

Exergetic Comparison of Electrical Heating Gasification and Water Electrolysis Assisted Gasification for Renewable Electricity Storage

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To develop an efficient solution for the storage of renewable electricity and utilization of biomass or waste within the power-to-X concept, the electrical heating gasification (EHG) technology for industrial-scale application was proposed and compared with water electrolysis-assisted gasification (WEG). The two technologies were compared in terms of composition, yield, and exergy efficiency. The results indicate that EHG consumes less electricity and generates syngas with higher chemical exergy. The maximum exergy efficiency of EHG was calculated as 80.76%. Electrical heating gasification is more efficient than WEG based on either the current state or the potential progress in the future. Additionally, the exergy efficiency of water electrolysis ranges between 54.1% and 79.1%, which implies that more efforts are needed in the future to reduce the specific electricity consumption. This work is valuable to guide the development of an electrical heating gasifier and to improve performances of power-to-X technologies.

DOI: 10.15376/biores.17.1.993-1000

Keywords: Gasification; Electrical heating; Water electrolysis; Exergy analysis; Renewable electricity storage

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INTRODUCTION

Renewable electricity storage plays a critical role in maintaining a robust and reliable modern electricity system. Power-to-X is emerging as a viable platform for storing excess renewables. The product X can be syngas, methane, or methanol. The carbon source can be biogas, syngas, or other CO₂ sources extracted from power plants, industrial processes, *etc.* (Bailera *et al.* 2017; Ghaib and Ben-Fares 2018). Biomass is widely available across the world and has less environmental impacts, ensuring that most communities can benefit spatially, financially, and environmentally. Thus, using biomass within power-to-X is of great practical value.

When biomass is used as carbon source, gasification is the key step for sustainable fuels production. The oxygen-steam gasification is commonly integrated to utilize the oxygen generated by water electrolysis (Mesfun *et al.* 2019). The integrated process is named as water electrolysis-assisted gasification (WEG) in this work. However, the energy efficiencies of such electrolyzers varies extensively from 62% to 90% (Schmidt *et al.* 2017; Dawood *et al.* 2020). There is plenty of energy loss during water electrolysis. Thus, the

ways to reduce specific electricity consumption are of great significance for this technical route.

A key to minimizing the amount of required energy is to take full advantage of integrating those unit operations with other processes that are already taking place within the same industrial facilities (Hubbe 2021). With the aim to use biomass for renewable electricity storage, all electricity-driven technologies can be considered for biomass gasification, such as microwave heating (Wang *et al.* 2016), and plasma torch (Rutberg *et al.* 2011; Ram *et al.* 2021), *etc.* Electrical heating technologies are efficient, mature, and have been widely used in various industrial processes. The energy efficiency of ohmic heating and resistance heating can reach 97% and approximately 100%, respectively (Sakr and Liu 2014). Although resistance heating is often used in biomass gasifiers at an experimental scale, there have been few studies on applications of the technologies on biomass gasification on an industrial scale (Zhao *et al.* 2020). Therefore, using electrical heating to drive the biomass gasification process is a potentially promising way to improve energy efficiency. Exergy is defined as the amount of work a system can be perform when it is brought into thermodynamic equilibrium with its environment. As electricity can completely be converted into work, it is reasonable to use the concept of exergy to evaluate such an electricity-driven process.

Motivated by the above analyses, the objective of this work was to evaluate and compare electrical heating gasification with water electrolysis-assisted gasification. The processes are modeled using Aspen Plus software, and the composition, yield, and exergy analysis are investigated. It is expected to offer an alternative and efficient solution for renewable electricity storage and biomass management.

CONFIGURATIONS AND METHODOLOGY

Process Configuration

Figure 1(a) shows the process configuration of WEG. It mainly consists of two parts: water electrolysis (WE) and oxygen-steam gasification (OSG). Dried biomass is converted into producer gas, tars, residual char, and ash *via* gasification process using oxygen and steam as gasifying agents. Then, the producer gas is cooled to ambient temperature and cleaned by the cooling and cleaning unit (CC), where the heat with temperature greater than 80 °C is recovered.

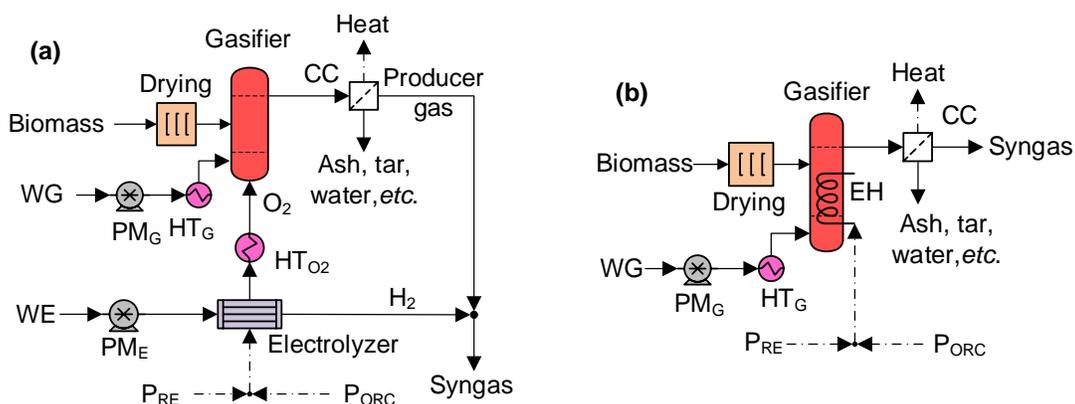


Fig. 1. Process configurations of (a) WEG and (b) EHG

Part of the recovered heat is used for biomass drying and the preheating of gasify agents. The water for gasification (WG) and the oxygen are preheated to 200 °C by the heaters HT_G and HT_{O₂}, respectively. The residual heat is utilized in two ways. The first way is to generate steam at 200 °C; the second way is to generate electricity by the Organic Rankine Cycle (ORC) to compensate partial electricity consumed by the process.

The water electrolysis unit driven by renewable power (P_{RE}) generates oxygen for OSG. The hydrogen generated in this unit is assumed to mix with producer gas to generate syngas in this study. Alternatively, producer gas and H₂ stream can be separately used. Today, the energy efficiencies of various electrolyzers (η_{WE}) range from 62% to 90% based on higher heating value of H₂ (Dawood *et al.* 2020). Thus, η_{WE} over 65 to 95% with the typical value of 85% was investigated as the important variable of WEG. The η_{WE} of 95% was considered for future technical progress.

Figure 1(b) indicates the process configuration of EHG, which is similar to but simpler than that of WEG. Only steam gasification is applied during the EHG process, and the required heat is completely supplied by electrical heating. The electrical heating technology includes various electricity to heat technologies such as resistance heating, arc furnaces, microwave processing, plasma processing, *etc.* (U.S. Department of Energy 2016). This work did not specify the electrical heating technology; instead, the energy efficiency of electricity-to-heat conversion (η_{EH}) over 70 to 99% was investigated as the important variable to represent the theoretical performance of various electrical heating technologies. The typical value of η_{EH} was set to 99% considering the potential application of resistance heating.

Based on previous studies, the gasifier is assumed to be operated at atmospheric pressure, gasification temperature of 800 °C, and a steam/biomass mass ratio of 0.5. In addition, heat dissipation accounts for 3% of input energy of biomass based on lower heating value. The simulations were performed based on the established models including steam gasification and producer gas cooling cleaning, and biomass and power-to-gas processes, including oxygen-steam gasification (Song *et al.* 2013, 2021). Briefly, it was assumed that all reactors are operated under a steady state and that residence times are long enough for the reactions to reach chemical equilibrium. Ash in biomass does not participate in any chemical reactions. The carbon conversion efficiency of the feedstock was 99%. The amount of oxygen for OSG in WEG or the required power for electrical heating in EHG were calculated by the use-defined subroutines *via* Aspen Plus 10.1 (AspenTech, Bedford, MA, U.S.). The net efficiency of ORC was set to 25%. The gasification simulations had been verified in the authors' previous studies (Song *et al.* 2013, 2021).

Exergy Analyses

Wheat straw was the feedstock (Qingdao Product Quality Test Research Center, Qingdao, China). The composition data are listed in Table 1 and the specific chemical exergy of biomass (*SCE*) is calculated to be 17758 kJ/kg on an air-dried basis (Song *et al.* 2012).

Table 1. Composition Data and Specific Chemical Exergy of the Feedstock

Proximate Analysis (wt%)				Ultimate Analysis (wt%)				
Moisture	Fixed Carbon	Volatile Matter	Ash	Carbon	Hydrogen	Nitrogen	Sulfur	Oxygen
5.46	19.42	68.59	6.53	41.99	5.58	0.61	0.28	39.55

Two exergy efficiencies are defined according to the final products. The first is cogeneration of syngas and steam, and the overall exergy efficiency (ε_1 , %) is defined as follows in Eq. 1,

$$\varepsilon_1 = \frac{Ex_{\text{syngas}} + Ex_{\text{steam}}}{Ex_{\text{bio}} + 3.6P_T} \times 100\% \quad (1)$$

where Ex_{syngas} and Ex_{steam} are exergy flow rates of syngas and steam generated by recovered heat, respectively (MJ/h), Ex_{bio} is the exergy flow rate of biomass (MJ/h), and P_T is the total electrical power consumed by the process (kW). Ex_{syngas} is calculated based on the specific chemical exergies of the components in syngas (Song *et al.* 2021).

The second overall exergy efficiency (ε_2 , %) only involves syngas as the final product, and surplus recovered heat is used to generate power by ORC. It is defined as follows in Eq. 2,

$$\varepsilon_2 = \frac{Ex_{\text{syngas}}}{Ex_{\text{bio}} + 3.6(P_T - P_{\text{ORC}})} \quad (2)$$

where P_{ORC} is the power generated by the surplus recovered heat using ORC (kW).

RESULTS AND DISCUSSION

Compositions and Yields

The compositions and yields of WEG and EHG are listed in Table 1. Due to the absence of oxygen, the syngas of EHG had a higher CO content and lower CO₂ content compared with syngas of WEG. Due to the addition of H₂ generated by WE, H₂ concentration in syngas of WEG was higher than that of EHG. The SCE_{syngas} of EHG was still visibly greater than that of WEG, because the total concentration of flammable species in syngas of EHG was higher than that of WEG. Additionally, EHG had a slight disadvantage in syngas yield.

Table 2. Compositions, Yields, and Exergy Efficiencies of WEG and EHG

Syngas	Composition (%)					SCE (MJ/Nm ³)	Yield (Nm ³ /kg _{daf})	ε_1 (%)	ε_2 (%)
	CH ₄	H ₂	CO	CO ₂	N ₂				
WEG	5.43	50.83	26.47	16.87	0.31	10.62	1.822	75.89	73.34
EHG	5.9	46.6	37.35	9.71	0.33	11.68	1.678	80.76	78.90

Exergy Flows and Losses

The exergy flows and losses of WEG and EHG per kg of biomass are as shown in Fig. 2(a) and (b), respectively. With respect to WEG, complex processes take place in OSG, such as oxidation reactions, heat transfers, pyrolysis, and reforming reactions. The exergy loss due to heat dissipation (HD) of the gasifier was 0.34 MJ. The sum of other exergy losses was 3.58 MJ, including intrinsic exergy losses in the gasifier and other auxiliary devices. The exergy efficiency of OSG was approximately 78%. More importantly, the exergy loss in WE was as high as 1.84 MJ, and its exergy efficiency (ε_{WE}) was 70.8%, which was approximately 14% less than η_{WE} (85%). The authors further checked the variation of ε_{WE} with η_{WE} over 65 to 95%. The results show that ε_{WE} sat between 54.1% and 79.1%, and the difference between the exergy and energy efficiencies varied from 10.9 to 15.9 percentage points, which gradually increased with the increase in η_{WE} . These

indicate that when electrolysis of water is evaluated by exergy, more researches should be carried out to improve the efficiency.

Concerning EHG, Fig. 2(b) indicates that the exergy loss in electricity-to-heat conversion was small (0.05 MJ). Other exergy losses of EHG (3.98 MJ) were approximately 0.4 MJ greater than that of WEG. Compared with WEG, EHG consumed less renewable electricity (4.84 MJ) and generated syngas with greater chemical exergy (17.70 MJ). Figure 2 also clearly shows that the water electrolysis process is the main reason causing the difference of the total exergy loss between EHG and WEG.

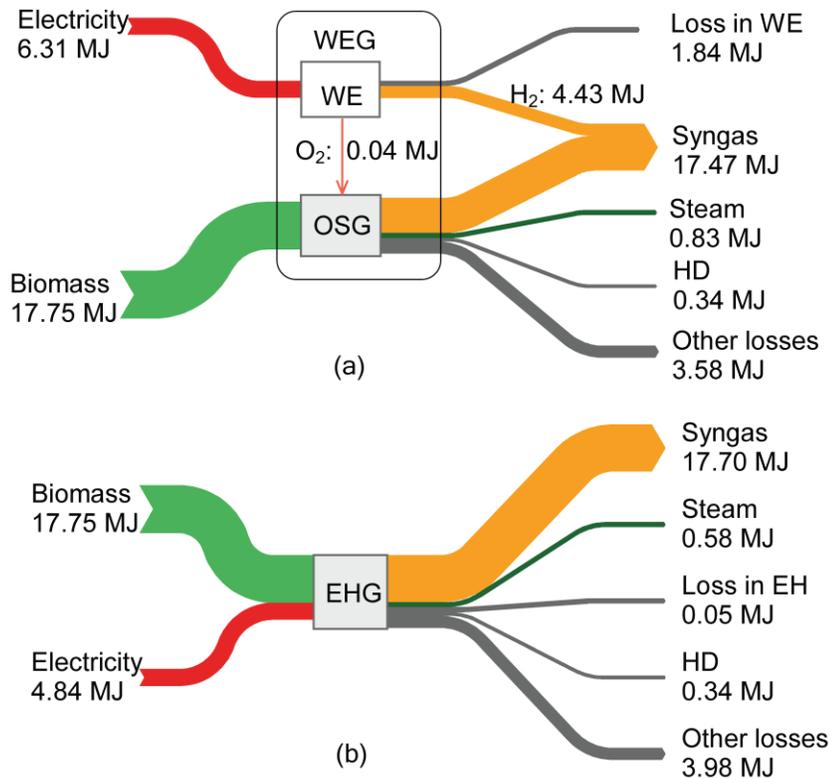


Fig. 2. Exergy flows and losses of (a) WEG with η_{WE} of 85% and (b) EHG with η_{EH} of 99%

Effects of η_{WE} and η_{EH}

Table 2 shows that either ε_1 or ε_2 of WEG at η_{WE} of 85% was approximately 5 percentage points lower than that of EHG at η_{EH} of 99%. Further, Fig. 3 shows that both ε_1 and ε_2 approximately have linear function relation with η_{WE} or η_{EH} . The maximum values of ε_1 and ε_2 of WEG are 78.04% and 75.44%, respectively, while those of EHG are 80.76% and 78.90%, respectively. At the current state and in the near future ($\eta_{WE} \leq 95\%$), when η_{EH} exceeds 87%, $\varepsilon_{1,EHG}$ is always greater than $\varepsilon_{1,WEG}$; while when η_{EH} exceeds 83%, $\varepsilon_{2,EHG}$ is always greater than $\varepsilon_{2,WEG}$. Additionally, $\varepsilon_{1,EHG}$ and $\varepsilon_{2,EHG}$ are on average 2.2 and 2.9 percentage points higher than those of WEG with the same values of η_{WE} and η_{EH} , respectively. It can be inferred that even if η_{WE} could achieve 99%, EHG would still have an obvious advantage over WEG in exergy efficiency. These confirm that electrical heating gasification is an efficient technology within the framework of power-to-X using biomass or wastes as carbon source.

Facing the demand of large-scale renewable power storage via power-to-X pathway, the mature electrical heating technologies can play an alternative and attractive

role in biomass or wastes gasification. Based on the authors' experiences, EHG probably has disadvantages in heat and mass transfers since the radiative heat transfer is the major way and the amount of gasify agent may be not sufficient to enhance the transfers. Additionally, the presence of alkaline ash may pose great challenges to the surface of the electrical heating parts. In the future, the electrical heating gasifier should be comprehensively developed based on the selected electrical heating technology, such as enhancing mass and heat transfers, accelerating reaction rate, high-temperature corrosion and protection, *etc.* It is worth promoting the application of electrical heating gasification within a power-to-X concept.

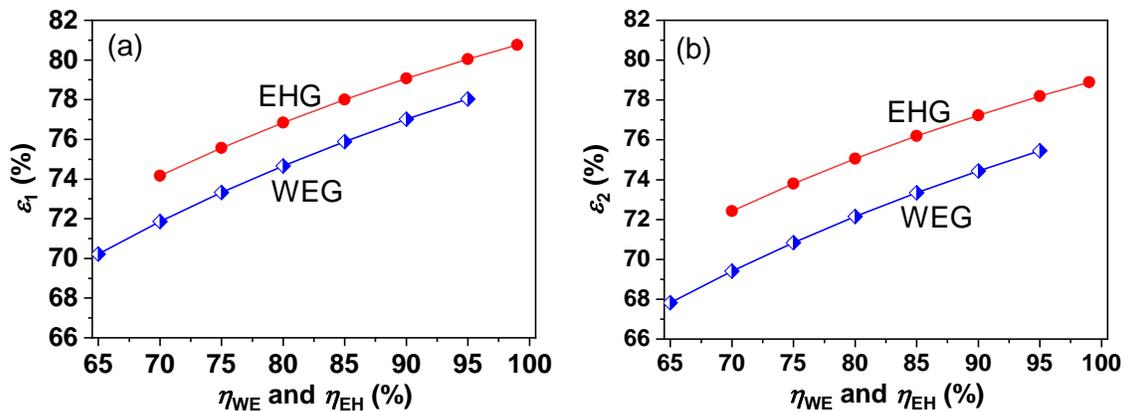


Fig. 3. Variations of (a) ε_1 and (b) ε_2 with η_{WE} and η_{EH}

CONCLUSIONS

1. For the same mass flow rate of feedstock, electrical heating gasification (EHG) consumes less electricity and generates syngas with higher chemical exergy value compared with water electrolysis-assisted gasification (WEG), although the yield of EHG is slightly less.
2. The maximum values of ε_1 and ε_2 of EHG are 80.76% and 78.90%, respectively. When η_{EH} exceeds 87%, exergy efficiency of EHG is always higher than that of WEG under current or future scenarios.
3. The exergy loss in water electrolysis is large and its exergy efficiency ranges from 54.1% to 79.1%. More effects should be made to improve the efficiency of water electrolysis.

ACKNOWLEDGMENTS

This work was financially supported by the Scientific Foundation of Nanjing Institute of Technology (YKJ201818).

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Article submitted: September 4, 2021; Peer review completed: December 11, 2021;
Revised version received and accepted: December 12, 2021; Published: December 16, 2021.

DOI: 10.15376/biores.17.1.993-1000