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Biomass fueled SOFC-Engine combined heat and power system: energy, exergy and thermo-economic evaluations

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ABSTRACT

A novel hybrid system using biomass as fuel for both power and heat generation, which consists of biomass gasification unit, solid oxide fuel cell, homogeneous charge compression ignition engine and waste heat recovery subsystems, is proposed in this work. Based on the thermodynamic modeling, the system is comprehensively evaluated by energy, exergy and thermo-economic analyses. The results show that the proposed hybrid system has an energy conversion efficiency of approximately 68% and the exergy efficiency of 51%, both of which are comparable to other biomass fueled hybrid fuel cell systems reported in literature. The exergy destruction of the gasifier is the largest, whose relative exergy destruction is up to 21.5%. The fuel cell component contributes to 71% of the total power but with small relative exergy destruction. Besides, the specific electric energy cost of the proposed hybrid system is calculated to be 0.054 $/kWh. The payback period and annual return on investment can reach 2.4 year and about 9.83%. These results reveal that the proposed conversion technology of biomass to power is efficient and economical, which could be a promising way for biomass utilization.

Keywords: Biomass gasification, SOFC, Thermodynamic modeling, Thermo-economic analysis

1. INTRODUCTION

With the rapid development of society and economy, human demand for energy is becoming more vigorous. Unfortunately, the reserve of the existing fossil resources is dramatically decreasing by rapidly increasing energy consumption, and the ecological environment is deteriorating accordingly. The resulting energy crisis and environment pollution urgently force the energy structure to be adjusted and optimized [1]. Generally speaking, exploring high-efficiency, low-cost, and clean energy conversion technology with renewable energy as fuel is deemed as the effective approach to alleviate the above-mentioned issues.

The biomass synthesis and utilization processes can achieve carbon dioxide recycling, which helps to reduce carbon dioxide emission effectively and thus mitigates the greenhouse effect. According to the statistical data of "Renewable Energy Medium and Long Term Development Plan" issued by China, biomass resources including forestry, agricultural resources, and urban waste, can be converted into energy with a potential of about 500 million tons of standard coal in China [2]. Biomass gasification (BioG) process could convert biomass into syngas including hydrogen, carbon monoxide, and low molecular hydrocarbons via pyrolysis, oxidation and reduction of reforming reactions with the help of gasification agents, which is the most effective process for the production of hydrogen from biomass. Meanwhile, hydrogen is the most promising energy source for fuel cell (FC). Therefore, the integration of BioG with FC, especially high temperature FC such as solid oxide fuel cell (SOFC), is predicted to be an efficient and clean energy system configuration.

Considering the merits of the integration of biomass gasification and fuel cell, some researchers have studied and evaluated the hybrid system from the perspectives of energy, exergy and exergoeconomic methods. Sigurjonsson et al. [3] proposed a novel concept of biomass-based SOFC polygeneration system in order to deal with intermittent energy sources, such as wind and solar energy. The techno-economic analysis showed that the district heating product is important for economic feasibility of the polygeneration plant. Lorenzo et al. [4] designed an SOFC system fed by syngas from the BioG to produce electric energy and thermal energy in the meanwhile. Then the hybrid system was analyzed from the energy view. It was found that the maximum energy conversion efficiency of the system is 88.9%. Shayan et al. [5] conducted a comparative exergoeconomic evaluation and optimization of biomass fueled SOFC system using steam and air as gasification agents. The results indicated that the steam as gasification agent helps to increase the net output power by 14.8%, the exergy efficiency by 24.9%, and reduce the unit product cost by 8.9% at the optimal operating conditions compared with air counterpart. Gadsbøll et al. [6] experimentally investigated the power plant consisting the SOFC and BioG, whose biomass to electricity efficiency is 43%.

The above-mentioned reports confirm that the BioG-SOFC hybrid power system is a feasible and promising energy conversion technology. However, it should be noted that the off gas from the SOFC still has a certain amount of heat and chemical energy that can be utilized to further improve the energy conversion efficiency of hybrid system. In fact, there have been some literatures investigated the topic on how to recycle the energy of SOFC off-gas by gas turbine or external engine efficiently [7, 8]. Compared with gas turbine (GT), the internal combustion (IC) engine generally has a smaller power capacity, which is more comparable to the SOFC power capacity. Besides, the IC engine is more stable in harsher environments. Therefore, using the IC engine recycling the thermal and chemical energy of SOFC off-gas is more suitable. In addition, some literatures have reported the relevant research and analysis of SOFC-Engine hybrid system in recent years [9, 10].

Based on the above analysis and discussion, a novel biomass-fueled hybrid power system including BioG, SOFC, engine, and waste heat recovery (WHR) subsystems is proposed and modeled in this work. Then, the proposed system is comprehensively investigated by energy, exergy, thermos-economic analyses, thus to evaluate its technical and economic feasibility as advanced energy conversion device in practical applications.

2. SYSTEM DESCRIPTION

Fig. 1 illustrates the schematic diagram of the proposed BioG-SOFC-Engine-WHR hybrid power generation system, which consists of the four subsystems including BioG, reformer SOFC, homogeneous charge compression ignition (HCCI) engine and WHR. HCCI is a kind of combustion mode for the engine, which enables to make the best use of the lean fuel for combustion. The off-gas from SOFC is a kind of thin fuel in fact, which can been better used by HCCI engine. The BioG subsystem, as the system fuel generator, aims to produce syngas for the reformer SOFC and HCCI engine subsystems to generate power. The reformer SOFC subsystem contributes to most of the electricity for the hybrid system and meanwhile produces the combustible fuel for the downstream engine via steam reforming and water gas shift reaction. The role of the HCCI engine subsystem is to make full use of the SOFC off-gas for additional power generation, thus to improving energy conversion efficiency of the hybrid system. Herein, the WHR subsystem is employed to recycle the waste heat of the main components SOFC and HCCI engine through heat exchangers and waste heat collector.

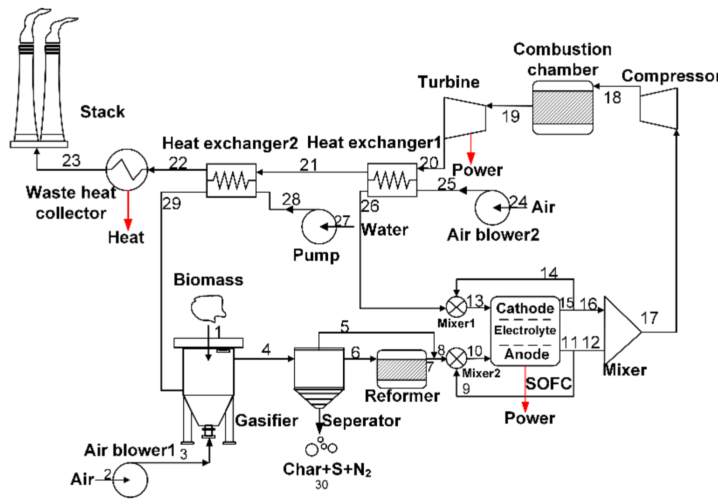

Fig. 1. Schematic diagram of the proposed BioG-SOFC HCCI engine-WHR system using biomass as fuel

3. SYSTEM MODELING

3.1 Model assumptions

Some basic assumptions are considered to simplify the modeling and analysis:

1) The molar composition of air is comprised of 79% N_2 and 21% O_2.

2) The system is in a steady-state operation and thermodynamic equilibrium.

4) The system is assumed to be insulated well so that the heat loss from equipment to environment is negligible.

5) The gas flow resistance and pressure drop in the system are neglected [11].

6) All the gases involved in the overall model obey Peng-Robinson equation of state [12].

3.2 Thermodynamic model

The thermodynamic model of the proposed BioG-SOFC-HCCI engine-WHR hybrid system is developed by Aspen Plus. Some relative complex components such as SOFC and biomass gasifier are modeled by Aspen blocks embed FORTRAN language.

- Biomass gasifier subsystem

This work employed the rice straw of Jiangsu province of China as biomass sample. The proximate and the ultimate analyses of the employed biomass are shown in Table 1 [13].

Table 1. The proximate and the ultimate analyses of the discussed rice straw biomass

Proximate analysis (wt. %)		Ultimate analysis (wt. %)	
Moisture	9.1	C	35.37
Fixed carbon	16.75	H	4.82
Volatile	63.69	O	39.15
Ash	10.46	N	0.96
LHV(MJ/kg)*	14.4	S	0.14

*LHV is Low heating value for biomass

Because biomass gasification is a complex chemical reaction process, which is simulated by using a stoichiometric reactor and a Gibbs reactor. Firstly, the stoichiometric reactor converts all elements of biomass except ash into basic elements. The process can be described by Eq. (1). Then these substances are fed into Gibbs reactor. When the reactor reaches the minimum Gibbs free energy, the composition of gasified gas is regarded to be in theoretical balance.

$$CH_xO_yN_zS_w \rightarrow C + \frac{x}{2}H_2 + \frac{y}{2}O_2 + \frac{z}{2}N_2 + wS \quad (1)$$

where $CH_xO_yN_zS_w$ is the chemical formula of rice straw biomass which can be calculated by Table 1.

- Reformer SOFC subsystem

Methane reforming reaction (MSW) and water gas shift (WGS) reaction occurring in the reformer can be described by the following Eqs. (2) and (3).

MSR: $CH_4 + H_2O \rightarrow CO + 3H_2 \quad \Delta H = 206\ \text{kJ/mol}$ (2)

WGS: $CO + H_2O \rightarrow CO_2 + H_2 \quad \Delta H = -41\ \text{kJ/mol}$ (3)

The corresponding heat generated by the SOFC can be calculated by Eq. (4), in which Δ*H* and *E* are the electrochemical enthalpy and electromotive force, respectively.

$$\Delta H = -nFE + nFT\left(\frac{\partial E}{\partial T}\right)_p \quad (4)$$

The relationship between the actual output voltage *V* and the polarization voltage of SOFC can be described by Eq. (5), where V_{re} is ideal reversible voltage, and can be calculated by Nernst equation as shown in Eq. (6).

$$V = V_{re} - V_{act} - V_{conc} - V_{ohm} \quad (5)$$

$$V_r = E_r^{\theta} - \frac{RT}{4F}\ln\frac{p_{H_2O}^2 p_0}{p_{H_2}^2 p_{O_2}} \quad (6)$$

where V_{act}, V_{conc} and V_{ohm} are activation, concentration overvoltage and ohm overvoltage, E_r^{θ} is standard voltage of SOFC, *R* is ideal gas constant, *p* is partial pressure of gas, p_0 is standard atmospheric pressure.

The current density of SOFC can be described according to Eq. (7).

$$J = \frac{I}{NA_c} = \frac{2\cdot\mu\cdot F\cdot\phi_{H_2}}{NA_c} \quad (7)$$

where μ is fuel utilization factor, φ_{H2} is molar flow of hydrogen fed into SOFC, *N* is the number of single cell, A_c is the area of single cell.

The output power of SOFC can be calculated by Eq. (8).

$$\dot{W}_{SOFC} = \eta\cdot I\cdot V = 2\eta\cdot\mu\cdot F\cdot\phi_{H_2}\cdot V \quad (8)$$

where η is efficiency of DC/AC inverter.

3.3 Thermo-economic model

The capital investment cost of each component is allocated averagely on an annual basis. The annual cost of the hybrid system includes the following parts: depreciation cost $\dot{C}_{dep}$, maintenance cost $\dot{C}_{mai}$, the annual interest on investment $\dot{C}_{int}$, the annual insurance $\dot{C}_{ins}$, operation cost $\dot{C}_{ope}$ and tax cost $\dot{C}_{tax}$. The meaning and equation of each annual cost can refer to [14]. The economic evaluating index, specific electric energy cost (SEEC), is proposed in Eq. (9) to estimate the economy of the hybrid system. The payback period (PP) is defined as the time required for the system to earn a profit exactly equal to the components total investment cost, as shown in Eq. (10). The return on investment (ROI) is defined as Eq. (11).

$$\text{SEEC} = \frac{\dot{C}_{dep} + \dot{C}_{ope} + \dot{C}_{mai} + \dot{C}_{int} + \dot{C}_{ins} + \dot{C}_{tax}}{(W_{SOFC} + W_{Engine})\cdot N_h} \quad (9)$$

$$\text{PP} = \frac{\text{Total components investment}}{(\text{SEEC-OGEP})\cdot\dot{W}} \quad (10)$$

$$\text{ROI} = \frac{\text{OGEP-SEEC}}{\text{SEEC}\cdot N_h\cdot\lambda} \quad (11)$$

where OGEP is on-grid electricity price, N_h is operation hours annual, W is system output electrical power, λ is system life cycle, 10 years.

3.4 Performance evaluation criteria

- The gross electrical efficiency:

$$\eta_1 = \frac{\dot{W}_{\mathrm{SOFC}} + \dot{W}_{\mathrm{HCCI}}}{\dot{m}_f \cdot LHV_f} \tag{12}$$

- The net electrical efficiency:

$$\eta_2 = \frac{\dot{W}_{\mathrm{SOFC}} + \dot{W}_{\mathrm{HCCI}} - \dot{W}_{\mathrm{AB1}} - \dot{W}_{\mathrm{AB2}} - \dot{W}_{\mathrm{pump}}}{\dot{m}_f \cdot LHV_f} \tag{13}$$

- The overall energy conversion efficiency:

$$\eta_3 = \frac{\dot{W}_{\mathrm{SOFC}} + \dot{W}_{\mathrm{HCCI}} - \dot{W}_{\mathrm{AB1}} - \dot{W}_{\mathrm{AB2}} - \dot{W}_{\mathrm{pump}} + \dot{Q}}{\dot{m}_f \cdot LHV_f} \tag{14}$$

- The exergy efficiency:

$$\eta_{\mathrm{ex}} = \frac{\dot{W}_{\mathrm{SOFC}} + \dot{W}_{\mathrm{HCCI}} - \dot{W}_{\mathrm{AB1}} - \dot{W}_{\mathrm{AB2}} - \dot{W}_{\mathrm{pump}} + \dot{E}x_{\dot{Q}}}{\dot{E}x_1 + \dot{E}x_2 + \dot{E}x_{24} + \dot{E}x_{27}} \tag{15}$$

4. RESULTS AND DISCUSSION

4.1 Energy analysis

The energy performance of the proposed hybrid system is predicted under the fixed biomass mass flux $\dot{m}_{\mathrm{bio}} = 500$ kg/h in this work. Table 2 lists the energy performance of the hybrid system, which could generate the electric power of 1078.4 kW and heat power of 359.1 kW. In fact, the expansion stroke of the burning gas can produce 1313 kW power, but it also consumes compression work of 998 kW before the combustion process of engine. Therefore, the net power output of the engine is 314 kW. In this case, the energy conversion efficiency of individual component SOFC and HCCI engine is approximately 38.2% and 15.7%, respectively. The gross power efficiency η_1, net power efficiency η_2 and overall energy conversion efficiency η_3 of the system are calculated as 54%, 50%, and 68%, respectively.

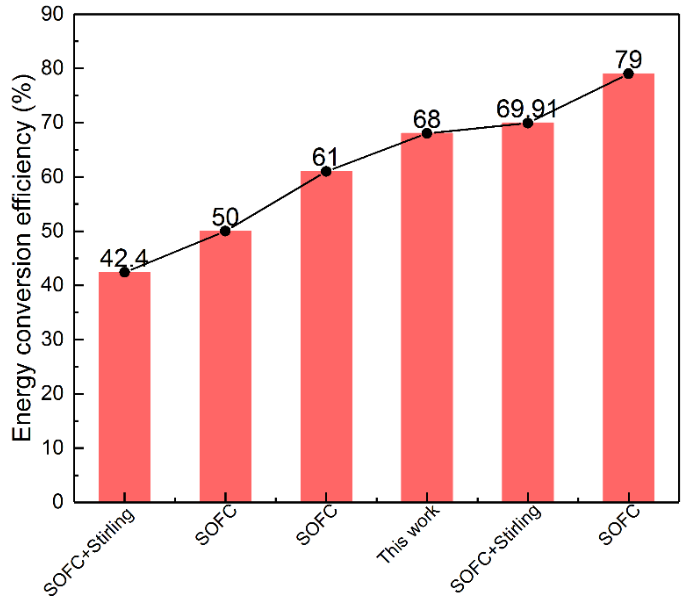

Fig. 2. The comparison of energy conversion efficiency of various biomass fueled FC systems

This work also compares the energy conversion efficiency of the proposed biomass fueled SOFC-HCCI engine hybrid system with other biomass fueled hybrid FC power systems such as simple SOFC, SOFC-Stirling engine illustrated in Fig.2. The comparison shows that the energy efficiency of this hybrid power system is comparable to those biomass fueled FC hybrid system reported in literature.

Table 2 The energy performance of the hybrid system

Parameter	Input energy (kW)	Total electric power generation (kW)				Heat power (kW)	Auxiliary power (kW)	Efficiency		
		SOFC	HCCI engine							
			Net power	Gross power	Compression power			η_1	η_2	η_3
Value	2000	764.4	314	1313	998	359.1	83	54%	50%	68%

4.2 Exergy analysis

The energy analysis only describes the energy flow of the hybrid system, which cannot give the irreversible exergy destruction during the energy conversion process. Therefore, it is essential to develop the exergy model of the proposed hybrid system based on the second law of thermodynamics. The exergy destruction of components are calculated and illustrated in Fig. 3. Herein, the exergy destruction of individual component is ranked in sequential increase from left to right. It can be seen that the overall exergy flow destruction of the proposed hybrid system is 1095.8 kW. The exergy efficiency is calculated to be 51%, which is a little lower than energy efficiency because of the consideration of irreversibility of energy conversion. The exergy destructions of the BioG, reformer SOFC, HCCI engine, and WHR subsystems are 381.5 kW, 82.6 kW, 178.3 kW, and 453.4 kW, which account for 34.82%, 7.54%, 16.26%, and 41.37% of the total exergy destruction, respectively.

The power ratio of engine to the whole hybrid system is about 0.3, which is thought to be relatively low. Nevertheless, the exergy destruction of the HCCI engine subsystem is 2.1 times that of the SOFC subsystem. This is mainly because the combustion reaction with large heat loss occurs inside the engine while the electrochemical reaction with waste heat recovery takes place inside the SOFC. Therefore, it could be concluded that the HCCI engine has a small contribution to the power generation but exhibits a large exergy destruction in the hybrid system.

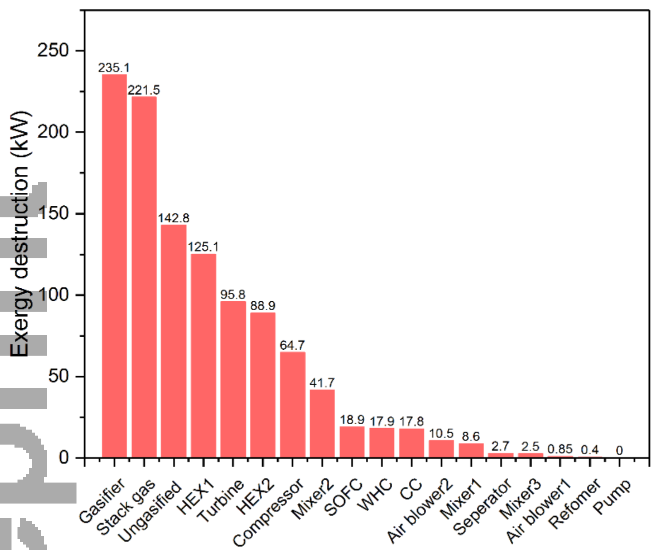

Fig. 3. The exergy destruction of the components in the proposed hybrid system

4.3 Thermo-economic analysis

The thermo-economic analysis is performed according to the same operation conditions of "Energy analysis". The SEEC of the biomass-fueled SOFC-HCCI engine hybrid system at the life cycle of 10 year is found to be 0.054 $/kWh when the biomass price is 0.05 $/MJ [15]. In China, the present on-grid electricity price of agroforestry biomass power generation is 0.75 CNY/kWh. In this case, the payback period of this system is calculated to be 2.4 years and annual RO is 9.83%. The results of payback period and ROI further confirm that the proposed biomass-fed SOFC-HCCI engine hybrid power generation system is economically feasible for the practical application.

The annual cost of the biomass fueled SOFC-HCCI engine hybrid system is related to the capital cost of each component. The components cost comparison of the biomass fueled SOFC-HCCI engine hybrid system and their cost contribution are demonstrated in Fig. 4. The total capital investment cost of the hybrid system is approximately 1017.7 k$, mainly consisting of 674.7 k$ for the SOFC, 64.6 k$ for the heat exchangers, 12.29 k$ for the engine, and 96.53 k$ for the gasifier.

Fig 5 illustrates the compositions of the annual cost of this hybrid engine system and their cost distribution. In the thermo-economic model, the annual cost consists of six parts. The largest annual cost is the operation cost of about 288 k$, accounting for 66.8% of the total annual cost, which is due to a large amount of biomass consumed in the hybrid system. The second largest annual cost is the depreciation cost of about 101.77 k$, which accounts for 23.6% of the total annual cost. The annual depreciation cost represents the total capital investment cost of the components. The remaining four parts of the annual cost contribute to approximately 9.6% in all. Therefore, the additional cost such as taxation fee, interest fee and maintenance fee should be

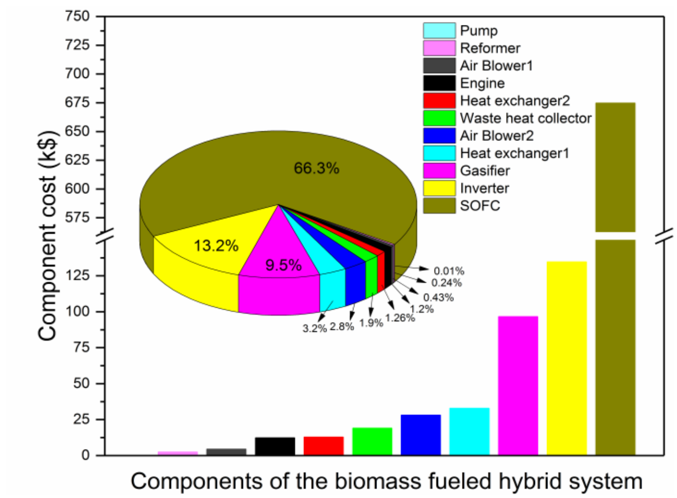

Fig. 4. The components cost comparison of the hybrid system

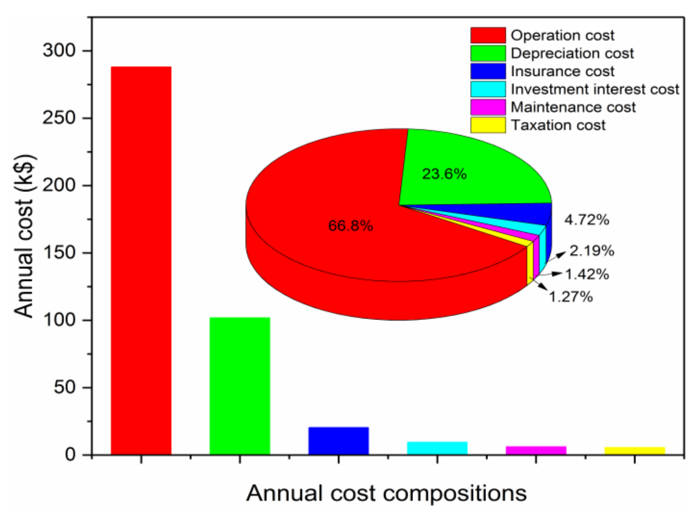

Fig. 5. The annual cost comparison of the hybrid system

considered for thermo-economic evaluation of the hybrid system.

5. CONCLUSION

In this work, a novel biomass fueled SOFC-HCCI engine hybrid system is proposed and modeled by Aspen Plus. The thermodynamic and thermo-economic analyses are performed to evaluate and optimize the performance of the hybrid system. The following conclusions can be drawn as below.

1) The energy conversion efficiency of the hybrid system with the SOFC power of 764.4 kW and the engine power of 314 kW. The energy conversion efficiency is 68%, which comparable with other biomass fueled system reported in literature.
2) The exergy efficiency of the hybrid system is 51%, lower than the energy efficiency. The component with the largest exergy destruction is gasifier whose relative exergy destruction is 21.5%. By comparison, the SOFC component has much smaller relative exergy destruction, which is 1.7% only.
3) The specific electric energy cost of the hybrid system is calculated to be 0.05 $/kWh. The payback period and annual return on investment can reach 2.4 year and about 9.83%. The results reveal that the proposed conversion technology of biomass to power is economical.

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