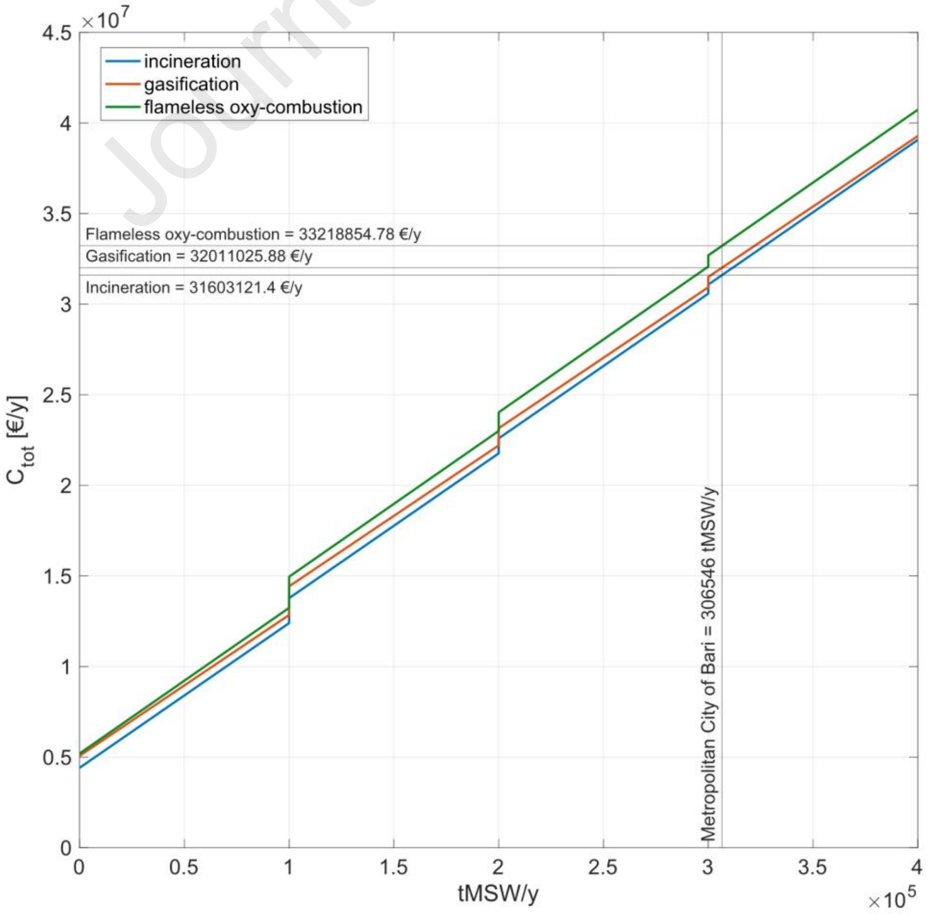

Figure 11. Overall yearly cost estimated by changing the annual capacity of the MSW to be treated

The comparison among the slopes of the total cost functions represented in fig. 11 shows that the highest slope is identified for the flameless oxy-combustion case. The slope is related to the variable costs of each WtE alternative, depending on variable costs supported to manage the WtE plants. In this case, the variable costs estimated for the flameless oxy-combustion, incineration, and gasification amount to 80.43 €/tonne$_{MSW}$, 79.9 €/tonne$_{MSW}$, and 77.78 €/tonne $_{MSW}$, respectively. Although the variable costs of the flameless oxy-combustion are independent of the costs due to carbon emissions; the highest consumable costs lead to increasing the variable costs of this WtE treatment compared to other alternatives (fig. 10). On the contrary, the highest emission value generated by the incineration treatment (i.e., 0.95 tonnes$_{CO2}$/tonnes$_{MSW}$) affected the variable cost of this WtE treatment. From this point of view, although gasification generates direct emissions, this alternative's lowest consumables cost leads to the lowest variable costs.

In the case of the Metropolitan City of Bari, the amount of MSW yearly produced is 306,546 tonnes. Therefore, the overall yearly cost estimated for the incineration is lower than gasification and flameless oxy-combustion by around 1.3% and 5%, respectively. In this case, the revenues, due to energy sales and tipping fees, allowed to evaluate the profitability of the three investment options in the plant lifetime (fig. 12). The flameless oxy-combustion technology ensures the highest incomes due to the best efficiency in energy recovery. Nevertheless, the highest costs related to this WtE treatment reduce the profitability of the investment compared to gasification (i.e., 12.4%) and incineration (i.e., 64.5%).

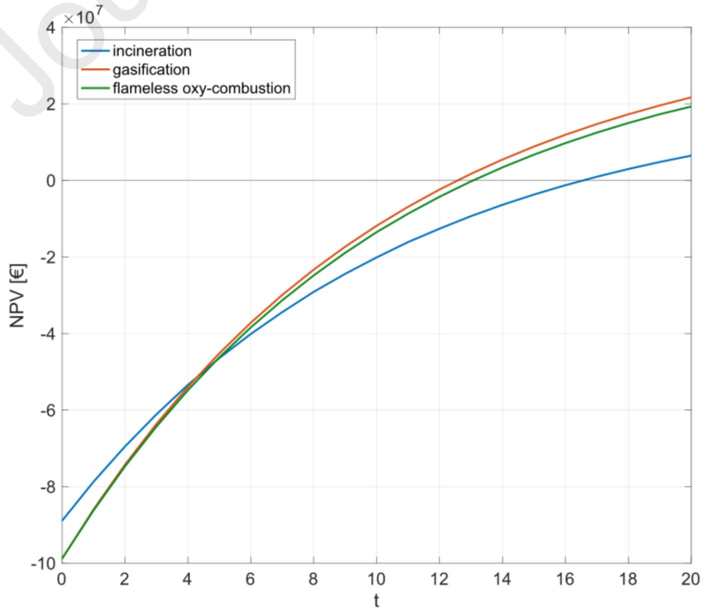

Figure 12. NPV of the three WtE alternatives evaluated in a lifetime period

The lowest PBPT was estimated for gasification (i.e., 13 years). The flameless oxy-combustion and incineration treatments show the highest PBPT values, equal to 14 and 17 years, respectively. This means that the investment in a gasification plant allowed to generate money liquidity over the mid-life of the plant, while the incineration generates cash at more than 75% of the plant life.

6. Sensitivity analysis

A sensitivity analysis was carried out with respect to economic and environmental assessment. In the first case, the NPV trend was analysed by changing the electricity price for the three WtE treatments (fig. 12). The investment in the gasification treatment is most profitable from an electricity price of about 30 €/MWh. Although the flameless oxy-combustion ensures the highest energy production, starting from an electricity price of about 44 €/MWh, it is more profitable than incineration. For the current electricity price (i.e., 84 €/MWh), gasification is most profitable than other WtE treatments. Nevertheless, the flameless oxy-combustion could be preferable for higher electricity prices (i.e., greater than 177 €/MWh). The increase of NPV by varying the p_e-values showed that the NPV of the flameless oxy-combustion increases more than the NPV of other WtE treatments for a given change of p_e-values. In other words, the electricity price mainly influences the profitability of the flameless oxy-combustion. This phenomenon depends on the greater capacity of this WtE treatment to produce electricity.

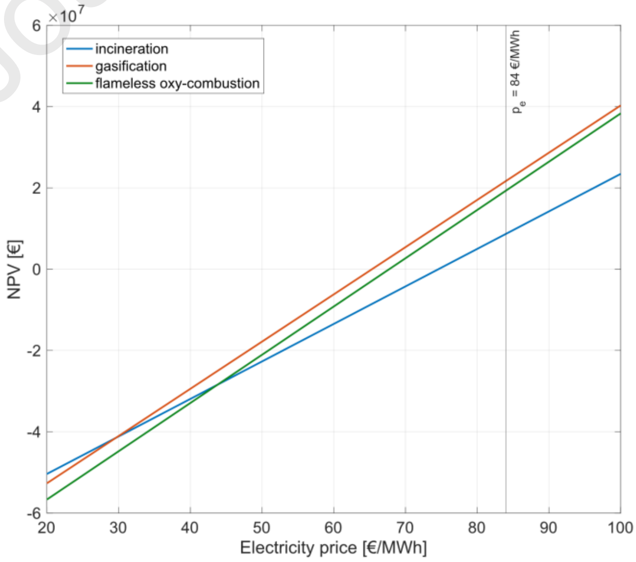

Figure 12. Profitability of the investment by varying the electricity price for each WtE treatment

In a second case, the NPV trend was analysed by changing the costs due to carbon emissions produced by the plant for the three WtE treatments (fig. 13). Gasification is the most sustainable alternative, given the current carbon price [58]. It is more convenient than incineration for each carbon price. Unlike the previous case, the NPV of incineration and gasification treatment decreases when p_{em} value increases since it represents a cost item than a revenue. However, the NPV of the flameless oxy-combustion treatment is independent of the p_{em} variable since it is the only one that does not generate direct emissions into the atmosphere. It should be more profitable than incineration for a carbon price higher than 44 €/tonnes$_{CO2}$.

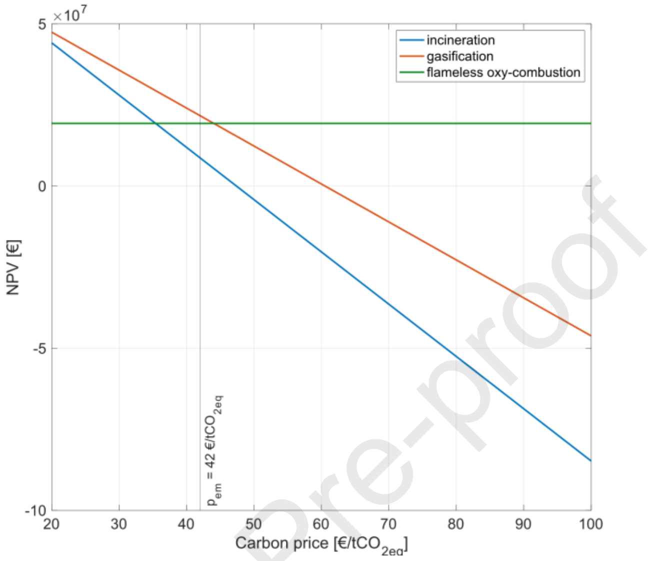

Figure 13. Profitability of the investment by varying the carbon price for each WtE treatment

The NPV trend was analysed in a third case by changing the tipping fee amount for the three WtE treatments. In this case, it is observed that the results do not depend on the technology since each alternative's tipping fee has the same impact.

7. Conclusions

The scope of the present research work consisted of assessing the investment in three different WtE to identify the best solution to support the current transitional phase towards a CE condition. Consistent with this purpose, an overall yearly cost analysis was developed by varying local municipal requirements, including investment, operating, and carbon emissions costs. The analysed WtE treatments can be considered the most representative options of conventional, promising and innovative WtE technologies among those available on the market.

The assessment allowed to identify gasification as the best option, at the moment, among the investigated technologies. Although gasification, compared to incineration, showed the highest variable costs (mainly due to higher consumable costs), the convenience of this alternative is ensured by high profitability over time due to high revenues. In this regard, the study showed a strong relationship between the carbon price, the electricity price and the investment profitability. In particular, a strong dependency on carbon price and NPV was observed; the flameless oxy-combustion could be preferable for slight price variations and, thus, in the next future this technology will gain an advantage over all the others when carbon price will increase over the actual price. Another parameter that will increase the oxy-combustion advantage will be the selling of the extracted CO_2 which has been neglected in this study. On the contrary, the tipping fee does not affect the choice among the WtE treatments considered (RQ2).

Similarly, it was proved that although the profitability of the three alternatives is strongly related to the MSW amount to be treated, the gasification ensures the highest profitability regardless of local municipal requirements (RQ1). According to the EU targets, WtE treatments are a viable alternative to support the transition phase to a CE condition. In order to identify the potential support offered by the available WtE technologies to this phase (RQ3), an economic analysis was conducted, and three technologies were compared (i.e., incineration, gasification, and *flameless* oxy-combustion). The variables considered for the cost and investment analysis were chosen consistently for this purpose. Revenues from electricity sales (r_e) at the current electricity market price (p_e) were considered, as well as a carbon price, to quantify the adverse effects associated with the emissions generated by the plants (p_{em}). The inclusion of these variables allowed to assess the benefit generated, in the case of each alternative, by electricity production, net of environmental, investment and operating costs and thus to quantify the support offered for achieving a CE condition, reducing the landfilling rate and treating MSW properly. The results achieved showed that the treatment that offers the most support, among those considered, is gasification at the moment. Although this is not the alternative that produces the largest amount of electricity per unit mass of MSW and does not show the lowest total costs (Figure 10), it is the one that shows the best NPV (Figure 11). Moreover, this treatment generates more profit in the shortest time over the plant's useful life (Figure 11). Therefore, in managing this transitional phase, gasification is the alternative that allows keeping a resource within the economic cycle for as long as possible, according to CE's definition, most efficiently, i.e., with the greatest benefits. It is noteworthy that the developed assessment is useful despite the current unstable situation in the energy market. Although in the last twelve months, there has been a 100% increase in the price of electricity for non-household consumers. The priority of preference among the three technologies analyzed does not change since, in all cases, revenue due to electricity sales it was considered.

Although the presented approach contributes to investigate the performance of different WtE alternatives, some aspects of the present work could be improved. Future studies and analyses will be performed, also including revenues from heat generation and the costs due to the CO_2 management (e.g., to bury it underground); the recovery options for the solid by-products generated will also be included in the analysis. In addition, the evaluation of transport costs due to MSW collection will be an interesting issue to face. To provide an even more reliable assessment, further analysis of different strategies for MSW management, including issues of end-of-life treatments and the logistics aspects, could be performed.

Appendix A. Cash flows Statements of the WtE treatments considered in the case of the Metropolitan City of Bari

Table A1. Cash flow statement of the incineration treatment [M€]

	t=0	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10	t=11	t=12	t=13	t=14	t=15	t=16	t=17	t=18	t=19	t=20
Investment	-88.9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
r_e	0.00	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
$r_{t_{fee}}$	0.00	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4
c_{lab}	0.00	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45
C_m	0.00	-0.111	-0.111	-0.111	-0.111	-0.111	-0.111	-0.111	-0.111	-0.111	-0.111	-0.111	-0.111	-0.111	-0.111	-0.111	-0.111	-0.111	-0.111	-0.111	-0.111
c_{cons}	0.00	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45
c_{SbP}	0.00	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36
c_{em}	0.00	-12.2	-12.2	-12.2	-12.2	-12.2	-12.2	-12.2	-12.2	-12.2	-12.2	-12.2	-12.2	-12.2	-12.2	-12.2	-12.2	-12.2	-12.2	-12.2	-12.2
Depreciation	0.00	-4.45	-4.45	-4.45	-4.45	-4.45	-4.45	-4.45	-4.45	-4.45	-4.45	-4.45	-4.45	-4.45	-4.45	-4.45	-4.45	-4.45	-4.45	-4.45	-4.45
Gross profit	0.00	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4
Net profit	0.00	6.76	6.76	6.76	6.76	6.76	6.76	6.76	6.76	6.76	6.76	6.76	6.76	6.76	6.76	6.76	6.76	6.76	6.76	6.76	6.76
Depreciation	0.00	4.45	4.45	4.45	4.45	4.45	4.45	4.45	4.45	4.45	4.45	4.45	4.45	4.45	4.45	4.45	4.45	4.45	4.45	4.45	4.45
CF	-88.9	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2	11.2
CCF	-88.9	-77.7	-66.5	-55.3	-44.1	-32.9	-21.7	-10.5	0.727	11.9	23.1	34.3	45.6	56.8	68	79.2	90.4	102	113	124	135
DCF	-88.9	10.2	9.26	8.42	7.65	6.96	6.33	5.75	5.23	4.75	4.32	3.9	3.57	3.25	2.95	2.68	2.44	2.22	2.02	1.83	1.67
CDCF	-88.9	-78.7	-69.5	-61.1	-53.4	-46.4	-40.1	-34.4	-29.1	-24.4	-20.1	-16.1	-12.6	-9.32	-6.37	-3.69	-1.25	0.969	2.98	4.82	6.48

Table A2. Cash flow statement of the gasification treatment [M€]

	t=0	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10	t=11	t=12	t=13	t=14	t=15	t=16	t=17	t=18	t=19	t=20
Investment	-98.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
r_e	0.00	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6	17.6
$r_{t\,fee}$	0.00	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4
c_{lab}	0.00	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45
C_m	0.00	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124
c_{cons}	0.00	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36	-7.36
c_{SbP}	0.00	-5.15	-5.15	-5.15	-5.15	-5.15	-5.15	-5.15	-5.15	-5.15	-5.15	-5.15	-5.15	-5.15	-5.15	-5.15	-5.15	-5.15	-5.15	-5.15	-5.15
c_{em}	0.00	-8.88	-8.88	-8.88	-8.88	-8.88	-8.88	-8.88	-8.88	-8.88	-8.88	-8.88	-8.88	-8.88	-8.88	-8.88	-8.88	-8.88	-8.88	-8.88	-8.88
Depreciation	0.00	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94
Gross profit	0.00	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2
Net profit	0.00	9.21	9.21	9.21	9.21	9.21	9.21	9.21	9.21	9.21	9.21	9.21	9.21	9.21	9.21	9.21	9.21	9.21	9.21	9.21	9.21
Depreciation	0.00	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94
CF	-98.8	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2	14.2
CCF	-98.8	-84.7	-70.5	-56.3	-42.2	-28.00	-13.9	0.271	14.4	28.6	42.7	56.9	71.0	85.2	99.3	114	128	142	156	170	184
DCF	-98.8	12.9	11.7	10.6	9.67	8.79	7.99	7.26	6.60	6.00	5.46	4.96	4.51	4.10	3.73	3.39	3.08	2.80	2.55	2.31	2.10
CDCF	-98.8	-85.9	-74.2	-63.6	-53.9	-45.2	-37.2	-29.9	-23.3	-17.3	-11.8	-6.88	-2.37	1.73	5.46	8.85	11.9	14.7	17.3	19.6	21.7

Table A3. Cash flow statement of the flameless oxy-combustion treatment [M€]

	t=0	t=1	t=2	t=3	t=4	t=5	t=6	t=7	t=8	t=9	t=10	t=11	t=12	t=13	t=14	t=15	t=16	t=17	t=18	t=19	t=20
Investment	-98.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
r_e	0.00	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18
$r_{t_{fee}}$	0.00	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4
c_{lab}	0.00	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45	-2.45
C_m	0.00	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124	-0.124
c_{cons}	0.00	-13.0	-13.0	-13.0	-13.0	-13.0	-13.0	-13.0	-13.0	-13.0	-13.0	-13.0	-13.0	-13.0	-13.0	-13.0	-13.0	-13.0	-13.0	-13.0	-13.0
c_{SbP}	0.00	-9.20	-9.20	-9.20	-9.20	-9.20	-9.20	-9.20	-9.20	-9.20	-9.20	-9.20	-9.20	-9.20	-9.20	-9.20	-9.20	-9.20	-9.20	-9.20	-9.20
c_{em}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Depreciation	0.00	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94	-4.94
Gross profit	0.00	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7
Net profit	0.00	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94	8.94
Depreciation	0.00	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94
CF	-98.8	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9	13.9
CCF	-98.8	-84.9	-71.1	-57.2	-43.3	-29.4	-15.6	-1.68	12.2	26.1	39.9	53.8	67.7	81.6	95.5	109	123	137	151	165	179
DCF	-98.8	12.6	11.5	10.4	9.48	8.62	7.83	7.12	6.47	5.88	5.35	4.86	4.42	4.02	3.65	3.32	3.02	2.75	2.50	2.27	2.06
CDCF	-98.8	-86.2	-74.7	-64.3	-54.8	-46.2	-38.4	-31.3	-24.8	-18.9	-13.5	-8.68	-4.26	-0.244	3.41	6.73	9.75	12.5	15.0	17.3	19.3

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Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: