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Perspective

Research and Innovation Needs for the Waste-To-Energy Sector towards a Net-Zero Circular Economy

Alessandro Dal Pozzo [1,*], Mathieu Lucquiaud [2,3] and Johan De Greef [4]

[1] Laboratory of Industrial Safety and Environmental Sustainability, Alma Mater Studiorum—Università di Bologna, Via Terracini n.28, 40131 Bologna, Italy
[2] Department of Mechanical Engineering, The University of Sheffield, Sir Frederick Mappin Building, Mappin Street, Sheffield S1 3JD, UK
[3] School of Engineering, The University of Edinburgh, The King's Buildings, Edinburgh EH9 3JL, UK
[4] ChEMaRTS, Leuven Group T Campus, Department of Materials Engineering, KU Leuven, Andreas Vesaliusstraat 13, 3000 Leuven, Belgium
* Correspondence: a.dalpozzo@unibo.it; Tel.: +39-051-2090296

Abstract: This perspective article aims to identify key research priorities to make the waste-to-energy sector compatible with the societal goals of circularity and carbon neutrality. These priorities range from fundamental research to process engineering innovations and socio-economic challenges. Three focus areas are highlighted: (i) the optimization of flue gas cleaning processes to minimize gaseous emissions and cross-media, (ii) the expansion of process control intelligence to meet targets for both material recovery and energy recovery, and (iii) climate neutrality, with the potential for negative emissions via the removal of atmospheric carbon dioxide across the full cycle of the waste resource. For each area, recent research trends and key aspects that are yet to be addressed are discussed.

Keywords: municipal solid waste; waste management; net zero; decarbonization; material recovery; energy from waste; carbon capture and storage

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1. Introduction

According to the EU principle of waste hierarchy, material reuse and recovery prevail over energy recovery from waste; this is also named 'Waste-to-Energy' (WtE). Nevertheless, WtE continues to be necessary for the treatment and valorization of waste fractions that are economically or technically not recyclable, to divert streams from landfilling [1], and to provide a safe sink for toxic substances [2]. On the other hand, the production of toxic ash fractions, gaseous pollutants, and greenhouse gases (GHG), combined with rather limited energy efficiency, constitutes a critical hurdle for WtE in the transition toward a climate-neutral and circular economy.

The present paper offers a brief overview of the research priorities to secure the role of WtE in a climate-neutral circular economy. As sketched in Figure 1, three key areas of improvement are identified: the reduction in air pollutant release and ash generation (i.e., objective "Near zero pollution"), the increase in material recovery (i.e, objective "Waste-to-Energy-and-Materials"), and the integration of CO_2 capture techniques (i.e., objective "Carbon neutrality and beyond").

In the following paper, these three themes are briefly discussed, focusing on the main open questions, ranging from fundamental research to process engineering to broader socio-economic issues. For a systematic review of the state-of-the-art existing WtE industrial practice in the three key areas, the reader is referred elsewhere: e.g., Vehlow [3] for WtE flue gas treatment technologies; Leckner and Lind [4] for waste combustion equipment and Syc et al. [5] for material recovery from waste combustion; Wienchol et al. [6] for carbon capture pilot installations in WtE facilities.

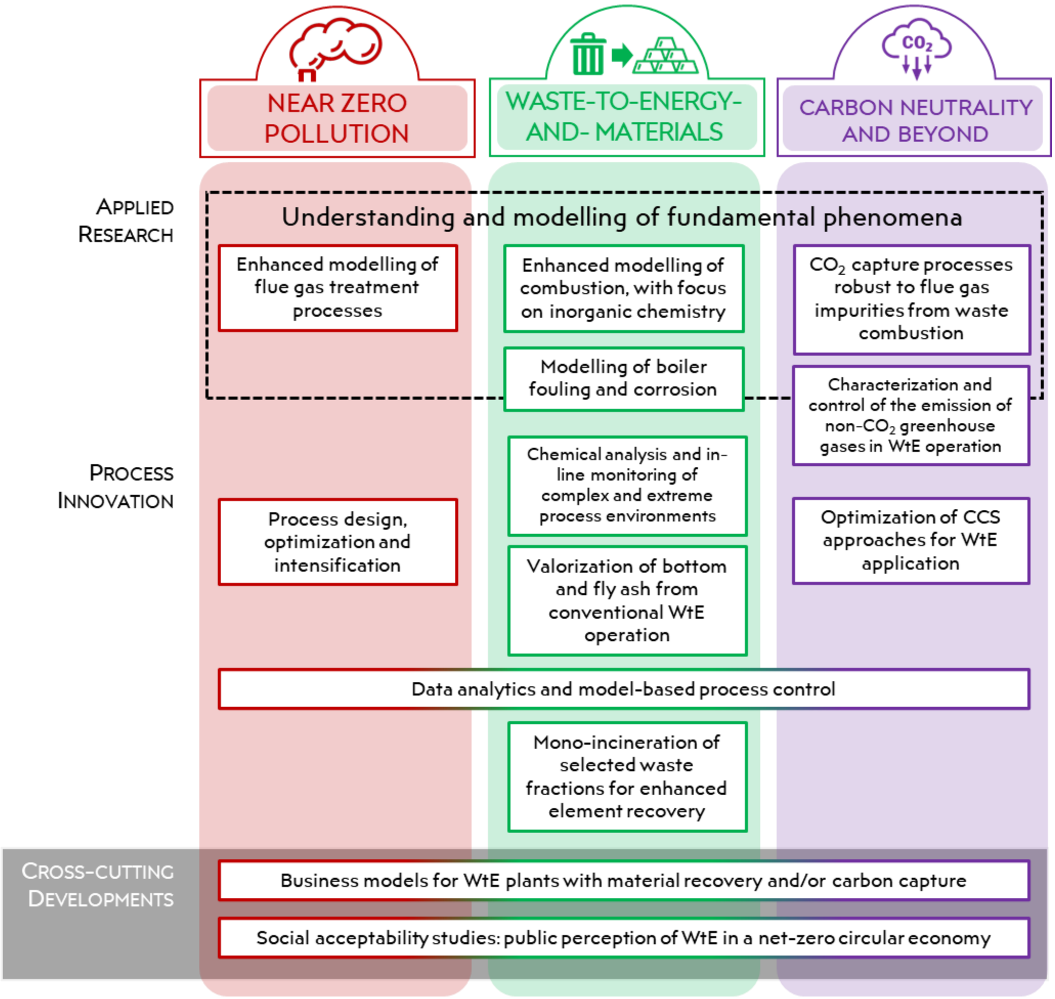

Figure 1. Research and innovation needs discussed in the present paper for the transition of waste-to-energy into a capstone for a net-zero circular economy.

2. Near Zero Pollution

Due to the chemical complexity of waste, the combustion of waste generates a variety of airborne pollutants, including acid gases (HCl, SO_2, HF, HBr, . . .), nitrogen oxides (NOx and N_2O), carbon monoxide (CO), particulate matter, trace metals such as Hg and Cd, and dioxins and furans (PCDD/Fs). Within the EU, legal emission limit values (ELVs) that are applicable to WtE plants are already the lowest across all industrial sectors for most pollutants [2]. Nevertheless, the most recent best available techniques (BAT) reference document on waste incineration (BREF WI [7]) sets further tightened targets and recommends, e.g., the online monitoring of trace pollutants such as Hg.

To date, WtE plant operators typically ensure compliance with ELVs in any operating condition by dosing reagents and sorbents in the flue gas treatment (FGT), on average, to significant excess. However, in a holistic approach, environmental protection should not be limited to reducing actual emissions at the WtE stack only but should strive for integrated pollution control optimization. Hereby, ultra-low emissions levels are to be coupled with minimal cross-media effects, i.e., minimal indirect environmental burdens associated with the operation of FGT (e.g., the consumption of reagents, generation of residues, and penalties due to energy inefficiency). Fulfilling this goal is particularly challenging in WtE plant operations, not only due to the variety in types of pollutants but also due to high fluctuations in the concentrations of these pollutants. These fluctuations originate from variations in the composition of the waste that is combusted, and from non-stationary operating conditions, among others, caused by waste layer control in the combustion furnace upstream and by the build-up of fouling deposits in the boiler system. Whilst waste layer control affects the HCl/SO_2 ratio in the raw flue gas [8], boiler fouling steadily increases the temperature of the raw flue gas that enters the FGT section. This way, both phenomena have a significant impact on the pollutant removal efficiency in FGT processes.

2.1. Applied Research Challenges

Enhanced Modelling of Flue Gas Treatment Processes

The challenge of holistic optimization in FGT starts from the advancement of fundamental knowledge on the reactions and the mass and heat transfer phenomena involved. As an example, we consider the abatement of acid pollutants (i.e., HCl, SO_2, HF, $SO_{3,}$ and other trace halides), which is the most relevant in WtE FGT in terms of operating costs and life cycle environmental impacts [9,10]. Despite the apparent simplicity of the chemistry of interactions between typical Ca- and Na-based solid sorbents and acid pollutants, several aspects are still poorly understood. Firstly, at the reaction chemistry level, there is a need to further disentangle the variety of synergistic and competitive reactions that take place during the (simultaneous) absorption of acid pollutants by solid sorbents in the presence of humidity, CO_2 (as a potential interfering weak acid [11]), and catalytically acting fly ash compounds. Secondly, at the reaction engineering level, mechanisms that govern the gas-solid reaction (i.e., mainly diffusional and thermodynamic limitations related to product layer growth [12]) and lead to the suboptimal conversion of the solid sorbents used need to be further clarified. Finally, at the overall process level, integrated modeling needs to be developed, which couples reaction kinetics with gas–solid interactions and the fluid dynamics of the flue gas flow in reactors and fabric filter units [13]. Such models, which take into account all aspects, are, indeed, essential for a full understanding of the phenomena involved in the FGT process. In turn, this would allow for the identification of process (control) conditions that maximize the efficiency of reagent dosing and consumption.

2.2. Process Innovation Challenges

2.2.1. Process Design, Optimization, and Intensification

Although most of the FGT technologies currently in use have been applied in WtE plants for decades, the aforementioned need to establish ever more tightened emissions with ever smaller amounts of reagents and sorbents has triggered the emergence of novel ways to combine these technologies. A clear trend in FGT systems is the adoption of multi-staged designs, such as two-stage dry systems for acid gas removal and combined SNCR + SCR systems for NOx abatement. Such designs offer extra degrees of operational freedom and allow a defined overall pollutant removal efficiency with different repartitions of removal between stages to be achieved, and, potentially, less reagent is consumed in total. A well-optimized multi-stage system can reduce the operating costs of FGT by 15–20% compared to a single-stage unit with the same overall removal efficiency [14]. Furthermore, the recycling of residues and optimized internal buffers for partially reacted lime can strongly contribute to achieving this target [15]. Parallel to the adoption of multi-staged designs, another significant trend in the FGT design for the WtE application is overall process intensification, i.e., the integration of multiple unit operations in a single stage. Relevant examples in this regard are catalytic filter bags for the simultaneous abatement of NOx and acid gasses [16] and the integration of NOx removal in wet scrubbers through the use of oxidizing chemicals [17]. Such innovations allow for retrofitting existing plants to become more efficient, intensified, and multi-staged FGT plants.

2.2.2. Data Analytics and Model-Based Process Control

The variation in flue gas composition over time is the main obstacle to making FGT systems work at their optimal operating point. In this regard, data analytics is a relevant area that allows for improvement. In a typical WtE plant, a wealth of data measured from hundreds of sensors is continuously collected and stored. Machine learning methods could be adopted to make more intensified use of these data in view of advanced process control. E.g., models derived from systems identification approaches [18] could capture complex inter-relationships between process variables that first-principles models are currently not able to describe. If sufficiently lightweight in terms of computational demand, such models could be incorporated into advanced control algorithms for FGT units. An example is the use of plant data to create a digital twin of the FGT system, which could allow the testing and tuning of alternative control approaches in a virtual environment [19]. In general, the ultimate goal of data analytics and a model-based control would be the substitution of current PID control approaches, on which most WtE plants are still reliant, with novel process control schemes. With the improved rejection of data disturbances, such control schemes are expected to be better able to maintain a stable operation, particularly under strong fluctuating operating conditions in WtE plants. However, PID-based control schemes, despite their shortcomings, act very much in line with human control intuitions. They allow the manual intervention or overrule of automatic plant control relatively easily when unexpected events and (electromechanical) failures occur that are typical for WtE plant operation. On the other hand, control schemes entirely based on numerical data routines (i.e., based on common black and grey box models) make it more difficult for plant operators in control rooms, as such schemes are not built on straightforward physical, chemical, or process principles. This explains, in general, why WtE plant operators are still reluctant to become entirely dependent on numerical data-driven process control, given the risk of a full forced plant shutdown in case legal ELVs are exceeded. In this regard, the process control systems of a hybrid kind, i.e., based on PID control but with the data-driven model prediction of setpoint values, are an interesting option, as they are compatible with the specific risk profile of WtE plant operations.

3. Waste-to-Energy-and-Materials

Historically, incineration facilities have been built since the last quarter of the 19th century for purposes of hygiene and waste volume/weight reduction [20]. From the late 1960s, the function of ensuring safe waste disposal was coupled with energy recovery, with incinerators becoming commonly equipped with industrial steam boilers [21]. Electricity and exportable heat subsequently generated with the produced steam (e.g., in waste-fired combined heat and power cycles; [22]) may be used as a substitute for an equal amount of energy from local electricity and/or heat generation. This may produce an indirect environmental benefit by avoiding emissions from electricity grids and heat networks with a carbon intensity higher than that of electricity generation from waste.

As the carbon intensity of electricity and heat generation decrease in the future, driven by climate policies, the benefits of displacing carbon-intensive electricity or heat generation are likely to diminish [23]. WtE plants are, however, likely to retain a relevant role as a supplier of heat, e.g., in industrial steam networks [24], and complement this by maximizing the added value that can be harnessed from the material recovery of unrecyclable waste streams.

3.1. Applied Research Challenges

3.1.1. Enhanced Modelling of Combustion with Focus on Inorganic Chemistry

In order to properly design and operate waste-to-materials thermal treatment systems, an improved understanding of the phenomena involved in waste combustion is needed. In particular, the key aspect is the determination of the fate of elements in waste during combustion, *viz.*, their partitioning between flue gas, fly ash (FA), bottom ash (BA), and tube deposits on the boiler, and their chemical speciation, and how operating parameters such as, e.g., waste layer thickness on grate furnaces, grate speed, O_2 excess and distribution, and flue gas recycling rate affect such a fate. Hence, a more enhanced combustion modeling specifically focused on non-carbon compounds and reactions is required to unravel these aspects [25]. Furthermore, such models require validation by industrially representative data, i.e., from experiments using well-characterized setups in a flow-through configuration instead of muffle furnaces with unidentified patterns of flow and heat and mass transfer around the waste samples investigated.

Enhanced combustion models, either ab initio or data-driven [26], can inform the operation of plants and constitute the basis for process control that is aimed at maintaining conditions that favor both element recovery and a stable flue gas treatment downstream, as mentioned in Section 2.2.

3.1.2. Boiler Fouling and Corrosion Modelling

The fate of chlorine is particularly relevant, as its interaction with alkalis, Zn, Pb, and S determine corrosion mechanisms that ultimately impact the efficiency of the WtE boiler [27,28]. The incidence of corrosion in WtE operations has arguably increased over the past two decades due to two distinct trends. On the one hand, increasing sorting and recycling rates have changed the types of waste streams that are conferred to thermal treatment, which, nowadays, include a higher share of industrial waste [29] and residues from plastic recycling operations [30], which is particularly rich in PVC and other chlorine-bearing plastics: the main source of chlorine in WtE waste feeds [31]. On the other hand, the focus on increased energy efficiency and the reduced formation of NOx has led to the application of lower excess air ratios in waste combustion [32] and, hence, the presence of more reductive operating conditions inside WtE boilers (gas side) increase Cl-related corrosion risks [27].

To properly address the issue of corrosion, more advanced modeling of the chemical, electrochemical, and mechanical phenomena involved is needed [33]. Fouling and corrosion in WtE boilers are governed by an interplay of several factors, mainly related to flue gas composition and temperature fluctuations [34]. Recent experimental evidence has proved in real plants that high rates of corrosion are associated with a high Cl/S ratio in ash and deposits, which in turn is linked to a local low oxygen level that inhibits the occurrence of protective sulphation reactions [27]. On the other hand, high SO_2 concentrations can be detrimental, as they favor the conversion of sulfates to pyrosulfates or eutectic polysulfate-chloride mixtures that lower the melting point of deposits and hence, trigger high-temperature oxidative corrosion [35].

Effective technical solutions for the control of the Cl/S ratio in the flue gas flowing in the heat recovery section of a WtE plant exist, e.g., sulfur recirculation for the reduction in the Cl/S ratio [36] or the furnace injection of dolomitic sorbents for the selective removal of SO_2 over HCl [29]. However, only by unraveling the corrosion mechanisms and obtaining reliable modeling of their thermodynamic and kinetic details is it possible to understand, e.g., via multiphase chemical simulations in CFD environments, under which conditions regions of the boiler will be affected by the type of corrosion and thus require the planning of interventions. Such an improved understanding is key to enabling improved asset management of WtE installations and allowing a more conscious maintenance planning and reliable prediction of the boiler's lifetime, depending on the waste combusted and the control conditions applied.

3.2. Process Innovation Challenges

3.2.1. Chemical Analysis and In-Line Monitoring of Complex and Extreme Process Environments

The implementation of the process knowledge devised in Section 3.1 in an actual plant operation would require putting into place adequate combustion diagnostics, i.e., the capability to acquire detailed, real-time information on the several parameters affecting furnace and boiler performance. In particular, to date, the earliest point at which the flue gas composition is measured in conventional WtE practice is at the boiler outlet. Measurements further upstream inside WtE boilers are made challenging by the high temperature and high dust concentration at which probes and sensors would be exposed [37]. Methods based on sampling might be affected by substantial uncertainties associated with the need to cool down and dehydrate the gas sample, especially for highly reactive components, such as HCl below the dew point [38]. Therefore, recent research has focused on the development of robust and reliable in situ measurements of the chemical species released by waste combustion. For example, tunable diode laser absorption spectroscopy (TDLAS) has been explored as a sampling-free sensing option for the measurement of HCl [38,39], while the release of alkali metals from combustion has been tested at grate incinerators by means of flame emission spectroscopy (FES, [40,41]). At the same time, the sampling of particulate matter in high-temperature flue gas, which is useful to characterize the role of the particulate phase in corrosion is still a technical challenge [42], and novel approaches have been tested in recent years [43].

As a complement to flue gas composition measurements, robust approaches for direct, in-line monitoring of corrosion are still lacking. The conventional assessment of corrosion in WtE boilers is typically retrospective and takes place only during maintenance shutdowns [44]. However, relying only on inspections performed six months or one year apart does not offer satisfactory control over the degree of damage being sustained by the equipment and the related causes. Here, the challenge consists of the development of reliable corrosion monitoring probes, typically based on electrochemical principles such as polarization resistance [45] or electrochemical noise [44], and proper calibration procedures for aggressive WtE environments to quantitatively correlate instrumental signal to corrosive degradation in terms of material loss.

Lastly, the boundaries of process monitoring have to be extended to include the characterization of the thermochemical and physical properties of the non-recyclable waste that is fed to the WtE plant. The possibility of improving material recovery in thermal processes starts from a more detailed knowledge of the waste feed, as well as in view of the evolving nature of the waste streams destined for thermal treatment in the transition to a circular economy framework. In particular, the inherent variability of the waste feed, even on short timeframes, is the key to stabilize the operation of the boiler and the FGT alike to achieve a time-resolved measurement of waste properties by developing advanced sensor systems for waste characterization [46]. Eventually, as mentioned in Section 2.2, machine learning algorithms can help put together the measurements of sensors and probes on both waste feed and flue gas to devise potential predictive tools for process control and asset management. An example is the use of data acquired on waste composition and combustion variables to estimate the release of pollutants from waste combustion and provide an even approximate prediction of pollutant concentration in the raw gas [26].

3.2.2. Valorization of Bottom and Fly Ash from Conventional WtE Operation

The combustion of waste generates two main types of ash: bottom ash (BA) and fly ash (FA). State-of-the-art systems already allow for the recovery of ferrous and non-ferrous metals through, respectively, magnetic and eddy current separators from BA [47,48]. Conversely, FA is usually classified as hazardous waste due to its high content of soluble salts (mainly chlorides), trace metals, and dioxins. As such, FA is sent to dedicated landfills after stabilizing to decrease its leaching potential or is used as backfilling material in depleted salt mines, where geological isolation is guaranteed [49]. Given the appreciable and relatively constant number of elements such as Zn, Pb, Cu, Cd, Sb, Sn, and Bi observed in FA, with limited temporal concentration fluctuations [50], the alignment of WtE operation to the paradigm of the circular economy calls for more sustainable management of FA. Therefore, the objective of the waste-to-energy and materials approach (Figure 1) is to devise solutions that make the extraction of valuable elements from FA economically attractive. Currently, several techniques, mainly of a thermal or hydrometallurgical nature [51], are under study. The greatest economic potential likely lies in the integration with other operations conducted at the WtE plant: for instance, zinc recovery via acid leaching by reusing effluents from wet flue gas cleaning systems, of which the feasibility at an industrial scale was demonstrated recently [52,53].

3.2.3. Mono-Incineration of Selected Waste Fractions for Enhanced Element Recovery

The valorization routes discussed above encounter an inherent limit in the low concentration of metals in FA derived from the combustion of mixed waste. A foreseeable strategy to overcome this problem is to target selected waste fractions that typically carry certain critical elements and feed them to dedicated mono incineration in order to operate on FA that is concentrated in the elements of interest.

A typical example is the mono-incineration of sewage sludges, already practiced at an industrial scale, which has attracted interest due to its potential for phosphorus recovery [54,55], but several waste fractions open specific recovery opportunities. To cite a few, the ashes of animal litter are another potential source of phosphorus [56,57]; tires and automotive shredder residues are particularly rich in Zn and Mg [58], while Zn oxides are also present in appliances that protect plastics from UV; Ag nanoparticles are increasingly incorporated in food packaging for their antimicrobial properties [59]; wood waste can be rich in chromium, copper, and arsenic, as a result of the use of chromate copper arsenate (CCA) as a wood preservative [60].

Mono-incineration poses new technical challenges in terms of combustion management and the operation of the FGT systems that are specific to the selected waste fraction. For example, the dedicated thermal treatment of electronic waste could unlock opportunities for the recovery of antimony, which is a component in brominated flame retardants [61], but the flue gas released by the mono-incineration process would be particularly rich in hydrogen bromide (HBr) [62]. Very limited data are currently available on HBr removal from flue gases [63] compared to the more abundant acid pollutants cited in Section 2; thus, dedicated experimental work is needed to optimize acid gas removal techniques for this specific compound.

4. Carbon Neutrality and Beyond

The transition towards a zero-carbon economy by 2050 is a legally binding target in the EU Green Deal and in the UK Climate Change Act. Such a generational challenge requires decarbonizing the overwhelming majority of the hundreds of waste-to-energy facilities in operation, which are collectively responsible for CO_2 emissions in the order of 100 million t/year in Europe alone [64], and making all new-build WtE facilities carbon capture-ready so that all barriers for the addition of CCS can be eliminated when these plants are constructed, as is advocated, e.g., by the UK Committee on Climate Change [65].

While the release of CO_2 is an inevitable consequence of waste combustion, WtE plants are uniquely poised to benefit from the application of carbon capture and storage (CCS) technologies, as they constitute stationary, point source emissions in a range from 100,000 to 1 million t CO_2/y which is well suited for CO_2 capture processes.

After re-using and recycling, the carbon of biogenic origin contained in the waste feedstock of WtE plants—in waste streams such as food waste, contaminated wood, textiles, and rubber—a carbon sink over the life cycle of these waste streams is created, provided that CO_2 capture from combustion is followed by the permanent locking of carbon dioxide from the atmosphere. Realizing a carbon sink from waste excludes the conversion of CO_2 to chemicals and fuels, where CO_2 eventually returns to the atmosphere.

Applying the balance between sources and sinks of greenhouse gases of the Paris Climate Agreement to the WtE sector requires that:

- The resulting carbon dioxide emissions from the combustion of *fossil* carbon in waste must be reduced, in effect, to zero, eliminating sources of carbon dioxide emissions in the WtE sector,
- *Biogenic* carbon dioxide emissions should be reduced to zero, so that the WtE sector maximizes its role as a sink of greenhouse gases.

The negative GHG emissions from the latter allow for the compensation of residual emissions of hard-to-decarbonized sectors of the economy, such as aviation, agriculture, or cement manufacturing. The application of CCS to WtE plants is a particular form of bioenergy with carbon capture (BECCS). Unlike more conventional forms of BECCS, it can be realized without the need to deploy extensive agricultural bioenergy supply chains, which are reported to present significant cross-media impacts on land and water use [66].

Since over half of the CO_2 emissions from the incineration of a typical municipal solid waste are biogenic [67–69], there is a growing interest in the deployment of combined WtE-CCS facilities both in academia and the industry. Early studies assessed the environmental soundness of WtE-CCS, quantifying a climate change reduction potential of ~0.7 kg CO_2 eq./kg of waste [70–72]. More recently, Herraiz et al. [23] conducted a rigorous life cycle assessment study of a WtE plant, including a full characterization of all avoided CO_2 emissions from material recovery, electricity, and heat supply. They showed that, for a case study in Scotland with a waste feedstock with 60% biogenic carbon of the total carbon, CCS significantly reduced the global warming impact of municipal solid waste incineration from 0.34 kg CO_2 eq./kg of waste to a negative global warming impact of −0.65 kg CO_2 eq./kg waste for a WtE plant exporting electricity, and −0.77 kg CO_2 eq./kg waste for a combined heat and power WtE-CCS plant. As previously noted, the net global warming potential strongly depends on the emissions factor of the displaced energy system, i.e., the electricity mix and the heating technology displaced. It can range from −0.54 kg CO_2 eq./kg of waste in Norway, with a large renewable share in its electricity system, to −0.90 kg CO_2 eq./kg of waste in Poland. As electricity and heat production continue to decarbonize, national differences are expected to converge.

4.1. Applied Research Challenges

Pilot-scale installations, such as the amine-based capture plant at Fortum Oslo Varme WtE [73] and commercial amine capture plants operating on a slipstream of flue gas for CO_2 utilization at AVR's and Twence's WtE plant in the Netherlands [74,75] are already testing carbon capture concepts at industrially relevant conditions. Yet, R&D challenges remain in the adaptation of CCS technologies to WtE.

4.1.1. Zero Residual Emissions from CO_2 Capture

Going forward, it is extremely likely that CO_2 capture processes deployed in the WtE sector will be expected to operate commercially, with capture rates at an excess of 95%, rising eventually to beyond 99%. Evidence of the first step in transitioning towards zero residual CO_2 emissions in carbon capture best practice is the design of a CO_2 capture rate of at least 95% in the best available technique guidance by the UK's Environment Agency [76].

This is supported by a growing body of evidence showing that ultra-high CO_2 capture fractions of more than 99% can be technically and economically feasible. Process modeling studies [77–79] reported that transitioning to 99% CO_2 capture from 90 or 95% can be achieved with a moderate increase in the thermal energy input to CO_2 capture. Pilot scale tests at the US National Carbon Capture Center (NCCC) completed by Gao et al. [80] found that increasing the CO_2 capture fraction of a coal-fired power plant from 90% to 99% resulted in an increase in the specific reboiler duty that was lower than 5%. Tests completed at the Technology Centre Mongstad in Norway also showed that 99% CO_2 capture could be achieved with a thermal energy input of 3.8 GJ/tCO_2 compared to 3.6 GJ/tCO_2 for a 90% CO_2 capture fraction [81]. Hirata et al. [82] investigated a 99.5% CO_2 capture fraction for a reference 650 MW_e coal fire power plant and predicted that near zero emissions could be achieved with a 3% increase in the total annualized cost of carbon capture ($/t$CO_2$). Su et al. [83] conducted the first study of ultra-high capture levels in the WtE sector, with a capture rate of 99.7%, corresponding to zero direct emissions from the combustion of waste. They show that the electricity output penalty of CO_2 capture and compression increased by 2% from 95% to 99.7% capture fraction.

There is not yet any evidence, at the time of writing, for the operation of CO_2 capture processes in the WtE sector with zero residual emissions.

4.1.2. Understanding the Role of Flue Gas Impurities in CO_2 Capture

As discussed in Section 2, WtE flue gas is a complex mixture in terms of a variety of components and their variability over time. Acid gases, metals, and aerosols might all potentially affect the performance of post-combustion CO_2 capture methods.

For solvent-based capture technologies, the interaction with flue gas components can cause two main issues: (i) solvent degradation and (ii) solvent entrainment in the flue gas. In particular, oxygen and acid compounds can trigger thermal and oxidative degradation pathways that reduce absorption efficiency [84]. The long-term stable operation of solvent-based capture units would require the capacity to maintain solvent degradation in a controllable regime even under the unsteady inlet flue gas conditions typical of WtE plants [85].

In order to mitigate the technology risks associated with long-term operations in a challenging flue gas environment, the only 'guarantee' likely to avoid unexpected problems and failures is evidence of a long period of successful operation. This can be provided by reference plants of a similar size for the deployment of CO_2 capture in other sectors than WtE. Yet, for initial deployments, fully realistic performance testing should be conducted over at least a year using representative pilot plants. This could possibly take place via the use of skid-mounted portable units that could be moved between sites to use actual flue gases. A summary of pilot testing to de-risk deployment is proposed in Gibbins and Lucquiaud [86] as part of a review of BAT for the post-combustion CO_2 capture of gas-fired and biomass plants.

For other CCS technologies, assessing the influence of flue gas impurities is similarly important. Components such as SO_2, NOx, and fine particles cause membrane fouling [87], while HCl, $SO_{2,}$ and FA can potentially inactivate a non-negligible share of the sorbent inventory in calcium looping capture schemes [88]. To assess the viability of oxy-fuel combustion schemes, the effect of the combustion atmosphere and temperature on pollutant formation behavior in the presence of complex waste mixtures has to be elucidated [89].

4.2. Process Innovation Challenges

4.2.1. Optimization of CCS Approaches for WtE Application

While the integration of CCS schemes in coal or gas-fired power plants is well established, very limited work has been dedicated to date on the optimization of CCS in the WtE context, with the aim of minimizing energy penalties in the face of the complex dynamics of WtE operation. As shown by Magnanelli et al. [90], this is a relevant aspect, as, e.g., the unutilized heat generated by the plant when district heating demand is low can provide cheap energy for solvent regeneration. Moreover, a thorough analysis of integration opportunities should consider the variety of existing WtE flue gas cleaning lines (dry, semi-dry, or wet-based concepts, [91]) to identify the best options for either retrofitting or greenfield applications.

4.2.2. Characterization and Control of the Emission of Non-CO_2 GHGs in WtE Operation

In addition to CO_2, for a full understanding of the climate change impacts of WtE operation, the emission of other greenhouse gases, such as methane (CH_4) and nitrous oxide (N_2O), should be addressed. Remote sensing has been recently employed for an experimental determination of CH_4 and N_2O emission factors in WtE plants [92], and the focus should now be put on the causal analysis of these emissions. For example, understanding how much N_2O is released from the N content of waste or from the use of urea in DeNOx systems [93] could help devise emission control strategies.

5. Non-Engineering Cross-Cutting Developments

In the concept devised in this paper, the fully integrated WtE facility in the circular economy framework, in addition to waste treatment and energy generation, would deliver two additional services to society: recovering critical secondary raw materials and generating negative CO_2 emissions from biogenic waste. Realizing this vision is not only an engineering challenge.

From an economic point of view, a favorable environment for carbon capture investments has yet to be created. Recent studies have started to discuss the most promising business models to incentivize CCS in WtE and the potential role of different stakeholders. It appears clear that, as relatively small point sources, WtE plants could consider capturing the bulk of their CO_2 emissions only if an external transport and storage infrastructure was available [94], either directly supported by the government or built as a shared facility by industrial CCS clusters [95]. Then, a revenue model would need to be developed: carbon capture could be financed by an increased waste fee and certificates for negative emissions, which would require a standardized monitoring, reporting, and verification system [96] or other schemes.

Finally, understanding the public acceptance of the new role proposed for WtE in the zero-carbon circular economy framework requires more research. WtE plants typically face social acceptability issues [97], as do CCS facilities. Combining WtE with CCS (and enhanced material recovery) could perhaps add acceptability problems, yet it could also change the perception of waste treatment with the application of CCS, resulting in the further reduction in emissions or pollutants to the air. Would the combination of WtE, CCS, and material recovery be seen as a legitimate way to valorize waste in a circular economy, especially by framing the need to create carbon sinks via negative emissions in the context of the circularity of biogenic carbon?

The addition of CCS to the WtE plant turns waste into a critical resource for climate control. As society decarbonizes electricity production, industrial clusters, transport, and the carbon intensity of human activity will also attempt this too. Eventually, the focus of climate action will shift away from addressing the addition of CO_2 to the atmosphere towards the engineering removal of the excess atmospheric CO_2. The negative emissions locked into society's waste may become too valuable to ignore.

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Abbreviations

BA	Bottom ash
BAT	Best available technique
BECCS	Biomass-enhanced carbon capture and storage
CCS	Carbon capture and storage
ELV	Emission limit value
FA	Fly ash
FGT	Flue gas treatment
GHG	Greenhouse gases
PID	Proportional–integral–derivative (control)
SCR	Selective catalytic reduction
SNCR	Selective non-cataytic reduction
WtE	Waste-to-Energy

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