Power Generation from Municipal Solid Waste and Biomass: Overview, Challenges, and Improvements

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Abstract

In this mini-review, the technologies of power generation from Municipal Solid Waste (MSW) and biomss are introduced. As new types of renewable energy, Municipal Solid Waste (MSW) and biomass have shown high application potential, especially due to their low acquisition costs. Generating electricity with them is the most direct and convenient form of utilization among various options.

Firstly, they are briefly introduced from a theoretical perspective. For Biomass, gasification followed by combustion, and mixing with traditional fuels for combustion, are two main forms of utilization. For MSW, they are usually sorted, shredded, namely made into refuse-derived fuel (RDF) and solid recovered fuel (SRF), and then directly burned. Then, the recent advances of these two technology are focused, cutting-edge contents from high-level research groups are discussed. Afterwards, current challenges and potential improvements are introduced and analyzed regarding MSW and biomass, repectively. Firstly, the development status of biomass gasification is analyzed from the perspective of its type and theory and analyzes its challenges in terms of energy conversion efficiency and environmental pollution. The use of SCR/SNCR technology to reduce nitrogen emissions from biomass power generation is discussed. Then, we deep dive into challenges from three factors (Tech, Social, Political) and take US and China as case study.To overcome the shortcomings of MSW power plant such as low efficiency and high NOx emissions, a few methods are studied and proposed as remedies for the issues.

1 Introduction

1.1 Overview

Renewable energy is a goal that humanity has always pursued. Its development and utilization can significantly reduce environmental pollution and carbon emissions. In addition to common forms of renewable energy such as wind power, hydropower, and photovoltaics, there are also some technologies that are still in the research and experimental stages and have not yet been widely applied. Among them, biomass and municipal solid waste (MSW) are two more unique categories. Unlike other forms of renewable energy, the main technological routes for these two forms of energy are to convert biomass (or MSW) into new fuels and provide electrical energy through thermodynamic processes. The main method of biomass power generation is to first convert it into three-phase clean energy of gas, liquid, and solid by various methods. There are both physical methods (making pellets) and chemical methods. MSW is mainly based on direct combustion after sorting, compressing, and crushing, and basically no chemical reaction occurs before combustion. Below is a simple introduction to each of them.

Biomass power generation

Biomass power generation is the process of utilizing biomass energy and converting it into electrical energy through various methods, mainly including anaerobic digestion for biogas, hydrothermal catalysis for alcohol and hydrocarbon fuel, pyrolysis liquefaction and bio-oil upgrading, and solid fuel production. The ultimate goal of these methods is to increase the energy density of biomass fuel that can be utilized during combustion. Although its energy density is not as high as that of traditional fossil fuels, the sulfur content of biomass is only about one-fourth of that of coal. From the perspective of utilization, direct combustion and conversion combustion are two main forms of utilization. Taking straw power generation as an example, a typical direct combustion power generation process is as follows. First, the straw is compressed and shaped (pretreatment), and then burned in a boiler in excess air. The high-temperature and high-pressure steam generated in this process drives the generator through the turbine to output electrical energy. Direct combustion technology has been industrialized and has the lowest cost. The gasification technology is not as mature as direct combustion. Typically, after biomass is converted into combustible gas, it is purified (the purpose is to remove impurities such as tar) to form high-energy-density gaseous fuel.

Another technology worth paying attention to is co-firing (coupling combustion). In other words, traditional coal-fired power plants are modified to achieve coupled power generation of coal and biomass. Therefore, increasing the proportion of biomass has become an important development goal. For example, Drax, the largest coal-fired power plant in the UK, began biomass co-firing renovations in 2003. Initially, the biomass proportion in the mixture was 5%. Currently, this proportion has been increased to 35%, and some generation units are fully fueled by biomass. Additionally, the gas produced by biomass gasification can also be mixed and burned with conventional fuels (also including coal).

MSW power generation

Municipal solid waste (MSW) is solid waste generated from the daily lives of urban residents or from activities that provide services for daily urban life. It is usually categorised into three types: (1) bio-based waste (BBW), such as food waste, paper/board, which is considered carbon-neutral (zero net carbon emission); (2) fossil-based waste (FBW), including plastics and tires, which contributes significantly to high carbon emissions from thermal treatment and pose considerable challenges for carbon reduction; and (3) residual waste beyond the first two categories, primarily comprising broken glass porcelain, masonry metal, with very low heating value [1]. In addition to direct combustion, MSW is often processed into refuse-derived fuel (RDF) and solid recovered fuel (SRF). RDF refers to the shredding of MSW after removing the recyclable parts, making it safer for use in boilers. SRF is more complex, with metals and dust also being removed, as they do not provide calorific value.

1.2 Recent Advances

For Biomass-based power generation, Liu Wei et al. reviewed its roadmap as well as future potential [2]. It is also this research group who developed direct biomass-to-electricity hybrid fuel cell with the help of solar energy, which has an energy density of 0.72 mW cm^{-2}, almost the best one [3]. Iwona Gajda used a microbial fuel cell (MFC) system to produce electricity. They proposed that, algal biomass may provide advantages in long-term practical applications as a slow release substrate [4]. Mohammad Fattahi et al. developed a two-stage model to achieve a production process with higher efficiency under the view of supply chain perspective [5]. J. Sun et al. investigated the feedsstock and activation process of high performance on a supercapacitor. Cyranoski et al. reported a technology using plasma technology to turn waste into energy [6]. H. Cheng et al. [7] and R.A. Ibikunle et al. [8] estimated the power generation from MSW based on Changchun, China, and Ilorin Metropolis, Nigeria, respectively. Santos et al. evaluated the potential of power generation with MSW. They assumed MSW could be a good alternative, especially for middle-to-large cities [9].

Some other works combine the above two, as they have lots of similarities. Liu Bo et al. analyzed the ultilization potential under the background of the U.S., and holding a very negative opinion [10]. They concluded that, including biomass and MSW, none of the power form by waste recycling could strongly and satisfactorily support the energy supply. N. Indrawan et al. investigated the power generation from co-gasification of MSW and biomass.

2 Biomass

2.1 Challenges of Biomass

To reduce the emission of greenhouse gas and prevent the development of global warming, biomass energy, as one of the foremost renewable types of energy, is being explored for power generation. It has many advantages in terms of diversity, availability, and sustainability. As a sustainable resources, it has a wide variety such as plants, forests waste and products, organic part of municipal solid waste, biomass originating from industrial wastes and so on. And according to the report of World Bioenergy Association, Bioenergy was the 4th largest renewable electricity source with production of 685TWh in 2020. The contribution of biomass to renewable power generation globally was about 9% [11]. However, although the technology is relatively mature to extract energy from biomass, still, there are many shortcomings, such as low efficiency and harmful gas emissions, waiting to be overcome.

Biomass gasification types and efficiency

Among all the thermochemical conversion methods, gasification is of vital importance that transforms carbonaceous solid materials to a gaseous product. And the main stages for thermochemical conversion are Drying, Pyrolysis, combustion, and reduction. The chemical reactions which explain these above main stages can be listed as below [12].

Oxidation zone

$$C + O_2 \rightarrow CO_2 \quad \triangle H = -406KJ/mol$$

$$2C + O_2 \rightarrow 2CO \quad \triangle H = -123KJ/mol$$

Reduction zone Water-gas reaction:

$$C + H_2O \rightarrow CO + H_2 \quad \triangle H = 131.4KJ/gmol$$

Boudouard reaction:

$$C + CO_2 \leftrightarrow 2CO \qquad \triangle H = 172.6KJ/gmol$$

Water-gas shift reaction:

$$CO_2 + H_2 \leftrightarrow CO + 2H_2O \qquad \triangle H = 42KJ/gmol$$

Methane formation reaction:

$$C + 2H_2 \leftrightarrow CH_4 \qquad \triangle H=-75KJ/gmol$$

Above are some gasification procedures representing in chemical formulars, and all these reaction stages can be accomplished in different gasifier types, including fixed bed gasifier, fluidized bed gasifier, entrained- flow reactors, and plasma reactors. But all these gasifiers have their pros and cons. For example, the fixed bed gasifier has a great thermal efficiency and low evaporation temperature but generates tar; the fluidized bed gasifier has a homogeneous temperature distribution and reduces the formation of tar, but the conversion is quite limited; and the Entrained flow reactors have a simple design, which makes it easy to feed raw materials, and have a relatively high conversion efficiency, but needing a large product container and cooling system [13].

Biomass low efficiency

There are many factors that affect the efficiency of biomass energy conversion, including temperature, inconsistent raw material characteristics, insufficient pretreatment, technological level and equipment limitations, and energy loss. For example, in the pre-treatment stage, the moisture content of biomass raw materials will affect energy conversion efficiency, which has been proved by Hosseini's study [14]. They increased the moisture content of biomass from 0.15 to 0.25, and the exergy efficiency of biomass gasification by steam and air gasification agents decreased from 18% and 19% to 16% and 18.5%, respectively. Moreover, temperature also has an inevitable influence on biomass exergy efficiency. For example, Zhang observed that the exergy efficiency of biomass increases with the rising of temperature but decreases with the increase of particle size [15]. These studies explain the efficiency of biomass exergy is governed by many factors waiting to be figure out.

Bioenergy harmful gas emissions

Although biomass gasification is a promising technology that can reduce the effect of carbon emission, the other pollution problems it causes still worth scientists' attention. When using biomass energy to produce energy, problems such as air pollution, noise pollution, water pollution, and biodiversity pollution may occur. How to solve these problems is still a problem that humans need to overcome when using biomass energy. The following mainly introduces the challenges faced in air pollution. Firstly, biomass energy may be burned incompletely during the combustion process, which will cause a large amount of particulate matter to enter the air after combustion, polluting the air, leading to the occurrence of harmful weather such as haze, and having a negative impact on human health. Furthermore, if the raw materials are not desulfurized and denitrified during pre-treatment, the sulfide gas and nitrogen gas produced during the combustion process will promote the formation of ozone, causing the ground ozone concentration to increase, thereby affecting air quality. Moreover, the large amount of carbon dioxide produced during the combustion process will also intensify the greenhouse effect and lead to global warming.

Therefore, although biomass energy is a quite promising renewable energy, there are still steps in knowledge to take to handle its full-scale applications.

2.2 Improvements of Biomass

Biomass boiler fuel is biomass fuel, biofuel combustion emits a lot of nitrogen oxides, NOx emissions not only harmful to the formation of the ozone layer in the atmosphere but also cause harm to human health, especially the impact on the respiratory system. In addition, NOx may also interact with other atmospheric pollutants to form fine particulate matter, causing further impacts on air quality. Common raw materials used in biomass power generation are residues after crop harvest, such as corn straw, straw, wheat straw, etc., and waste generated in the agricultural production process, such as rice husk, wheat bran, soybean residue, etc. These raw materials contain nitrogen converted from nitrogen fertilizer used on crops during the growth process and are the main source of nitrogen emissions from biomass fuels. Compared with fossil fuels, the sulfur content of biomass fuels is relatively small, mostly less than 0.12%, and the boiler does not need to set up a desulfurization device.

According to the characteristics of flue gas produced by biomass fuel, the SCR/SNCR denitrification process is widely used in industry at present.

SCR process for denitration

Selective Catalytic Reduction (SCR) refers to the use of reducing agents (such as NH_3) under the action of catalysts to "selectively" react with NOx in flue gas and generate non-toxic and pollution-free N_2 and H_2O, to achieve NOx reduction, shown in **Fig 1**. Selectivity means that the flue gas denitrification catalyst selectively reduces NOx to nitrogen in the process of flue gas denitrification, and the SO_2 in the flue gas is rarely oxidized to SO_3. The mixture of V_2O_5 and WO_3 based on TiO_2 is generally used as a catalyst. The specific formula is determined according to the flue gas parameters.

In the SCR reactor, NOx is reduced by the following reactions:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \text{ (main reaction 1)}$$

$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O \text{ (main reaction 2)}$$

$$6NO + 4NH_3 \rightarrow 5N_2 + 6H_2O \text{ (side reaction 3)}$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O \text{ (side reaction 4)}$$

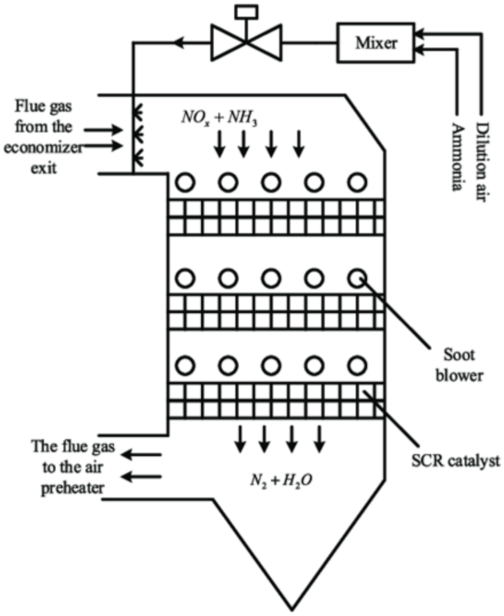

Fig 1. Structure of SCR.

SCR denitrification technology is the most effective fixed-source NOx treatment technology with the highest denitrification efficiency, and the denitrification rate can reach more than 90%. In the SCR denitration system, the catalyst, as the core component, is usually placed before the air preheater, that is, the high temperature and high dust arrangement. When the catalyst works under such conditions, because the biomass fuel itself contains K, Na, Ca, and other alkaline substances, the fly ash formed after combustion enters the SCR system, adsorbs on the surface of the catalyst, or blocks the pore of the catalyst, and reacts with the active ingredients on the surface of the catalyst, resulting in catalyst poisoning and deactivation, which has an impact on the service life of the catalyst. To ensure the safe operation of the catalyst and minimize the flue gas resistance of the newly added catalyst, the alkali-resistant metal plate catalyst should be selected. If the catalyst is arranged in the arrangement of low temperature and low dust, that is, after the desulfurization and dust removal device, the catalyst can avoid the problems of sintering caused by high-temperature flue gas and the blockage of catalyst pores by fly ash.

SNCR denitration

SNCR denitration technology is Selective Non-Catalytic Reduction (SNCR) technology. In contrast to SCR technology, there is no precious metal catalyst in the reaction process, and the reactions of equations 1 and 2 can only occur in a narrow high-temperature range (900-1,000°C). Is a kind of catalyst, in the temperature range of 850 ~ 1100℃, the amino-containing reducing agent (such as ammonia water, urea solution, etc.) is injected into the furnace, under high-temperature conditions, the reducing agent is first decomposed into NH3 and other by-products, after the NOx in the flue gas and NH3 generated by decomposition further REDOX reaction. Clean denitrification technology that reduces NOx in flue gas to N2 and H2O, reduces NOx in flue gas and generates ammonia and water. In the appropriate temperature region, and ammonia as a reducing agent, the reaction equation is:

$$4NH3+4NO+02 \rightarrow 4N2+6H20 \text{ (reaction 1)}$$

However, when the temperature is too high, the following side reactions can also occur:

$$4NH3 + 502 \rightarrow 4NO + 6H20 \text{(reaction 2)}$$

The denitration efficiency of SNCR flue gas denitration technology is generally 30%~80%, which is greatly affected by the boiler structure size. With SNCR technology, the current trend is to use

Tab 1. Comparison of SCR and SNCR Processes

Process	**SCR**	**SCR**
NOx removal efficiency/%	70~90	30~80
Operating temperature/℃	200~500	800~1100
Mole fraction of NO3/NOx	0.4~1.0	0.8~2.5
Leak of ammonia/10-6	< 5	5~20
Total investment	High	Low
Operating costs	Medium	Medium

urea instead of ammonia as a reducing agent. When the appropriate catalyst is used, the reaction activation energy is reduced, and the reaction temperature is reduced to 300-400 °C, close to the exhaust gas temperature between the boiler economizer and the air preheater, which is suitable for actual conditions. The specific process of these two technologies is shown in **Tab 1**.

3 Municipal Solid Waste Power Plant

3.1 Challenges of MSW

To deal with the urgent trends of global warming, developing MSW fueled power plants has become an effective solution for increasing generation and accumulation of MSW. By decreasing the dependence on the fossil, these plants can promote economic and social growth for country. At the same time, they also provide electricity energy by reducing waste. On the technical factor, the MSW fueled power plants are constructed following two basic routes. One is thermal route including incineration, gasification and pyrolysis. Another is biochemical including anaerobic digestion, landfills gas recovery/composting. The chosen and implementation of these two routes depends on the climate of country and type of waste. However, each methods have the limitations as **Tab 2**. We will deep dive into the challenges of these two power generation routes by taking US and China as case study.

Tab 2. Methods limitations faced by MSW power plants

Routes	Methods	Limitations
Thermal	Incineration	Air pollution, bad effect of bottom & fly ash
	Gasification	High cost
	Pyrolysis	High cost
Biochemical	Anaerobic digestion	High power cost (Aeration)
	Landfill gas recovery / Composting	Time-consuming

For US, they focus more on thermal route for most MSW fueled power plants. And incineration is the main thermal method which are being practiced. All the plants recycle tones of MSW feedback every day. Then electricity generated will be transmitted to the usage for local citizens. Among the thermal treatment types, mass burning is the most popular way. MSW will be mixed with air and burn in the huge incinerators. Then the electricity will be produced by a boiler and a generator. In US, there are 58 mass burn facilities, 4 modular facilities and 13 refuse derived fuel-based facilities [16]. To meet the stringent pollution permit requirement in some states of US, it is still challenging for the power plants to develop appropriate air pollution control system. The inorganic pollutants contained by leftover ash needs proper disposal and landfilled. Pyrolysis and gasification are the rest methods. In gasification method, it requires preprocessing including treatment and cleaning of syngas. However, this operation will be challenging. Using catalysts for gasification of waste can better the yield of syngas by improving the purity but it increases the production cost. What's more, it is still challenging to deal with particulates like tar and char existing in the syngas. Because under a low temperature tar condenses which have a probability of clogging equipment such as downstream pipes. Most plants are facing this challenge currently. In pyrolysis method, the requirement of catalysts also increases the plant cost. And catalysts also have the limitations. Most heterogenous MSW are impurity and contain other contaminants. In the feedback, this material construction will deactivate the catalysts which will have a bad effect on the power generation efficiency.

In China, most incineration MSW plants will retire between 2030 and 2040. After their retirement, the future MSW treatment will be a big challenge. It may hinder the development of the recyclable processes. Due to the Not-In-My-Backyard [17], most China incineration plants located in urban areas are facing the construction challenge of heating pipelines. It will limit them to achieving

CHP. What’s more, the energy efficiency range of them is 40%-75% which are approximately 15% below the international standards [18]. New ways and technologies need be found out to increase the efficiency and reduction for the existing MSW power plants in China. One of the most prospect way for removing the carbon generated from fossil-based waste, CCUS’ investment is currently expensive and still development for MSW [1].

Thermal route is preferable for MSW with little moisture fraction [19], while the biochemical route is preferable for MSW having a relatively higher biodegradable and moisture fraction. For Asia, anaerobic digestion is the best way for wet MSW [20]. However, the main challenge of anaerobic digestion is the sorting and segregation of MSW. Because when fed into the plant digester, the lack of organic waste like tracing heavy metals and hazardous compounds may bring toxicity. In addition, the waste should be properly segregated and classified at collection point of MSW power plants. There are novel technologies arising such as pyrolysis to biofuel. But most of them have the disadvantage of high capital investment, which made them occupy a small market [1].

Apart from those technical challenges (high cost and lack tech breakthrough), there are also challenges existing in social and political factor determining the collection of MSW and plants setup. On the social factor, the attitude of society towards MSW plays an important role in optimization for MSW management. Major challenges behind it are bad segregation of MSW and improper collection of power plants. People are not motivated enough to minimize the production of waste, recycle/reuse the waste. What’s more, they are under less promotion to classify waste at their homes before sending it to the specific collection units. In most developing countries, the current challenge for MSW management is the improper practice of MSW disposal. People is short of waste categorization and there are few professional facilities for MSW management existing in these countries. The lack of awareness and citizens’ low motivation have inhibited the implementation of the novel technologies previously mentioned. On the political factor, the government still lack the incentives to promote MSW power plants setup. The limited support from government and inadequate industrial planning will not boost the implementation of new technologies providing higher efficiency.

3.2 Improvements of MSW

As mentioned, there are some challenges faced in the operation of municipal solid waste (MSW) power plant. Even though MSW power generation is favorable as a renewable energy solution, these shortcomings are holding back the implementation of MSW power plant at a larger scale. In the following sections, some recommendations to improve these disadvantages are discussed.

MSW Drying

Drying methods can help to increase the low heating value of MSW. Drying of MSW leads to the reduction of moisture, volume, and weight of MSW which then results in higher energy density for power generation. A study has been carried out comparing different drying methods of MSW in terms of different aspects [21]. The methods studied are biodrying, biostabilization, solar drying and thermal drying. To briefly describe each of these drying method; 1) biodrying uses natural and forced aeration along with the heat generated by natural aerobic bioconversion of organic matter to dry the waste, 2) biostabilization involves the enhanced biological degration of organic matter, 3) Solar drying is the removal of moisture by forced convection of solar heated air, 4) thermal drying is a process where an external auxiliary energy source is used to heat the waste. The moisture, weight and volume reduction, drying time as well as heating value increased of these methods are analyzed and compared. The study shows that different drying methods excel in different parameters. It is also worth noting that the heating value increase of MSW varies between developed and developing countries due to the deference in composition of the waste, as shown in **Fig 2**. Hence, the optimum selection of drying method should be analyzed and applied on a case-by-case basis.

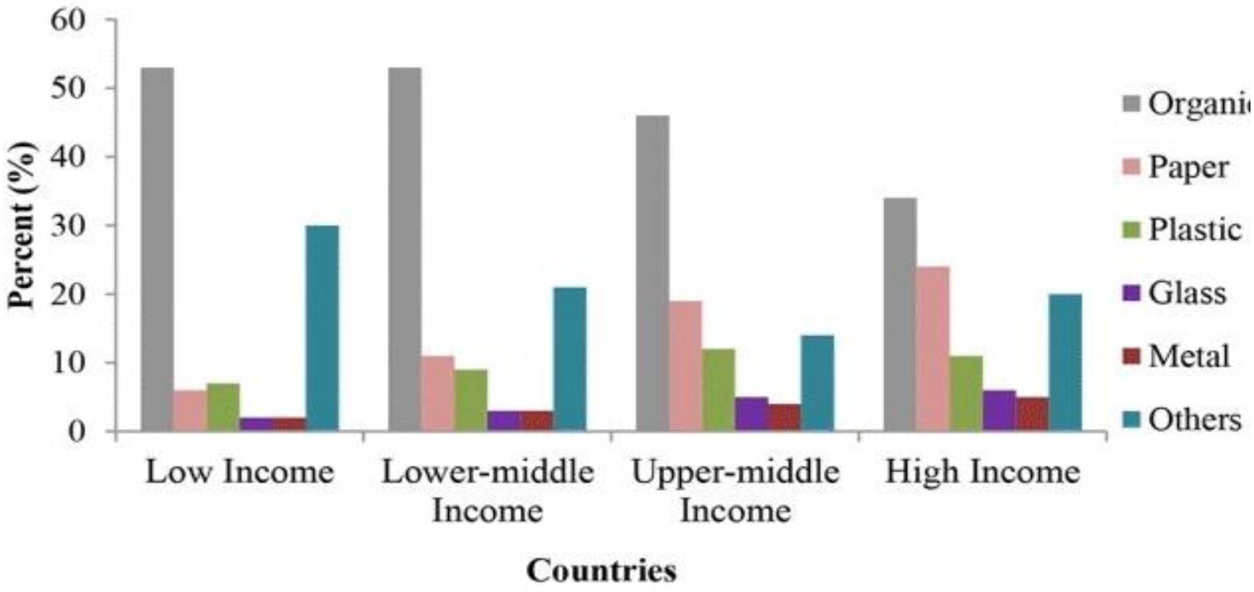

Fig 2. Comparison of waste composition around the world (2015).

Power Plant Modification

Other than treatment of the MSW, the power plant can also be modified to increase the efficiency of power generation. An evaluation has been done on MSW power plant to determine the various enhancements that can be made for both the individual components and the overall base case plant [2]. Exergy analysis is performed to evaluate efficiency of the systems such as boiler, stream turbine, condenser and so on. The results of case study and theoretical process are then compared to identify the components with the highest potential for improvement. Based on **Tab 3**, boiler has the highest improvement potential and therefore modifications were made to the boiler. These modifications include changing the bed material, converting the water boiler into gas boiler, using Inconel in the boiler walls and so on. After the modifications, a case study is performed and the analysis shows that an overall more than 20% improvement in exergy efficiency for all the modifications done to the boiler. This proves there is still much potential in MSW power plant. By applying the right modifications, the efficiency of the power plant can be significantly improved.

Tab. 3. Evaluation of the performance of case study (CS) and theoretical processes (TP) [22].

Components	**CS**	**TP**
	η_{ex} (%)	η_{ex} (%)
Boiler	37	62
Steam turbine	77	100
Condenser	66	68
Condenser pump	72	100
Feed-water pump	74	95
Feed-water heater	94	96
De-aerator	87	93
Primary steam air heater	48	54
Secondary steam air heater	74	75
Hypothetical component	0	100
Overall plant	25	56

Coupling Technologies on NOx Reduction

There are a few technologies available to reduce the production of NO_x in MSW power plant, such as flue gas recirculation (FGR), over-fired air (OFA) and selective non-catalytic reduction (SNCR). The research of the combination of these technologies in NO_x reduction efficiency has been conducted and the results show very promising potential [3]. FGR is the recycling of the exhausted flue air back through boiler or burner. OFA is the process of introducing fire into the top zone of burner to ensure complete combustion of carbon monoxide. SNCR utilizes ammonia reactant into the burner as an emission-controlled method to reduce NO_x. In the study, these three technologies are coupled in different combination and the various resultant parameters are determined. Among these parameters is the NO_x removal efficiency and its result is as shown in **Fig 3**. From the figure, it is shown that case#9 has the highest NO_x removal efficiency at 76%. In this case, case#9 represent the coupling of all three of FGR, OFA and SNCR technologies. In conclusion, instead of using only one particular technology, coupling NO_x reduction technologies in MSW power plant can improve the overall NO_x removal efficiency.

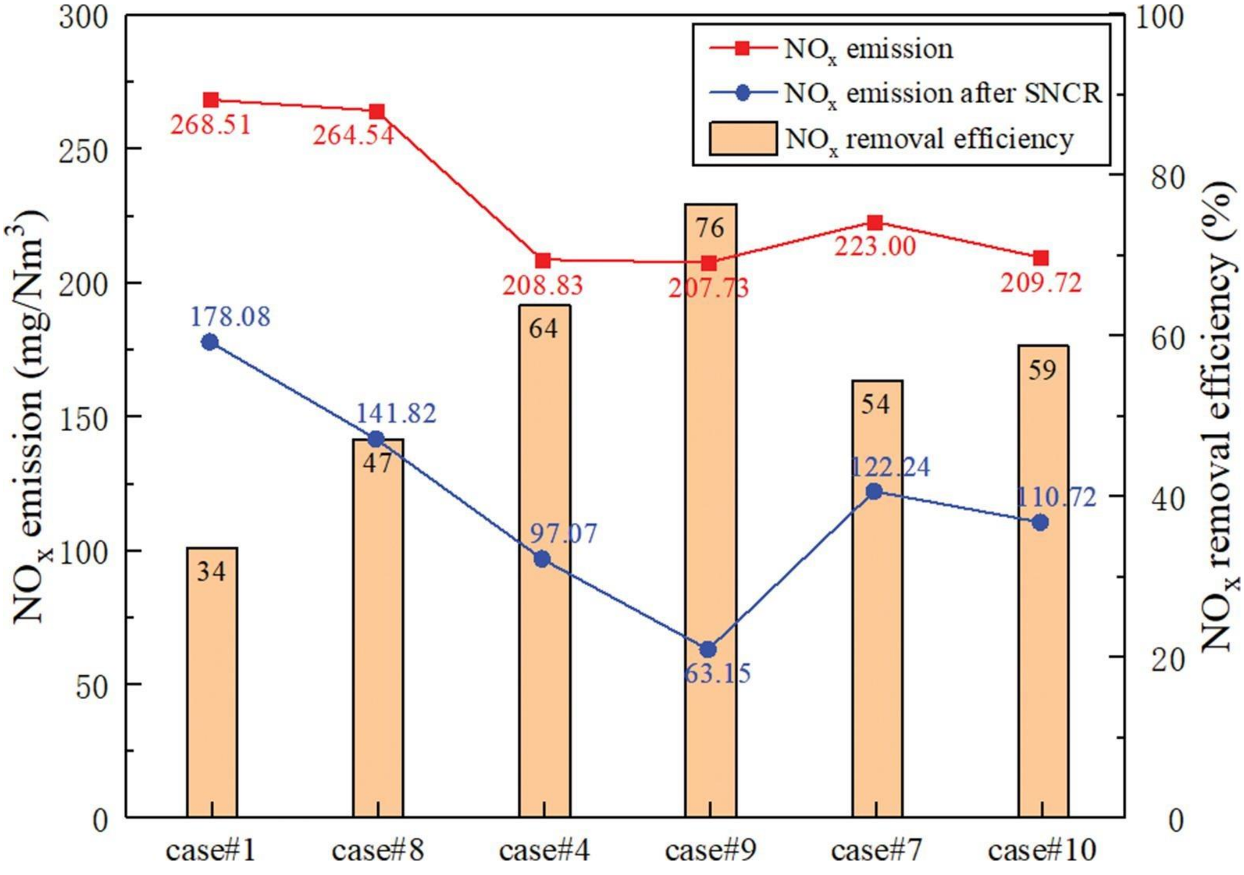

Fig. 3. The NO_x emission at third flue outlet and NO_x removal efficiency [23].

4 Conclusion

MSW and biomass are two kinds of renewable energy sources with great potential, which are current research hotspots in the energy erea. For MSW, Cost investment , social awareness and government support are three main challenges for current MSW Power Plant. Improvement on MSW power plant can be achieved by implementing MSW drying, power plant modifications and coupling technologies on NOx reduction. As for biomass, Although its use as a renewable energy source can alleviate the energy crisis to some extent, there are still many challenges that need to be addressed, especially nitrogen emissions. SCR/SNCR can effectively reduce nitrogen emissions. In conclusion, although there are still obstacles on the way, the MSW and biomass still show their application potential in the near future.

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