



Waste-to-energy technology integrated with carbon capture – Challenges and opportunities



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ARTICLE INFO

Article history:

Received 17 December 2019

Received in revised form

24 February 2020

Accepted 8 March 2020

Available online 12 March 2020

Keywords:

Oxy-fuel combustion

MSW

Waste

Incineration

BECCS

ABSTRACT

Carbon dioxide emission is a serious environmental issue that humankind must face soon. One of the promising technologies for reducing global CO₂ emissions is oxy-fuel combustion (OFC) technology, which belongs to the carbon capture methods. OFC involves the use of oxygen and recirculated flue gas as an oxidizer in the combustion process. Application of oxy-fuel combustion in waste incineration can result in negative CO₂ emission since some part of the carbon in municipal solid waste is biogenic. Such technology is often described as BECCS or Bio-CCS and it has attracted the attention of scientists recently. In addition to easier CO₂ capture, oxy-fuel combustion of municipal solid waste offers other advantages, such as reduced flue gas volume, increased combustion temperature and the possibility of retrofit existing incineration plants. In the present paper, studies of oxy-fuel combustion of waste materials, in particular, municipal solid waste and sewage sludge are presented and summarized. The study shows the opportunities and challenges that have to be addressed to fully exploit the potential of the oxy-fired incineration plant.

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1. Introduction

Nowadays, climate change is a major challenge for scientists around the world that needs to be addressed immediately. Therefore, some actions have been taken in recent years. For instance, during the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC), representatives of member states established the common goal of decrease greenhouse gases (GHGs) emissions to maintain global average temperature well below 2°C above pre-industrial levels and to pursue efforts to limit the growth to 1.5°C [1]. To achieve the set goal, the EU commission prepared Energy Roadmap to 2050, which highlights that almost complete transition to renewable energy sources (97% of RES in electricity consumption) is crucial to decarbonize the energy sector. Besides, in most scenarios, the implementation of carbon capture and storage (CCS) is taken into account since it is currently considered the only technology that can significantly reduce carbon dioxide emissions from large-scale energy generation systems [2,3].

Carbon capture processes comprise pre-combustion, post-

combustion, and oxy-fuel combustion, which includes chemical looping combustion [4]. At present, post-combustion is considered the most mature technology for carbon capture with minimum impact on the existing systems and is therefore widely used. However, the main drawback is a large energy penalty since the separation of CO₂ from the exhaust gases after air combustion is a complicated process. As a result, the efficiency of the power plant drops by 8–12%, which is economically unfavourable [5]. A considerably better way in terms of efficiency is the pre-combustion system that is usually combined with IGCC plant, however, it is still unreliable, expensive and needs further development to become competitive [5,6]. Although oxy-fuel combustion (OFC) is not yet industrially applicable, it is the most promising among available technologies mostly due to easy CO₂ capture and the low efficiency penalty (around 4% mainly caused by CO₂ compression). Moreover, according to Pettinau et al. [5] if oxy-fuel combustion were commercial, it would be the best option for near-zero CO₂ emission power generation. In addition, application of oxy-fuel combustion reduces the volume of flue gas, increases the boiler efficiency, eliminates nitrogen oxides (NO_x), stabilizes the temperature and allows modernization of existing systems [5,7,8].

Nevertheless, problems that scientists highlighted are the high capital cost investment, as well as energy consumption of the air

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separation unit (ASU), because currently the only available technology that can meet the requirements for a large amount of high purity oxygen is based on cryogenic distillation. Hence, investigation of new methods of air separation, such as oxygen transport membrane, ion-transport membranes or chemical looping, is essential to increase the efficiency of the oxy-fuel combustion process [8,9]. Taking into account that chemical looping technology can significantly improve the oxy-fuel combustion process, it has attracted the attention of scientists recently [10]. It is also considered as a next-generation CO₂ capture process [11]. Chemical looping air separation can be applied in both oxy-fired and IGCC plants instead of ASU resulting in the increase of net plant efficiency by around 3%, the reduction of capital investment by roughly 10–18% and the decrease in electricity cost by 7–12% [12].

1.1. Oxy-fuel combustion of solid fuels

Oxy-fuel combustion (Fig. 1) involves the replacement of air as an oxidant into high purity oxygen, usually above 95 vol%, and recirculated flue gas. Consequently, produced flue gas stream contains mainly carbon dioxide and water vapour that can be easily removed by condensation. Finally, carbon dioxide can be purified, compressed and stored in a geological formation [13], or used in geothermal technology [14,15], in agriculture [16], and for the production of biofuels, such as methanol (CH₃OH) and dimethyl ether (CH₃OCH₃) [17] creating the carbon capture storage and utilization (CCUS) system.

The employment of a mixture of oxygen and carbon dioxide instead of air significantly affects the combustion process, therefore the technology of oxy-fuel combustion should be carefully integrated with the rest of the system. For example, the heat transfer profile differs due to the higher concentration of three-atomic gases (CO₂, H₂O) with different physical and chemical properties, such as emissivity and heat capacity. It was thoroughly examined both numerically and experimentally by several researchers [18–23]. It was found that both the convective and radiative heat transfers were higher under the oxy-fuel conditions. The ignition, flame propagation, and stability under oxy-fuel combustion were evaluated in Ref. [24–29]. It was reported that ignition delay increased and flame speed decreased during oxy-combustion due to higher heat capacity of CO₂ and lower O₂ diffusivity in CO₂. Besides, many attempts have been made [30–35] aimed at estimating emission of pollutants during oxy-fuel combustion. Studies showed that under oxy-fuel combustion (a) emission of NO_x, SO₂ and CO can be reduced, however, it highly depended on oxygen concentration in O₂/CO₂ mixture (with higher amount of oxygen, pollution emission decreased), (b) a big impact on gas emission had a type of fuel and (c) emissions differed since volumetric flue gas flow rate was reduced and flue gas stream was recycled.

Over the past decade, the number of studies on oxy-fuel combustion has increased drastically, as shown in Fig. 2. Currently, there are many literature reviews concerning oxy-combustion of

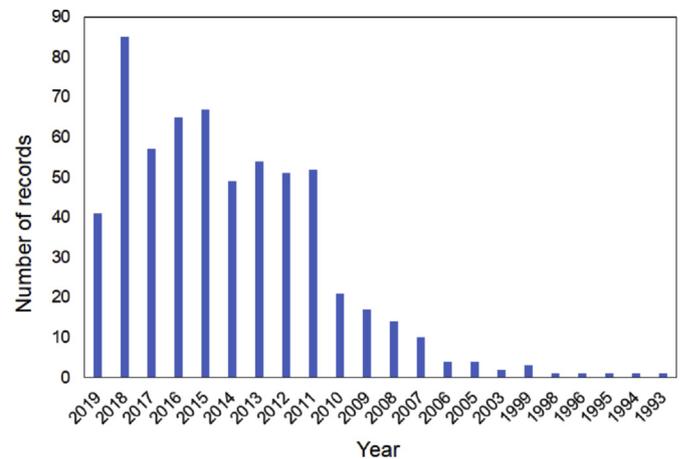


Fig. 2. The number of publications on oxy-fuel combustion, source: Web of Science (WoS).

coal since this is the most widespread fuel [36–41]. Authors focused on the trends and current issues, associated mainly with the retrofitting of existing power plants. Nevertheless, they pointed out that oxy-fuel combustion is a cost-effective and technically feasible method of CO₂ capture. Recently, biomass has started to play a key role in the energy sector due to the excessive depletion of non-renewable resources. It was found that biomass can support countries that do not have natural energy resources, thereby reducing their energy dependence and increasing energy security [42]. Thus, Liu et al. [43] published the first review on oxy-fuel co-combustion of coal and biomass in fluidized bed boiler, at which they underlined that such technology attracted attention in both the academic and industry sectors.

The presented works indicate that oxy-fuel combustion is a potentially efficient technology, which can be introduced to both new and existing power plants as well as for different types of fuels, such as biomass. A large number of studies have shown that oxy-coal combustion technology has evolved in recent decades, but there are still many research questions that have been noted by scientists. The concerns are related to the implementation of OFC technology in existing power plants and the use of low-quality fuels, such as biomass or municipal solid waste. One of the biggest challenges of oxy-fuel combustion is the high energy consumption of ASU, therefore to improve the performance of oxy-fired power plants a crucial aspect is research on effective methods of air separation.

1.2. Waste composition

By 2050, the amount of waste is expected to increase from 2.01 billion tonnes to 3.4 billion tonnes [44]. Until then, the waste

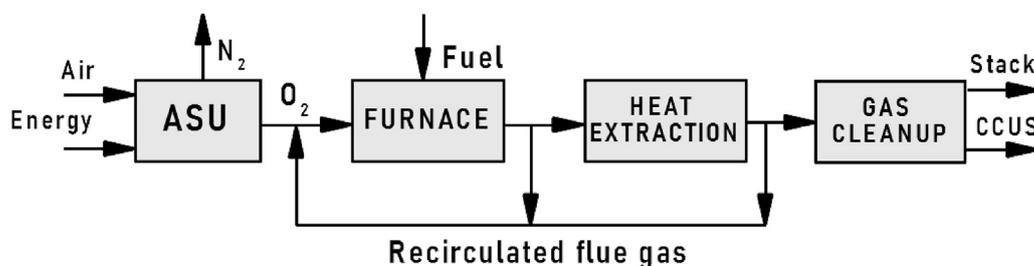


Fig. 1. Schematic draw of the oxy-fuel combustion process.

management sector should develop so that waste does not become a dangerous threat to the environment and human health. As stated in the European Directive [45], biomass is a biodegradable fraction of products, waste, and residues from a biological origin, including municipal solid waste. Thus, such MSW as, paper, cardboard, wood, cloth, green waste, and food can be classified as a renewable source of energy, what from a legal and economic point of view can be crucial in the development of systems based on recovering energy from waste because renewable energy is more often financially and politically supported.

According to the World Bank [44], the composition of waste varies around the world mainly due to the value of the gross domestic product (GDP) and consumption pattern. Middle- and low-income countries generate about 64% of materials with biological origin. While, in high-income countries, MSW contains mostly inorganic fractions with high calorific value, which can be recycled. However, barely 28% of MSW, which comes from developed countries is biogenic [46]. As can be observed in Fig. 3, globally, more than half of the waste has a biological origin.

Taking into account that waste is not only available worldwide but also the average heating value of the waste is approximately 10 MJ/kg [47], using waste as a source of valuable energy seems reasonable and could be a key factor for sustainable development and the circular economy, which aims to maintain the value of products, materials and resources as long as possible, to reduce waste and resources consumption.

1.3. Bio-energy with CCS

Since oxy-fuel combustion can be applied to any type of fuel used for thermal power production, the interest of research on the combustion in O_2/CO_2 atmosphere of biomass has recently increased. Speaking of the use of biomass as the source of energy in a system integrated with carbon capture and storage technology, one should not forget about the bio-energy with carbon capture and storage (BECCS or BioCCS) process. It is a combination of two CO_2 mitigation methods, which in consequence give a net-zero or negative carbon dioxide emission [48], and thus cools the Earth. According to Gładysz and Ziębik [49] the cumulative CO_2 emission of net electricity production for oxy-fuel combustion of biomass is $-0.2722 \text{ kgCO}_2/\text{M}_{el}$ and emissions from MSW incineration integrated with CCS system is around $-0.7 \text{ kgCO}_2, eq/\text{kg}$ of wet MSW [50]. This shows that BioCCS technology can significantly contribute to the decarbonisation of Europe.

There are 20 BECCS projects worldwide, which relate to various bio-energy technologies, e.g. waste-to-energy plants (WtE) in Norway and the Netherlands, ethanol plants in France, Brazil and Sweden, biomass combustion and co-firing in Japan, two pulp and

paper plants in Sweden, biomass gasification in the United States and biogas plant in Sweden [50,51]. According to Bui et al. [52], Ricci and Selosse [53], the deployment of BECCS is technically possible, however, negative emissions are not covered by the Kyoto framework, thus the main drawbacks to commercially adopting this system is the lack of economic and political drivers supporting the technologies based on bioenergy with carbon capture. Therefore, it would be necessary to financially encourage electricity generation with negative CO_2 emissions.

2. Aim and scope of the work

Understanding the importance of the role of bio-energy integrated with carbon capture technology in the sustainable development scenario leads to consideration of the oxy-fuel combustion of waste as a prospective solution for mitigating a climate change. Since currently, there is a lack of overview of the combustion of municipal solid waste and other problematic fuels, such as sewage sludge, in O_2/CO_2 atmosphere the objective of the present work summarizes the current knowledge status of technology.

Section 3 contains an overview of available waste-to-energy technologies, in particular, thermal methods of energy recovery from waste since they are effective solutions for waste management that should be developed. Besides, the possibility of integration of WtE plants with carbon capture is presented and compared, as well as existing incineration plants with CO_2 capture are discussed.

Section 4 is devoted to examining works on oxy-fuel combustion of waste since the oxy-incineration plant seems to be potentially a more effective way of waste disposal than those, which are available currently. The collected papers present the most important findings on the kinetic parameters obtained during thermal degradation of waste under different atmospheres, as well as the emission of pollutants and heavy metals during oxy-fuel combustion since these are key design parameters. Summarizing current knowledge is important in order to build reliable combustion modelling tools, necessary to optimize the combustion of specific types of waste and scale-up of furnaces. This article exposes opportunities that oxy-fuel combustion technology can bring and the challenges that need to be addressed before the implementation of oxy-fuel combustion of waste process.

3. Waste to energy technology

There are many options for waste management, i.e. composting, landfilling, recycling and utilizing waste for energy production. Although landfilling and dumping causes a negative impact on the environment due to uncontrolled methane release, this practice is a dominant method of waste management, especially in developing countries [54]. Unlike landfilling, energy recovery from waste is an efficient and ecological way of handling waste, however, the investment cost is relatively high. Therefore, most of the WtE plants are placed in high-income countries [55]. Waste-to-energy technologies include thermal conversion (pyrolysis, gasification, and incineration), biological conversion (anaerobic digestion), as well as a landfill with energy recovery [56]. WtE processes allow to reduce the volume of waste, recover energy and decrease fossil fuel consumption. Besides, waste is a cheap source of energy or can be even considered as an income since municipalities have to pay other parties to manage their waste. Thus, the WtE industry is developing dynamically and it is expected that the Waste-to-Energy industry will be worth approximately USD 37.6 billion in 2020 [57].

3.1. Pyrolysis

Pyrolysis is a decomposition of feedstock into gaseous, liquid

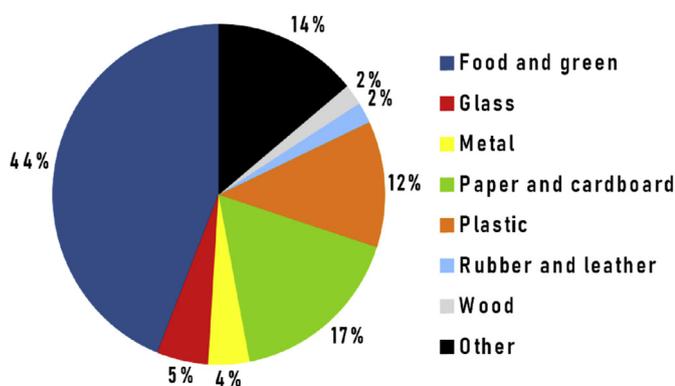


Fig. 3. Global waste composition, data source [44].

and solid materials at elevated temperatures between 300 °C and 650 °C in an inert atmosphere, for example, nitrogen or argon. Pyrolytic products vary depending on the feedstock composition and pyrolysis parameters, such as temperature, heating rate and residence time [55,58]. The main reason for employing the pyrolysis of MSW is bio-oil and synthesis gas production, which can be a substitute for transportation fuel or can be used in power generation and petrochemical industry [59]. Besides, produced char that is classified as a by-product can be used for water treatment applications or as an agricultural soil amendment. However, one of the problems the researchers have pointed out is that biofuels are heavily contaminated and require cleaning and the employment of sophisticated methods for improvement before use. Moreover, pyrolysis of waste is not economically viable and need further research [60].

3.2. Gasification (IGCC and IPGCC plants)

Gasification is partial oxidation with oxygen, produced by an Air Separation Unit (ASU) and steam at high temperatures during which carbonaceous materials are converted into syngas (CO_2 , H_2 , CO , CH_4) [55]. Depending on the process temperature, gasification (800–1200°C) and plasma gasification (from 5000°C up to 15 000 °C) are distinguished [61]. Typically, a technology that employs gasification is the Integrated Gasification Combined Cycle (IGCC), while the process that utilizes plasma gasification is the Integrated Plasma Gasification Combined Cycle (IPGCC). Both methods allow for the carbon capture resulting in zero- CO_2 emission power generation [62]. There are several studies concerning plants based on the MSW gasification and plasma gasification [63–66], as well as co-gasification of waste and other fuels [67,68] to produce not only electricity but also district heat and gaseous hydrogen. The overall conclusion is that gasification-based systems are very efficient and can handle problematic low-grade fuels. In addition, the gasification plant is highly flexible and depending on the desired product, the gasifying agent should be modified. If the main objective is the production of hydrogen, the steam should be injected into the reactor, while during electric power generation, using oxygen-enriched air is recommend. In general, gasification is a promising method of waste management, however, there is currently only one commercial plant that uses waste as an energy source in the gasification process for electricity and heat production. Furthermore, the cost required for gas cleaning is higher than in the case of waste incineration.

3.3. Chemical looping (CLC plant)

During chemical looping combustion, two reactors are employed. Fuel is introduced in the fuel reactor, in which it is oxidized by metal oxide. The reduced metal oxide is then transferred into the air reactor where it is oxidized. Similarly to oxy-fuel combustion, the exhaust gas from fuel reactor only contains CO_2 and H_2O and consequently, carbon dioxide can be easily captured after condensation [69,70]. To date, only a few studies focused on chemical looping combustion/gasification of waste. Moreover, works regard mostly the fate of heavy metals, such as chlorine or cadmium since it is considered that the emission of heavy metals is one of the challenges in the CLC and CLG of waste [71].

Bi et al. [72] studied the impact of different oxygen carriers on dioxins formation during chemical looping combustion. They found that CLC based on CaSO_4 effectively inhibits the formation of PCDD/Fs. While Zhao and Wang [11], Ma et al. [73] established that *in situ* gasification-chemical looping combustion using CaO -decorated $\text{Fe}_2\text{O}_3/\text{Al}_2\text{O}_3$ as oxygen carrier is highly efficient and suppress the PCDD/Fs emission.

3.4. Incineration (MSWI plant)

Incineration is the full oxidative combustion of waste in a furnace at high temperatures between 850°C and 1200°C. Among the thermal treatment of waste methods, incineration is the most mature and widely used technique [74]. Furthermore, according to Dong et al. [75], from the life cycle assessment (LCA) point of view, the incineration process is currently better than pyrolysis and gasification-melting due to the highly efficient flue gas cleaning section, use of combined heat and power (CHP) cycle and the recycling of ash.

The first waste incineration plants were introduced in the 19th century during the Industrial Revolution and were intended exclusively to utilize waste. However, this changed in the mid-20th century, when oil prices soared, resulting in the idea of waste-to-energy technology [57]. Today, according to Kaza et al. [44], about 11% of municipal waste is treated through modern incineration plants that correspond to roughly 1200 incinerators around the world. It means that the application of carbon capture in incineration plants could cause a sudden decrease in CO_2 emission in the near future. In Poland, the waste-to-energy sector is developing rapidly. There are currently seven municipal solid waste incineration plants (MSWI) with a total capacity equal to almost one million tonnes of waste per year, which corresponds to 9% of the MSW produced in the country [76]. Moreover, there is planned that the number of incineration plants will increase up to 30 [77]. In Norway, meanwhile, waste management is well-developed, i.e. 58% of waste is recycled or incinerated. The WtE plant's number is 17 (total capacity is around 1.70 Mt/year), including one incineration plant in Oslo with implemented carbon capture and storage (CCS) system [78].

3.4.1. Modern waste incineration

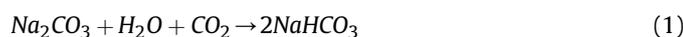
Modern waste incineration plants are not only obligated to comply with environmental protection regulations but also have to face a difficult challenge to arouse public confidence and acceptance. Therefore, more and more plants are designed in an integral way with the environment. For example, a combined heat and power (CHP) waste incineration plant in Copenhagen that in addition to excellent efficiency, also has a recreation area, which includes a ski slope, viewpoint and climbing wall [79].

Currently, there are three main groups of MSWI technologies: (a) moving grate, (b) rotary kiln and (c) fluidized bed incinerators [57], of which grate boilers are used in 80% of WtE plants worldwide [80]. During the combustion of MSW, many pollutants are produced, including fly ashes, heavy metals, carbon compounds, acid gases, and others, and they have to be removed according to limits included in European Union documents or in other national regulations. To fulfill the requirements waste incineration plants should be planned and designed in accordance with the guidelines of the "Best Available Techniques (BAT) for Waste Incineration" document [80]. Moreover, in order to ensure complete combustion of waste, the EU Parliament introduced the Directive, which requires all installations to keep the incineration or co-incineration gases for at least 2 seconds at a temperature of at least 850°C, whereas incineration process of hazardous waste with a content of more than 1% of halogenated organic substances expressed as chlorine must occur at 1100°C for at least 2 seconds. To guarantee proper conditions, the plant should be equipped with auxiliary burners.

3.4.2. Incineration with CO_2 capture

Currently, to the best knowledge of authors, there are four incineration plants that are coupled with a carbon capture system. They are located in Norway (Klemetsrud CHP), Japan (Saga City)

and in the Netherlands (Twence and AVR plant). AVR plant, Twence and Saga City are examples of the CCU facilities. In Japan, an alkaline aqueous amine method of carbon capture is introduced designed by Toshiba. The obtained carbon dioxide is used for local crops cultivation and algae cultures formation [81]. In this way, the waste incineration plant captures 10 tonnes of carbon dioxide every day [82]. AVR is the first waste-to-energy company with a large-scale CO₂ capture system. In 2019, 60 000 tonnes of carbon dioxide was expected to be captured, liquefied and transported to end-users that was mainly greenhouse agriculture industry. In the future, AVR will seek to capture 800 000 tonnes of CO₂ per year and use it in building materials (concrete) or chemical industry for plastic and biofuels production, supporting the local circular economy [83]. While, at Twence waste incineration plant, 830 000 tonnes of waste is processed annually, producing 405 000 MWh of electricity and 1.5 million GJ of thermal energy for district heating [84]. The CO₂ capture process was implemented in 2011. Carbon dioxide is scrubbed from the flue gas stream, purified and used to produce a sodium bicarbonate slurry (SBC) according to equation (1).



Then, SBC is injected to remove the acid components from the flue gas, such as HF, HCl and SO₂. Consequently, the incineration plant is more independent of the operating costs, because expenditures for the flue gas cleaning can be reduced, and global carbon footprint is lower [85]. Waste incineration plant in Oslo (Klemetsrud) processing around 400 000 tonnes of non-recyclable waste. As a result, 55 MW of heat and 10.5 MW of electricity is produced for city residents. The carbon capture method that will be implemented in the plant is based on amine absorption and it will reduce the carbon dioxide emission by 400 000 tonnes every year. The plant in Klemetsrud will be an example of a CCS facility, therefore it is foreseen that carbon dioxide will be permanently stored in the North Sea [86].

Presented examples have indicated that carbon capture can be successfully implemented in a waste incineration plant resulting in near-zero (or even negative) CO₂ emission power generation. As shown, carbon dioxide capture methods used in waste incineration plants so far are based on post-combustion since this method is relatively easy to implement and the most mature. However, sequestration of CO₂ after air-combustion is very complex and reduces efficiency by 14.7%. While according to Tang et al. [87] oxy-fuel combustion would reduce the efficiency of the incineration plant by 12.6%. Additionally, Ding et al. [88] shows that after the optimization of the oxy-fired incineration plant, the decrease in efficiency can achieve the level of 9.57%. Key parameters, which could improve the oxy-fuel combustion process are the recirculation of flue gas, which can be used to heat the molecular sieve regeneration gas of ASU and the primary condensate as well as the waste heat generated by ASU compressors, which also can be utilized to heat the primary condensate. The issue that can occur in the case of oxy-fuel combustion is that it requires more adaptations to the incineration plant compared to post-combustion, thus uncertainties in process performance are higher.

According to Sathre et al. [89], the energy penalty for the use of CCS technology in WtE plants would be reduced to 7% in the future (Fig. 4). It can be accomplished by the employment of highly efficient MSW gasification technology integrated with a gas turbine (IGCC), in which CO₂ is separated from hydrogen that is relatively easier than the separation of carbon dioxide from nitrogen. Thus, the energy penalty of pre-combustion is potentially lower than that of post-combustion. The next option for reduction of energy penalty of CCS can be presumably the development of air separation

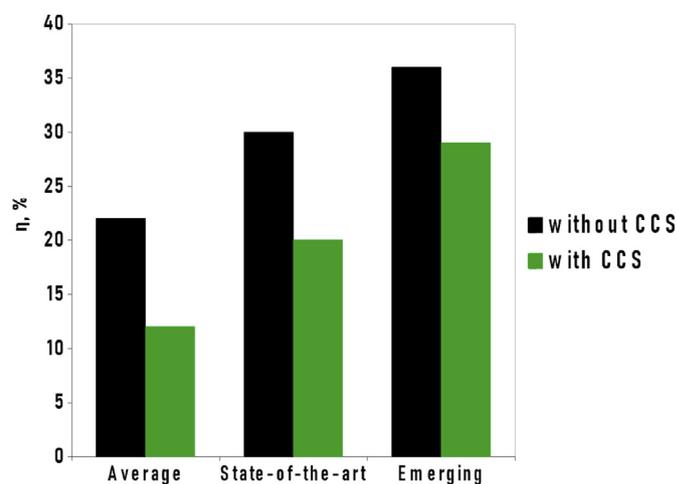


Fig. 4. Efficiency of WtE plants with and without CCS in dependence of development level, data source: Sathre et al. [89].

methods in oxy-fuel combustion and replacement of cryogenic distillation by more efficient technologies, such as chemical looping air separation.

Nevertheless, it is difficult to say whether a 7% decrease in efficiency will be sufficient to make carbon capture technology attractive to waste incineration plants. In our view, carbon capture technology should be improved to reduce the efficiency of incineration plants as little as possible. However, taking into account that waste is cheap, partly organic and widely available, a decrease in efficiency is not as relevant as in the case of coal-fired power plants.

4. Oxy-fuel combustion of MSW

Application of oxy-fuel combustion in the incineration plant is noteworthy since, except carbon capture, it can bring several merits, such as an increase in process temperature due to higher oxygen concentration and the decrease of the auxiliary fuel consumption that is usually used to keep the required temperature. Besides, oxy-fuel combustion causes that the volume of flue gas decreases to roughly 1/5 since during air combustion, approximately 80% of the flue gas is nitrogen. As a result, the efficiency of the boiler is higher, which is confirmed by Tang et al. [87] and it also allows to reduce the size of the flue gas cleaning devices, thus the investment costs will be probably lower. Higher oxygen concentration results in greater oxidation of hydrocarbons. Besides, due to the absence of nitrogen in flue gas, the concentration of pollutants is higher, so the efficiency of desulphurisation or other impurities removal can increase. To the best of the authors' knowledge, with the exception of waste from sewage sludge, there is currently a lack of available research on oxy-fuel combustion of waste in pilot facilities. The papers that will be presented focus mainly on thermal degradation of waste samples under various conditions, with particular emphasis on combustion parameters such as ignition, combustion rate, and burnout, as well as gaseous and heavy metal emissions in order to draw conclusions and propose the possibilities of further technology development.

4.1. Thermogravimetric analysis

To obtain useful data of thermal behaviour and calculate kinetic parameters that can be used to model the oxy-fired combustion chamber, the first logical step of the research is the analysis of

thermal decomposition of various waste feedstocks, separately and as fuel mixture, under different conditions, i.e. various heating rates, atmospheres or temperatures. To carry out the study, thermogravimetric analysis (TGA) is usually employed, which is often coupled with Fourier-transform infrared spectroscopy (FTIR), gas chromatography (GC) or mass spectrometry (MS) to identify gaseous products that are released during the process.

4.1.1. Pyrolysis of MSW in CO₂ and N₂ atmosphere

Pyrolysis is an important initial stage of the combustion process since it determines such parameters as ignition, the stability of flame, product distribution and burnout. Therefore, in most cases, oxy-fuel combustion and pyrolysis are examined in parallel or pyrolysis is investigated before oxy-fuel combustion tests [90]. Lai et al. [91] investigated pyrolysis of waste in different atmospheres, including N₂, CO₂ and N₂/CO₂ mixtures. The results showed that under the carbon dioxide conditions the volatilization occurred between 200°C and 550°C, while above 650°C the thermal decomposition of mineral and the char gasification took place. Furthermore, authors noted that replacement of N₂ by CO₂ encouraged the char gasification and solid residue differed remarkably since in the nitrogen atmosphere residues were char and ash and in CO₂ residues were practically ash.

The next study, conducted by Tang et al. [90] concerned the pyrolysis of rubber, plastics, wood, paper, textile and kitchen waste in CO₂ atmosphere. They used thermogravimetric analyzer (TGA) coupled with Fourier transform infrared (FTIR). The results showed that CO₂ below 600°C behaved as the inert atmosphere. Whereas, above 600°C atmosphere changed the location of DTG peaks as well as formation mechanisms. Authors observed that CO₂ atmosphere inhibits polymerization reactions of tars and intensifies cracking of tars into gases. Moreover, it was found that pyrolysis in CO₂ at high temperatures enhances char cracking and its reactivity as well as decreases the amount of char. What is more, they suggested that these phenomena may affect the char combustion and fuel burnout during oxy-fuel combustion. Tang et al. [92] employed tubular electrical furnace to investigate char characteristics, including the analysis of char pore structure, during pyrolysis of waste in N₂ and CO₂ atmospheres. Results confirmed the previous findings that char reacted with CO₂ at high temperature. Since at the temperature of 800°C, the pore surface area of CO₂ char was smaller than of char obtained in N₂ atmosphere.

Petrochemical wastewater is also considered a problematic waste material, especially in countries where the petroleum and petrochemical industry has a vast scale, such as China, because improper management of wastewater sludge can cause serious environmental pollution. In Ref. [93] authors investigated pyrolysis of petrochemical wastewater sludge in N₂ and CO₂ atmospheres. Similarly to previous studies, they found that at lower temperatures CO₂ behaves as an inert atmosphere. Moreover, they distinguished three stages of material decomposition under CO₂ conditions: drying, devolatilization and char-CO₂ gasification at high

temperatures, while under N₂ conditions only two steps (drying and devolatilization). Additionally, they observed that curves of weight loss are moved in toward direction, which means that reactions are delayed. It can be explained by higher density and specific heat of CO₂ compared to N₂ as well as different radiative properties.

Summarizing findings on pyrolysis of different waste materials under N₂ and CO₂ atmosphere one should be said that at low temperatures there is no significant differences between atmospheres, while at high temperatures, CO₂ acts like a gasification agent that reacts with char. These conclusions are supported by Ref. [94–96], and they can be explained by the fact that char-CO₂ gasification is highly endothermic reaction, which means that it requires a lot of energy, and therefore occurs only at high temperatures.

4.1.2. Combustion of MSW under CO₂/O₂ conditions

Lai et al. [97] examined combustion process of MSW, they employed different atmospheres to compare the results, namely N₂/O₂ and CO₂/O₂ with various O₂ concentrations. Besides, kinetic parameters were calculated based on the nth order reaction fitting model. Table 1 presents the results of the kinetic analysis. Scientists found that the largest decrease in sample weight was between 200°C and 540°C, and the maximum mass loss rates increased when oxygen concentration was higher. Moreover, higher heating rates resulted in superior weight loss rate and some reactions can be overlapped. Besides, the authors claimed that the three-step reaction model can adjust the mass loss of samples accordingly.

In [98–100] authors presented a thermogravimetric analysis of waste materials combustion under CO₂/O₂ conditions in order to obtain kinetic parameters (Table 1) and evaluate the thermal degradation of different feedstocks. The conclusion was that the direct replacement of nitrogen with carbon dioxide negatively affects combustion since ignition is delayed and the maximum weight loss rate is lower. However, as the oxygen concentration in the CO₂/O₂ mixture increases, the combustion parameters approach those occurring during air combustion. The similar combustion performance as under 80%N₂/20%O₂ conditions was obtained in 70%CO₂/30%O₂ atmosphere. It should be stressed out that similar observations were noted during the oxy-combustion of coal and other fuels [36,38] and it was ascribed to the lower heat loss caused by a decreased amount of diluent gas (CO₂) as well as enhanced heat transfer and oxygen propagation. Besides, they reported that reactions of char oxidation (Eq. (2)) and calcium carbonate decomposition (Eq. (3)) during the oxy-fuel combustion was inhibited to toward direction due to a very high carbon dioxide concentration. While at elevated temperatures (around 900°) Boudouard reaction (Eq. (4)) appeared.



Table 1
Results of kinetic analyses of different waste materials in 80%CO₂/20%O₂ atmosphere.

| Material | logA ₁ , 1/s | E ₁ , kJ/mol | n1 | logA ₂ , 1/s | E ₂ , kJ/mol | n2 | logA ₃ , 1/s | E ₃ , kJ/mol | n3 | Correlation coefficient | Source |
|------------------|-------------------------|-------------------------|-------|-------------------------|-------------------------|-------|-------------------------|-------------------------|-------|-------------------------|--------|
| MSW ₁ | 19.692 | 209.443 | 3.137 | 11.456 | 145.744 | 1.465 | 2.277 | 58.302 | 2.119 | 0.999647 | [97] |
| MSW ₂ | 19.08 | 209.44 | 3.14 | 11.46 | 145.74 | 1.47 | 2.28 | 58.30 | 2.20 | 0.999647 | [99] |
| PCV | 12.87 | 165.72 | 1.53 | 10.37 | 185.89 | 2.69 | -2.80 | 11.22 | 0.07 | 0.999882 | [100] |
| Leather | 11.93 | 150.36 | 2.09 | 6.55 | 128.3 | 2.99 | 13.09 | 349.58 | 0.46 | 0.998619 | |
| Rubber | 3.79 | 91.64 | 2.65 | 2.93 | 132.27 | 0.17 | 7.10 | 195.49 | 3.47 | 0.995446 | |
| Paper | 11.5 | 157.7 | 3.9 | 32.5 | 255.8 | 0.8 | -5.6 | 90.5 | 0.4 | 0.998266 | [98] |
| Fruit waste | 6.4 | 97.4 | 4.6 | 32.0 | 250.0 | 0.3 | -1.6 | 86.2 | 1.0 | 0.994585 | |
| Plant residue | 6.7 | 93.7 | 1.0 | 2.4 | 58.0 | 2.9 | 6.5 | 39.0 | 1.2 | 0.998081 | |



Oxy-fuel combustion of petrochemical wastewater sludge was presented in Ref. [93]. Authors examined combustion under different combustion parameters, including the atmosphere, heating rate and oxygen concentration, using a thermogravimetric analyser (TGA). They found that the combustion rate in the CO_2/O_2 atmosphere was lower compared to N_2/O_2 , because of different properties of gases. Moreover, higher heating rates can result in quicker ignition and better burnout. While an enriched oxygen atmosphere can intensify heat production. Besides, Niu et al. [101] investigated the oxy-fuel combustion of sewage sludge. The results indicated that (a) the decomposition of sewage sludge consisted of two peaks that were located at devolatilization and oxidation periods, (b) the thermal lag decreased with increasing heating rate, (c) during combustion in O_2/CO_2 atmosphere at an analogous concentration of oxygen as in air combustion, combustion performance was worse and (d) ignition index and comprehensive performance indices of the sample in 30% O_2 /70% CO_2 were similar to that obtained during air combustion.

In conclusion, presented studies indicated that direct replacement of nitrogen by carbon dioxide causes that the ignition is delayed and the combustion rate is lower. Nevertheless, some authors reported that with the higher content of oxygen in CO_2/O_2 mixture the combustion performance can be improved, and the most similar combustion characteristics to air burning were obtained in 30% O_2 /70% CO_2 atmosphere. Besides, the model-fitting was the most frequently chosen approach for calculating kinetic parameters of MSW degradation. This is the most practical approach to estimate kinetic parameters, while there are other theoretical approaches that are also in use, for example, density functional theory (DFT) [10].

4.2. Heavy metals

During combustion of municipal solid waste (MSW), knowledge about heavy metal behaviour is crucial for the control of emission of pollutants since, in comparison with other solid fuels, such as coal or biomass, the waste contains a relatively high amount of heavy metals that are highly harmful to both natural environment and human health. Furthermore, the amount of ash can be a serious issue in the combustion process since there is a high risk of slagging, bed agglomeration, fouling and corrosion of the devices, as well as ash, could inhibit a heat transfer and consequently, decrease combustion efficiency [102]. Sørnum et al. [103,104] studied the impact of varying operational parameters and the composition of waste on the devolatilization, chemical composition of heavy metals and condensing behaviour under air combustion conditions in a grate furnace, using equilibrium calculations. Whereas, Wang et al. [105] used X-ray spectroscopy (SEM-EDX) and X-ray fluorescence (XRF) to characterise ash deposits from municipal solid waste-to-energy (WtE) plants.

The first study of the behaviour of heavy metals during oxy-fuel combustion of municipal solid waste was presented by Tang et al. [106]. Authors used a lab-scale electrically heated tube furnace to assess the impact of MSW combustion in various atmospheres on hazardous heavy metals (Pb, Cd, Zn, Cr, Ni and Cu) in the bottom ashes. The overall conclusion was that the CO_2/O_2 atmosphere increased enrichment of heavy metals in bottom ashes, which meant that a lower amount of heavy metals was in the fly ash and thus, the emission to the atmosphere was lower. The effect of temperature on evaporation of heavy metals was the most

pronounced for the medium volatile metal Pb, and the smallest for the low volatiles Cr and Ni. Moreover, change in temperature had a bigger impact on (PVC) than for wood sawdust and paper mixture. Nevertheless, the content of heavy metals in ashes during oxy-fuel combustion was higher than China's requirements of soil environmental quality standards.

The volatilization of cadmium, chromium and zinc during the oxy-fuel combustion of food waste and plastic (PVC) in a lab-scale tubular furnace was studied by Ke et al. [107]. In general, the results indicated that the amount of ash was greater for food waste. Besides, during oxy-fuel combustion, ash rate of food waste was bigger than during air combustion. However, at higher temperatures, the amount of ash rate decreased because of decomposition of CaCO_3 . While, the ash rate of PVC did not change notably after the replacement of nitrogen by carbon dioxide and it was explained by the fact that PVC did not contain calcium carbonate, which reacted with CO_2 . Moreover, the volatilization of Cd and Cr was lower in oxy-combustion conditions, however, the volatilization of Zn increased in CO_2/O_2 atmosphere. Furthermore, researchers claimed that incineration operating conditions just slightly reduce the volatilization of heavy metals and using sorbents is required to meet the requirements.

Magdziarz et al. [102], Jang et al. [108] studied the sewage sludge ashes from combustion in N_2/O_2 and CO_2/O_2 atmospheres in a 12-kW bench-scale circulating fluidized-bed combustor. The temperature of the process was held at 850°C and different CO_2/O_2 ratios were tested. Moreover, such analytical techniques as X-ray diffraction (XRD), SEM-EDX and TG-DSC were applied to perform analyses of ashes. Generally, results showed that the main compounds of the ashes of sewage sludge are SiO_2 , Fe_2O_3 , P_2O_5 , CaO , Al_2O_3 , MgO , TiO_2 , K_2O , Na_2O and SO_3 . Moreover, the combustion atmosphere did not influence significantly the chemical composition of ash and corrosion should not be a problem during oxy-fuel combustion of sewage sludge due to low levels of potassium, sodium and chlorine. Thus, sewage sludge can be successfully combusted in oxy-fuel technology.

4.2.1. Sorbents effect

The next works focused on finding effective sorbents to control the emission of heavy metals. Tang et al. [109] investigated the behaviour of copper (Cu), nickel (Ni) and zinc (Zn) during oxy-fuel combustion of tire rubber and high-density polyethylene (HDPE) under N_2/O_2 and CO_2/O_2 atmosphere with the addition of limestone and calcium oxide (CaO). Results demonstrated that the replacement of N_2 by CO_2 as well as the addition of limestone decreased the evaporation of heavy metals. Moreover, the capture efficiency of limestone for Zn, Cu and Ni was affected by the waste composition. In the case of tire rubber, combustion in CO_2/O_2 atmosphere favoured the capture of Zn, Cu and Ni, but not in the case of HDPE. Although the performance of limestone was worse than CaO for capturing Cu and Ni, the cost of limestone was lower than CaO. Therefore, limestone offered the potential for a low-cost effective medium to control heavy metals during MSW combustion.

Furthermore, Ke et al. [110] studied the effect of the temperature of the furnace, sorbents types and ratio between carbon dioxide and oxygen on adsorption of heavy metals (Al, Cr and Zn). They found that at higher temperatures more aluminium was in the bottom ash, however, the volatilization of zinc increased. Besides, CaCO_3 did not absorb Al, while calcium oxide (nature or modified) had an excellent performance for Al capture. None of the sorbents could capture the chromium. CO_2/O_2 ratio had a large impact on the capture of Cr and Zn but did not affect Al, and the decrease of CO_2/O_2 ratio helped capture Cr and Zn.

Summarizing, the heavy metal problem is a very complex issue and there is still not enough research on heavy metals behaviour

during oxy-fuel combustion. Studies presented in this paper show that a major impact on heavy metals had the composition of waste and process temperature. The oxy-fuel combustion of waste requires the use of sorbents to reduce volatilization of heavy metals, and the addition of the limestone can be an effective method to control the heavy metals.

4.2.2. Emissions

A major concern associated with waste combustion is pollution emission, therefore they are subject to the research of many scientists. Emissions are highly related to fuel composition as well as combustion conditions. Tang et al. [111] investigated the oxy-fuel combustion of MSW and the effect of heating rate, temperature, and oxygen concentration on NO_x and SO₂ emissions. The results showed that both temperature and atmosphere have an impact on emission levels. In the case of NO_x, with increasing oxygen concentration in the CO₂/O₂ atmosphere, emission was higher. Besides, replacement of N₂ by CO₂ decreased NO_x emission only at a temperature above 800°C, and reduced SO₂ emission when the temperature was below 1000°C. At 1000°C, in order to simultaneously remove SO₂ and NO_x in 80%CO₂/20%O₂ atmosphere sorbents were required. While Sung et al. [112] presented an investigation on oxy-fuel co-combustion of sewage sludge and wood pellets. Experiments were performed in a 30 kWth CFB system. They continuously registered the temperature and the concentration of O₂, CO₂, CO and NO in flue gases and evaluated the impact of fuel composition, oxygen injection rates, and flue gas recirculation. They observed that the most uniform temperature gradient appeared at 60% of the flue gas recirculation rate and the CO and NO concentration decreased to 0.91% and 14 ppm, respectively. Moreover, Dai et al. [113] performed co-combustion of PVC and food waste in CO₂/O₂ atmospheres to gain the knowledge of the HCl emission due to high content of chlorine in the waste. They found that temperature as well as CO₂/O₂ ratio have an impact on Cl–HCl conversion.

5. Conclusion

The work provides the overview of currently available CO₂ capture methods, with particular attention to oxy-fuel combustion since it is considered as a most promising method of carbon capture methods. Besides, a review of waste-to-energy facilities is presented and the possibilities of their integration with CO₂ capture technology. Among available methods of thermal conversion of waste to energy, gasification is considered as the most efficient, however, it is currently only one commercial IGCC plant, in which waste is a source of energy. In addition, cleaning of the syngas is expensive causing that from the LCA perspective, incineration is still a better option for waste management. A promising method of waste utilization, which potentially increase of overall plant's performance is chemical looping combustion/gasification. Besides, it was found that using CaSO₄ as an oxygen carrier demonstrates a significant reduction of dioxins, however, this method is far from commercial use. While incineration is the most mature and common technique of WtE systems (the number of operating incinerators is more than 1200) and the application of carbon capture in existing plants will contribute to a large reduction of CO₂ concentration in the atmosphere and mitigate climate change.

Nowadays, there are four incineration plants, in which post-combustion carbon capture technology is successfully integrated. However, it was found that CO₂ capture based on the MEA technique results in a large energy penalty. Hence, to decrease the plant's efficiency drop causing by carbon capture process, further research should be focused on the implementation of more efficient methods of carbon sequestration, such as oxy-fuel

combustion that according to Ref. [88] can reduce the drop in efficiency to 9.57%. However, this result was obtained under the assumption of the steady-state process. To obtain more reliable results and predict the behaviour of the system in changing conditions, dynamic simulations of the oxy-incineration plant should be studied, especially that municipal solid waste are non-homogeneous materials [70,114].

It is expected that application of oxy-fuel combustion in incineration plant (a) decreases the energy penalty of the use of CCS, (b) reduces exhaust gas stream by 80% compared to air combustion and thus, increases boiler efficiency, (c) increases of process temperature due to higher oxygen concentration and results in smaller auxiliary fuel consumption and (d) decreases emission of NO_x and other pollutants. However, it should be remembered that O₂/CO₂ atmosphere affects the combustion process significantly and MSW is very demanding fuel. Some crucial aspects of the quality of bottom and fly ash and air leakage in the feeding system still remain unsolved. Thus, oxy-fuel combustion should be integrated very carefully to the incineration plant. Besides, to improve the efficiency of oxy-fuel combustion the new air separation method with lower energy demand should be developed.

From the literature review of the current state of knowledge of oxy-fuel combustion of waste the following conclusions can be made:

- During the pyrolysis of waste materials, the replacement of N₂ to CO₂ has a significant impact only at high temperatures (usually above 600°C) since the reaction between carbon dioxide and char is highly endothermic.
- Combustion performance highly depends on oxygen concentration, flue gas recirculation, and type of fuel. Researchers reported that during oxy-fuel combustion in 30%O₂/70%CO₂ atmosphere, the combustion characteristic is similar to those obtained during air combustion.
- The most often employed method to calculate the kinetic parameters is model-fitting method and during degradation of MSW three steps are considered.
- The fate of heavy metals is ambiguous because it largely depends on the composition of the waste, but it can be stated that during oxy-fuel combustion more heavy metals are found in bottom ashes, and therefore less heavy metals are emitted to the atmosphere. Nevertheless, sorbents should be used to reduce heavy metal emissions to acceptable standards.

5.1. Future work

As shown, oxy-fuel combustion of waste is a very promising technology that can be implemented in hundreds of waste incineration plants in Europe and worldwide, but it still requires a lot of research. In our opinion, the investigation of oxy-fuel combustion should be mainly focused on (a) searching of optimal O₂/CO₂ ratio to minimize the emission level and maximize the combustion performance, (b) research on new air separation methods, for example, chemical looping, and (c) looking for the most favourable adaptation of oxy-fuel combustion to incineration plant, for example by using of waste heat to power the auxiliary devices, such as ASU and compressors. Besides, further research should consist of combining the kinetic data of individual fuels with the waste incinerator chamber model, which will enable the design of furnaces optimized for the disposal of a particular type of waste, as well as analyses of dynamic simulations of the oxy-incineration plants.

Declaration of competing interest

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

CRedit authorship contribution statement

Paulina Wienchol: Methodology, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Andrzej Szląk:** Conceptualization, Methodology, Writing - review & editing, Supervision. **Mario Ditaranto:** Conceptualization, Writing - review & editing, Supervision.

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