Chapter

Chemical Looping Combustion Power Generation System for a Power-to-Gas Scheme

Muhammad W. Ajiwibowo, Arif Darmawan and Muhammad Aziz

Abstract

Renewable energy provides a quick win solution for global warming, but it comes with drawbacks. Renewable sources such as solar and wind are not available for continuous use; thus, intermittency of electric power generation is an issue. Fluctuation of electricity production could damage the grid. Throughout the years, researchers have come up with solutions to solve this problem by storing the excess electricity via an energy storage system. One of the most efficient options is through solid oxide electrolysis cell (SOEC) to produce H_2. In itself, H_2 contains a lot of energy and can be converted to electricity via combustion or fuel cell. Therefore, storing electricity in the form of H_2 could prove to be effective. Energy storage systems such as power-to-gas may provide a clean and efficient way to store the overproduced electricity. In this work, a power-to-gas system coupled with a chemical looping combustion combined-cycle system is proposed to provide base and intermediate load power from the unused electricity from the grid. Enhanced process integration was employed to achieve optimal heat and exergy recovery. This chapter focuses on the design of a system consisting of a power-to-gas conversion method and a H_2-powered chemical looping combustion power generation system.

Keywords: chemical looping combustion, solid oxide electrolysis cell, system modeling, power to gas

1. Introduction

Combustion of fossil energy sources for industrial processes around the world contributes massively to the creation of greenhouse gases (GHG) and mainly CO_2. This has been a major problem worldwide as it directly increases the pollution level and the likelihood of the earth's increase in temperature. This led the international community to investigate ways to prevent this phenomenon [1]. Besides, fossil fuels are inevitably bound to be depleted in the future [2]. As of right now, as much as 84% of the world energy consumption is still fossil fuel driven, less than what the previous year had (85%); even so, it is still very high. Without a radical transformation, fossil fuel will still be the majority of energy source in the foreseeable future. This condition necessitates scientists and engineers to provide a sound solution. Efforts to reduce the fossil fuel usage and transition to sustainable energy sources remain a challenge for scientists and engineers alike. Alternative renewable and clean energy technologies are actively being developed now [3, 4]. Fossil fuel combustion for power generation and industrial processes around the world is a key contributor to CO_2 emissions and had caused the earth's temperature to increase ever since the industrial revolution. This brought the international community to implement emission regulations and policies to mitigate GHG effect on the earth while transitioning to sustainable alternatives to fossil fuels [1]. This is also supported by the fact that fossil fuel reserves are depleting due to massive use around the world [2]. Right now, as much as 84% of the world energy consumption is still derived from fossil fuels, which is less than what the previous year had (85%). Without a radical change, fossil fuel will still be the key energy source in the foreseeable future. Thus, efforts to reduce the fossil fuel usage and transition to sustainable energy sources remain a big challenge. Alternative renewable and clean energy technologies are actively being developed now [3, 4].

It is widely agreed and practiced that the conversion of fossil fuels into energy is mainly through combustion. It is an extremely efficient process and very mature in terms of technology. Its development dates back to the seventeenth century when the first steam engine was introduced. Regardless of its convenience now, combustion processes release lots of GHG and harmful gases (e.g., CO_2, SO_x, NO_x). Even so, combustion technologies will still thrive as a primary contributor to the world's power generation. This necessitates scientists to develop a combustion method that is also environmentally friendly. Many research and development efforts have been put into finding new combustion methods. One of the major drawbacks of traditional method for combustion utilizes air, where, upon reaction, NO_x and sometimes SO_x will form and will potentially cause health indications if inhaled over time. One of the most promising solutions for a clean combustion process is to react the fuel directly with pure oxygen, or simply called oxy-combustion. This method will only generate CO_2 and H_2O emissions. Although being clean and efficient, the drawback of this process is that it requires prior separation of oxygen from the air in the atmosphere, which directly increases cost and efficiency penalty for the power plant.

Moreover, one similar solution, the emission could just be removed completely if renewable energy is used. Even so, the drawback of renewable energy usage is the intermittency of its production. Thus, the development of renewable energy systems throughout the years has generated a new interest in energy storage technologies. It is a dominant contributor in a renewable energy system. Despite being sustainable and clean, it has been reported that the use of renewable energies from solar and wind power sources has caused burdens to the electricity grid. Energy storage technologies include H_2, batteries, flywheels, compressed air, ultracapacitors, pumped hydro, and compressed gas [5]. Energy storage could mitigate power variations, enhance the system's flexibility, and provide a scheme where surplus electricity from the grid could be stored and dispatched on demand [6].

Driven by the same problem, overproduction of electricity is also being demonstrated in Indonesia where renewable energy is not widely available yet. Heavily reliant on fossil fuels, the country consumes as much as 87.5% of all its power generation right now [7, 8]. Furthermore, according to the National Electricity Company in Indonesia (PLN), by default, Java-Bali sector of Indonesia's power generation generates as much as 6000 MWe excess electricity production, which is wasted due to lack of energy demand. Likewise, this indicates a strong need for energy storage option. It is widely considered that the conversion of fossil fuels into energy is mainly through combustion. The development of combustion processes for power dates back to the seventeenth century when the steam engine was first founded. With all its convenient characteristics, combustion process releases lots of GHG and harmful gases (e.g., CO_2, SO_x, NO_x). Seeing that combustion technologies will remain as a primary contributor to the world's power generation, many research and developments have been put into finding new combustion methods. One of the promising ideas for clean combustion is to react the fuel directly with pure oxygen, or simply called oxy-combustion. This method will only generate CO_2 and H_2O emissions. Although being clean and efficient, this method requires prior separation of oxygen from the atmospheric air, which may increase cost and cause efficiency penalty for the power plant.

Moreover, the GHG emission could just be removed completely if renewable energy is used. The development of renewable energy systems throughout the years have generated a new interest in energy storage technologies. It is a dominant contributor in a renewable energy system. Despite being renewable and clean, it has been reported that the use of renewable energies from solar and wind power sources have caused burdens to the electricity grid. Energy storage technologies include H_2, batteries, flywheels, compressed air, ultracapacitors, pumped hydro, and compressed gas [5]. Energy storage could mitigate power fluctuations, enhances the system's flexibility and provides a scheme where surplus electricity from the grid could be stored and dispatched on demand [6].

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1.1 Hydrogen production and utilization

Hydrogen as an alternative energy source is predicted to have a powerful role in the low-carbon future [9]. It is long recognized as a sustainable fuel due to its favorable characteristics [10]. Besides that, hydrogen is greatly abundant on earth, albeit in its oxidized state (H_2O) [11]. Presently, H_2 is commercially produced using reforming technologies on hydrocarbon fuels. Researches for the production of H_2 have been a great interest for a long time. The routes to produce H_2 vary from chemically to electrochemically. Chemically, supercritical water gasification (SCWG) of biomass and syngas chemical looping (SCL) are among the most efficient ways to produce hydrogen [11, 12]. Compared to other types of gasification, SCWG utilizes more steam, thus promoting more reforming of the gases to produce H_2.

Moreover, from the electrochemical routes, many types of water electrolysis are considered to be effective for H_2 production by splitting water. Proton-exchange membrane (PEM) electrolysis and alkaline water electrolysis are the most used technology due to their maturity [13]. Typically, PEM electrolysis and alkaline water electrolysis have energy efficiencies of around 50–80%. Furthermore, solid oxide electrolysis cell (SOEC) is another type of electrolysis method that utilizes a high temperature of around 750–1000°C and 10–15 bar of pressure [14]. In higher temperatures, higher efficiency could be achieved due to smaller energy requirements.

The utilization of H_2 also varies from just energy storage to electric power production. Various H_2 energy conversion technologies are already generally understood, and many are already under commercial real-world developments

[10]. Fuel cells are among the best and are among the most efficient ways for energy conversion from H_2 for electric power production [15]. Integration of fuel cells with other technologies remains a challenging puzzle. Various integrations of fuel cell and other systems are currently being investigated [16]. Generally, fuel cell is very versatile in terms of fuel types and various operating conditions. Nevertheless, one of the major drawbacks of fuel cell is that the membrane used in the cells may have a relatively short lifetime and, hence, could potentially add costs to fuel cell systems.

Numerous efforts have been made to integrate fuel cells, especially SOEC with other energy conversion technologies. Cinti et al. proposed and investigated an integrated SOEC and Fischer-Tropsch system to produce methane from surplus renewable energy [17]. Energy and exergy evaluation of an SOEC-methanation system is also evaluated by Luo et al. [18]. Kezibri et al. also modeled a power-to-gas system for oxy-combustion power generation [19]. But they utilized and considered a proton-exchange membrane-based electrolyzer, which is heavily reliant on the membrane and did not further evaluate the possibilities of system and heat integration. All these efforts can prove high potential of hydrogen energy utilization in the future. Unfortunately, there is still no significant effort made to provide an efficient energy system utilizing SOEC technology for hydrogen and, subsequently, power.

1.2 Chemical looping combustion power system

Chemical looping combustion (CLC) is a new and leading-edge energy conversion method that utilizes metal oxides or otherwise called oxygen carriers to oxidize the fuel instead of atmospheric air. It uses two reactors, namely, the reducer and the oxidizer. Mixtures of metal oxide and some inert solids for heat dilution are being circulated throughout these two reactors. The process starts when fuel is oxidized in the reducer reactor; afterwards, the reduced metal oxide will be re-oxidized by air in the oxidizer while also generating heat in the process. These processes are being repeated in a looping fashion. There have been many reports on the use of various types of fuels, including hydrocarbon and biomass. Typically, exhaust gas containing CO_2 and H_2O will be generated from the fuel oxidation, and CO_2 will be easily separated by condensation. Inherent CO_2 separation and storage are possible in this system due to the separate combustion processes. Furthermore, if H_2 is used, the combustion product will be just H_2O. Thus, this combustion technology has a high potential as a zero emission power generation system due to its favorable characteristics, namely, the inherent separation capability for CO_2. As a comparison, this system could achieve the same advantage that an oxy-combustion power plant has without the need to separate air first with an air separator unit (ASU).

Thus, this paper tries to focus on the effort to propose an efficient energy system which comprises of SOEC and chemical looping combustion (CLC) combined cycle power generation to produce baseload power from hydrogen as a sustainable zero emission energy source. The produced H_2 is fed to the CLC power generation system where it is mixed with natural gas. This way, environmental burden caused by GHG can be decreased as we are producing less CO_2 compared to traditional natural gas-fired power generation system. Detailed process integration and the calculation are discussed in Sections 2 and 3. Besides that, parameters and operation conditions are evaluated to further improve the system's energy conversion efficiency and its key design parameters.

This paper focuses on the effort to propose an efficient energy system that comprises of SOEC and chemical looping combustion (CLC) combined cycle power generation to produce base and intermediate loads power from both natural gas and renewable energy-based hydrogen. The produced H_2 from renewable energy source is fed to the CLC power generation system where it is mixed with natural gas. By this way, environmental burden caused by GHG can be decreased as the process is producing less CO_2 compared to traditional natural gas fired power generation system. In addition, the inherent fluctuation characteristic of renewable energy can be stabilized, producing a stable and reliable power generation to the grid. Detailed process integration and the calculation is discussed in Sections 2 and 3. Besides that, parameters and operation conditions are evaluated to further improve the system's energy conversion efficiency and its key design parameters.

2. Proposed integrated system

2.1 Integrated SOEC and chemical looping combustion power generation system

Figure 1 depicts a simplified process flow diagram for the proposed system. The system itself consists of an SOEC as the H_2 producer module and a chemical looping combustion combined cycle (CLCCC) as an electric power generation module. Theoretically, the CLCCC could act as the main electric power generator providing a stable electrical power output that is suitable for base and intermediate loads. The CO_2 emitted from the combustion process is basically separated. This leads to low CO_2 emission and potentially zero CO_2 emission if H_2 is used. For this system, a dual fuel system is considered where natural gas is considered, while the H_2 produced from the electricity from renewable energy sources or surplus electricity from the grid becomes additional fuel. Theoretically, the produced H_2 is consumed without being stored; therefore, the flow of natural gas to CLCCC decreases accordingly. Although, a storage infrastructure could also be considered for H_2 in such system, it is not considered for this study. Hence, the generated electric power from the system is assumed stable, without being influenced by the fluctuation that comes with renewable energy sources and grid surplus electricity.

Overall, surplus electricity from the grid is used to convert H_2O into H_2 and O_2 via the SOEC process. Afterwards, as described in the previous part, the H_2 is directed and fed directly to the CLCCC module. On the other hand, additional O_2 is also being fed into the CLCCC power system along with air, which potentially leads to higher combustion temperature. **Table 1** describes the main assumptions and parameters used for the developed CLCCC system.

In order to achieve highest energy efficiency for the system, enhanced process integration methodology is utilized. This approach primarily focuses on heat and exergy recovery in the system via heat exchanger integration and compression [20, 21].

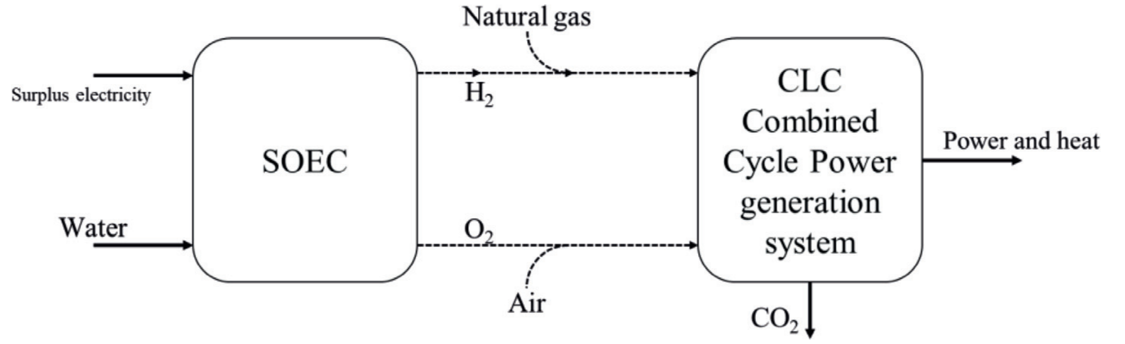

Figure 1.
General overview of the integrated system.

Component/system	Unit	Value
Solid composition		70% metal oxide
		15% SiC
		15% Al_2O_3
Generator efficiency	%	98
Compressor isentropic efficiency	%	90
Turbine isentropic efficiency	%	90
Fuel flow rate	kg/s	6
OT inlet temperature	°C	1400
RT inlet temperature	°C	800–900
ST inlet temperature	°C	700
Operating pressure	Bar	15–35
ST inlet pressure	Bar	250

Table 1.
Details on the parameters and assumptions used in the CLCCC.

Waste heat from hot downstream processes is utilized to support the heat requirements of upstream processes recuperatively. Exergy is also elevated in cold streams via compression. It is a proven methodology that has been demonstrated by various works for producing electricity or hydrogen from various sustainable sources, especially biomass [9, 11, 22].

Basically, the CLCCC is somewhat similar to a traditional combined cycle with a gas turbine, but the combustor in such system is replaced by two chemical looping combustion reactors that act as the heat source for the downstream turbines. As opposed to the traditional method, the produced fuel gas that is rich in CO_2 could be directly separated as it does not produce other by-products except CO_2 and H_2O. Thus, the separation of CO_2 is significantly less energy intensive than the traditional separation method. The schematic diagram of CLCCC is shown in **Figure 2**. In a dual fuel scenario, H_2 and CH_4 (natural gas) are considered to be fuels for this system, with the key assumption of a reactor design that would support the use of these two fuels. Two fuel gas streams coming out of the CLC process, namely, the reducer gas and the oxidizer gas, are expanded via the reducer turbine (RT) and the oxidizer turbine (OT). Afterwards, the CO_2-rich stream leaving the RT is directly separated by condensation and then compressed and stored. On

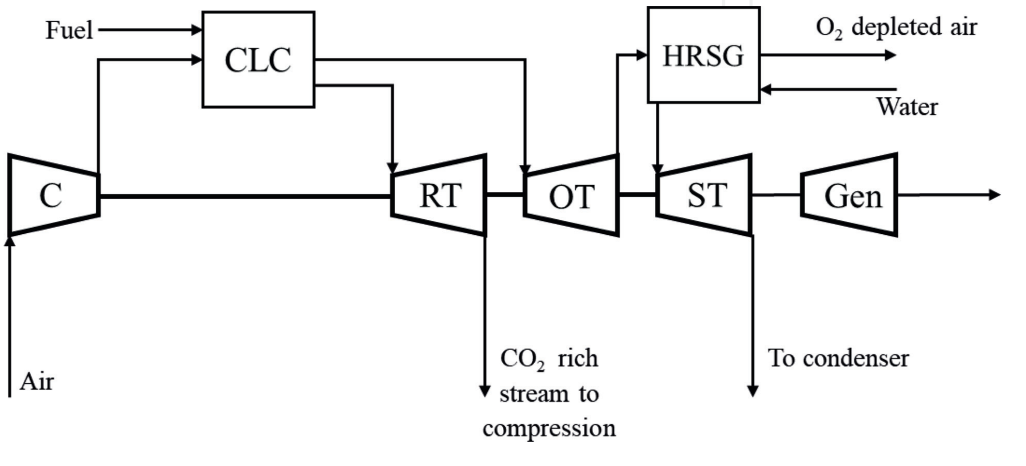

Figure 2.
CLCCC power generation system.

Component/system	Unit	Value
Power input	MW	350
Produced hydrogen	Nm^3/h	87,803
Produced oxygen	Nm^3/h	43,901
Operating temperature	°C	750
Operating pressure	Bar	10
Efficiency	%	88

Table 2.
Assumptions for the SOEC used in the model.

the other hand, the high-temperature gas leaving the OT is used to generate steam for generating more power via a steam cycle.

2.2 Solid oxide electrolysis cell for H_2 production

As discussed in the previous section, SOEC is regarded as one of the most efficient electrolysis processes to produce pure H_2 [23]. For the purpose of this study, SOEC is considered favorable if it is used for power-to-gas energy storage. In this case, the input electricity used for the SOEC is the surplus electricity from the grid (especially due to surplus from renewable energies) or directly from renewable energy sources. Afterwards, the generated H_2 will be stored temporarily or can be directly integrated with the CLCCC system described before. The SOEC parameters in this study are based on the research conducted by Udagawa et al. [23]. The detailed parameters are provided in **Table 2**.

3. Process modeling and calculation

For the purpose of system, mass, and energy balance simulation, ASPEN Plus V8.8 from Aspen Technology, Inc., is utilized in this study. Key assumptions made for this model are listed in **Table 1** that are primarily taken from other experimental and numerical researches. The operating conditions are chosen based on other literatures [23–25]. Key thermodynamic assumptions are as follows: (i) ambient temperature is set to 27 °C; (ii) no heat loss is assumed; and (iii) air is assumed to contain 79% mol N_2 and 21% mol O_2. RStoic reactor blocks are used to model the reducer and oxidizer reactors in ASPEN Plus. Simplistically, in the reducer, the metal oxides will be reduced by the fuels, which are H_2 and CH_4, and then circulated to the oxidizer where it is re-oxidized by air. The operating reactors are assumed to be an entrained flow type for the oxidizer, and a moving bed type is used for the reducer.

To identify different parameters used in this study, three types of metal oxides are evaluated for the CLCCC process. Two of the most studied oxygen carriers, nickel oxide (NiO) and iron oxide (Fe_2O_3), are each utilized for the CLCCC process. Additionally, $CaSO_4$, also known as gypsum, is also utilized and evaluated in this study due to recent interests for this material as an oxygen carrier due to its favorable chemical characteristics [26]. All of these metal oxides have many distinctive characteristics, such as resistance to elevated temperatures, high oxygen concentration, and so on that could provide extra benefit and efficiency boost to the CLCCC system. **Table 2** provides the description of the metal oxides used in this study.

And then, for parametric purpose, different H_2 and CH_2 mix flow rates are considered. It is aimed to simulate different intermittent or fluctuating renewable energy source used to generate H_2 in the SOEC. The key assumption is that the heat rate for the CLCCC is assumed to be the same for each different mixture. The base case is 6 kg/s of H_2. And then, for the metal oxide mixture, inert solids are also considered as heat diluents and heat carriers. The mass fraction is assumed to be 70% metal oxide and 30% inert materials, which consist of 15% SiC and 15% Al_2O_3 as suggested by Fan [25]. **Figure 3** shows the detailed process flow diagram of the proposed system (**Table 3**).

As described in previous parts, the process begins with the fuel produced in the SOEC entering the CLCCC along with natural gas. The mixture is then directly combusted in the reducer. The fuel gases leaving the reducer and oxidizer are expanded in the RT and OT, respectively, for electricity production. The CO_2 leaving RT is separated and compressed up to 200 bars for storage. Besides that, the fuel gas leaving the OT is utilized for heat addition of air and water streams. On the other hand, the heat in reducer gas is also used to heat the water feed stream in HX-1 and compressed air in HX-2. And then, HX-2 is also utilized to cool down the compressed air coming from C2 to reduce additional compression work in downstream processes.

The system's total energy efficiency is defined and calculated as follows:

$$W_{Gen} = W_{RT} + W_{OT} + W_{ST} \quad (1)$$

$$W_{Used} = W_{Compressors} + W_{Pump} + W_{Auxilary} \quad (2)$$

$$\eta_{tot} = \frac{\mathrm{W_{gen}\text{-}W_{used}}}{\mathrm{LHV}.\dot{\mathrm{m}}_{\mathrm{fuel}}} \quad (3)$$

where, W_{GEN}, W_{RT}, W_{OT}, and W_{ST} are the total work obtained from the system, works obtained from RT, OT, and ST, respectively. In addition, W_{Used},

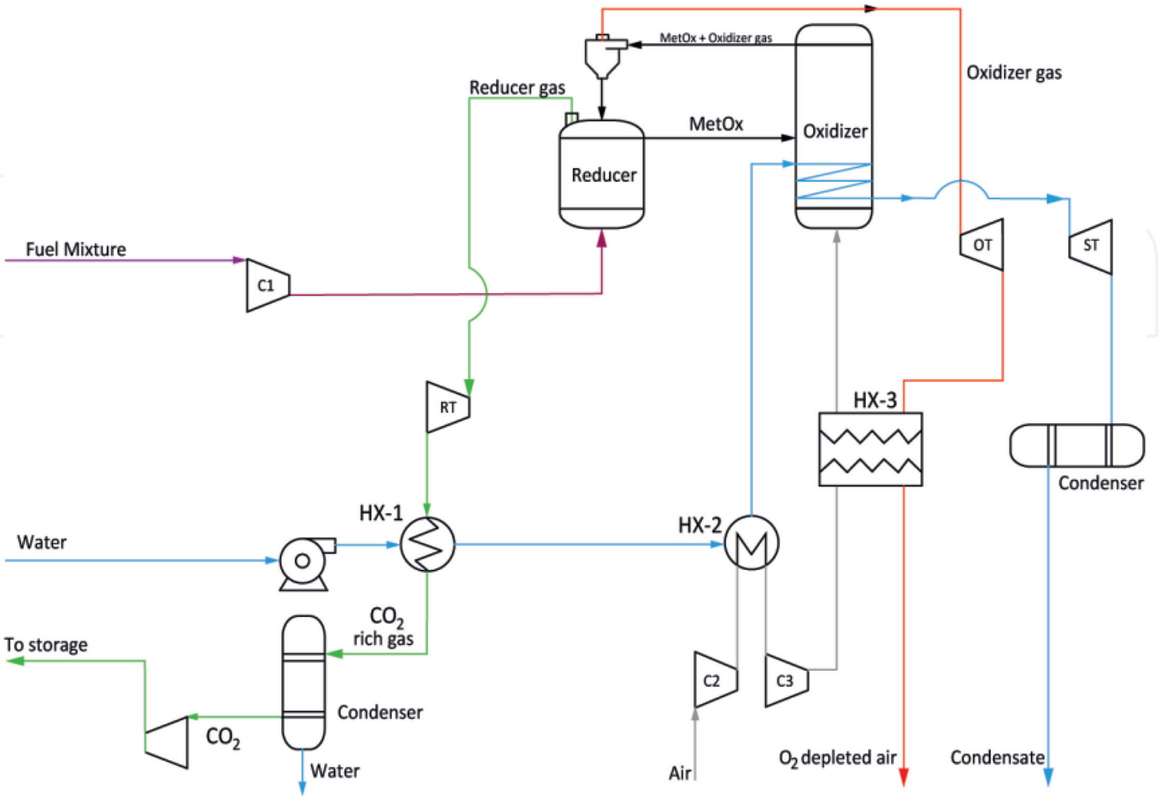

Figure 3.
Detailed process flow diagram of the CLCCC power generation process.

Metal oxide	Characteristic		
	Minimum melting point (°C)	Oxygen transport capacity (wt%)	Representative reactions*
Fe_2O_3/FeO	1565	10	(R)$Fe_2O_3 + H_2 \rightarrow 2FeO + H_2O$
			(R)$FeO + H_2 \rightarrow Fe + H_2O$
			(R)$4Fe_2O_3 + CH_4 \rightarrow 8Fe + 3CO_2 + 6H_2O$
			(O)$4Fe + 3O_2 \rightarrow 2Fe_2O_3$
NiO/Ni	1455	21.4	(R)$NiO + H_2 \rightarrow Ni + H_2O$
			(R)$4NiO + CH_4 \rightarrow 4Ni + CO_2 + 2H_2O$
			(O)$2Ni + O_2 \rightarrow 2NiO$
$CaSO_4/CaS$	1460	47.06	(R)$CaSO_4 + 4H_2 \rightarrow CaS + 4H_2O$
			(R)$CaSO_4 + CH_4 \rightarrow CaS + CO_2 + 2H_2O$
			(O)$CaS + O_2 \rightarrow CaSO_4$

**(R) reactions occur in the reducer and (O) reactions occur in the oxidizer.*

Table 3.
Details of the oxygen carriers used in the system.

$W_{Compression}$, W_{Pump}, and $W_{Auxiliary}$ are the total consumed work by the system, works consumed by compressors, pumps, and auxiliaries, respectively. Finally, the total energy efficiency η_{tot} is defined as the ratio of net produce power to the total calorific value of the fuels, including H_2 and CH_4.

4. Results and discussion

The parametric analysis has been done to provide a better understanding of the key design parameters of the SOEC-CLCCC system. First of all, as mentioned in the previous section, $CaSO_4$, Fe_2O_3, and NiO are each adopted and evaluated in the CLCCC system as oxygen carrier. Afterwards, different operating pressures from 15 to 35 bars, with an interval of 5 bars, are simulated for each system. Furthermore, different percentages for the H_2 used as fuel are also being investigated.

For the case of $CaSO_4$ as the oxygen carrier, the results are presented in **Figure 4**. The effects of different pressures and fuel mixtures are evaluated in the graph. The main characteristics of this particular oxygen carrier are high oxygen transport capacity, high temperature resistance, and highly exothermic reactions with the fuels used. Generally, the main driver for efficiency is the different fuel mixture. The highest energy efficiency obtained is 53%, with full H_2 feed. The efficiency decreases along with decreasing H_2 use. Basically, more CH_4 is required with each incremental reduction of H_2. Thus, more compression duty is required for the fuels due to higher flow rate. By the same token, lower pressures are more favorable for this case due to high compression work required. Thus, 15 bars achieve the highest efficiency of 54%.

Afterwards, when Fe_2O_3 is used as oxygen carrier, the highest energy efficiency obtained by the system rises to about 56%. The relationship is depicted in **Figure 5**. Basically, the trend is similar to the $CaSO_4$ system. When the H_2 percentage decreases, the energy efficiency decreases accordingly to about 45–47%. And then, lower pressures tend to be more preferable to achieve higher energy efficiency. This

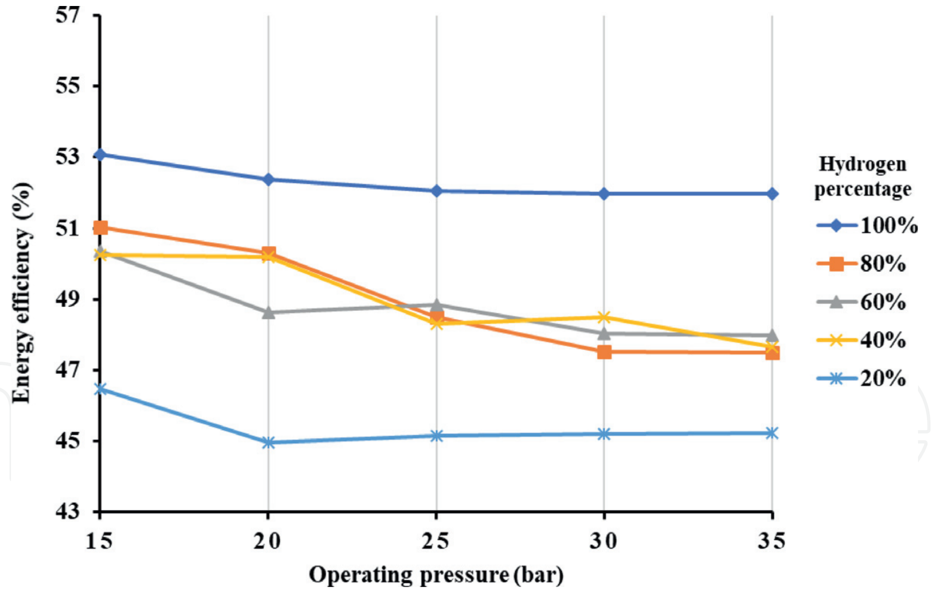

Figure 4.
System energy efficiency vs. operating pressure for the $CaSO_4$ system.

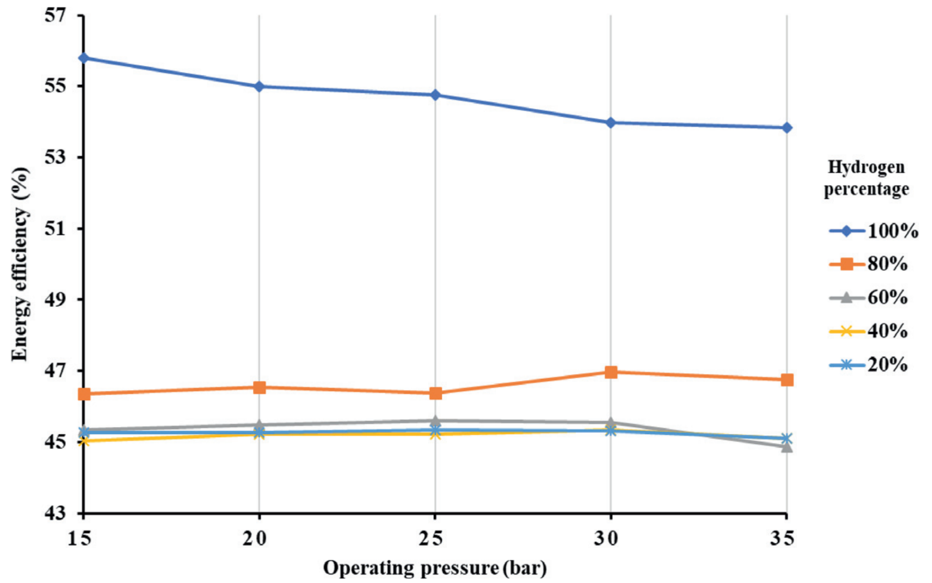

Figure 5.
System energy efficiency vs. operating pressure for the Fe_2O_3 system.

oxygen carrier has the lowest oxygen carry capacity compared to the other two oxygen carriers, but it has the highest melting temperature.

Furthermore, **Figure 6** shows the relationship of the operating pressures and the hydrogen percentages to the energy efficiency when NiO is used as oxygen carrier. In this case, the achievable maximum energy efficiency is about 56%. When H_2 percentage is reduced, the energy efficiency of the system further decreases to about 45–47%. Moreover, when larger amount of CH_4 is supplied, larger energy is required for CO_2 compression. NiO as an oxygen carrier has the second highest oxygen carry capacity and melting temperature compared to the other two oxygen carriers used in this study. These differences in efficiencies are driven by the difference of the heat released by the reactions that exist in the reducer and oxidizer.

Generally, from process modeling, operating pressure of the CLC system plays a significant role on changing the system's power intake and production. Process modeling suggests that the highest compressor work is consumed for the air compression process. Due to lower heating value of CH_4 compared to H_2, the system

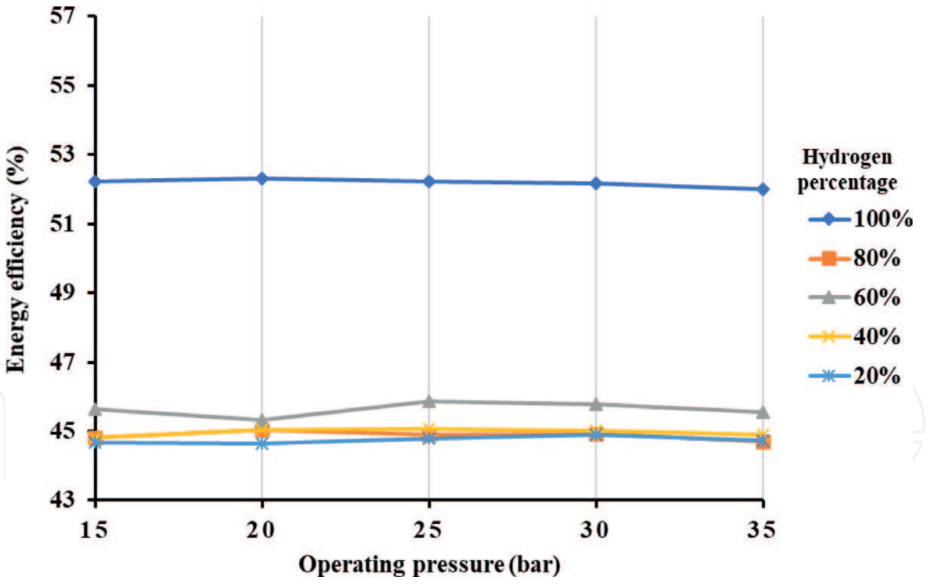

Figure 6.
System energy efficiency vs. operating pressure for the NiO system.

energy efficiency decreases accordingly when larger amount of CH_4 is used as fuel. Besides that, the thermodynamic characteristics also played a significant role to determine the heat produced and requirement in the combustion system. Subsequently, in case of $CaSO_4$ is used as oxygen carrier, as the reaction of CH_4 with $CaSO_4$ is endothermic, the input energy is required. This is opposite to the H_2 that provides an exothermic reaction releasing a considerable amount of heat. From process modeling, it can be inferred that the highest amount of heat exchange occurs in the oxidizer, where the heat from the oxidizer is utilized to heat up the steam to a higher temperature.

Compared to other power generation systems, the proposed system does not require additional process for air separation unit (ASU) and CO_2 separation process. Yet, the proposed system can achieve relatively high energy efficiency, which is similar to the energy efficiency of oxy-combustion power system that requires further CO_2 separation process and ASU.

Figure 7 shows the required solid flow rate for each different system. It shows that $CaSO_4$ requires the least amount of solids for the system for complete reduction of fuel and also for heat dilution. $CaSO_4$ has the highest O_2 transport capacity compared to the other two oxygen carriers. Fe_2O_3 comes second and NiO comes third in this comparison. The use of solids for heat dilution has to be considered for

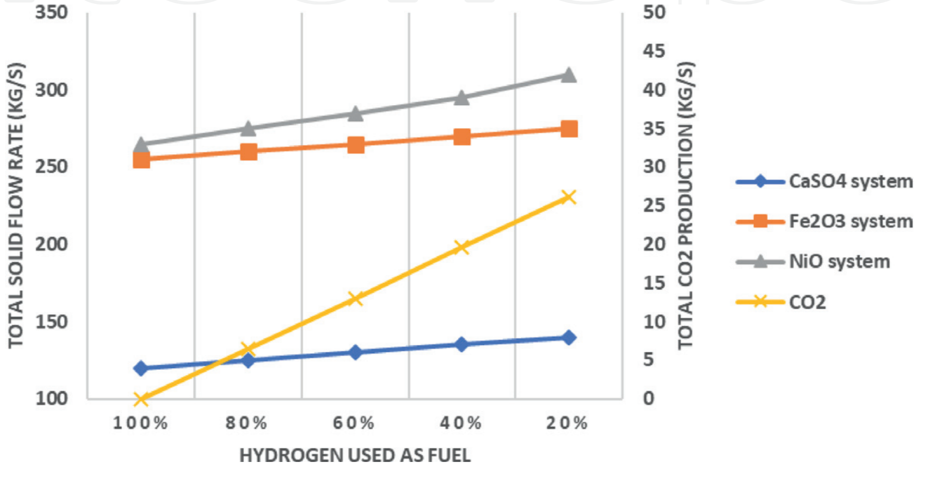

Figure 7.
Total solid flow rate and the CO_2 production for each system.

the CLCCC system, because air that is usually used for heat dilution could be replaced totally with solids. For further optimization of the system, excess air or excess solids can be considered as temperature reduction agents in the oxidizer. Higher amounts of solids circulated will require bigger reactors and more solid control infrastructure, and higher amount of air flow would require more compressor work.

5. Conclusion

A clean and efficient energy system to utilize efficiently hydrogen produced from renewable energy or surplus electricity is proposed. The proposed system is based on the chemical looping combustion using CH_4 as the base fuel. The system consists of SOEC for hydrogen production, chemical looping combustion, and combined cycle for power generation. The cleanliness of the developed system is promising as it can separate CO_2 directly via condensation due to the clean combustion process of CLC. A high energy efficiency of about 56% can be obtained. The results of this study are useful for further improvement and developments toward an actual CLC power generation system.

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References

[1] Szulejko JE, Kumar P, Deep A, Kim KH. Global warming projections to 2100 using simple CO_2 greenhouse gas modeling and comments on CO_2 climate sensitivity factor. Atmospheric Pollution Research. 2017;**8**(1):136-140

[2] Sorrell S, Speirs J, Bentley R, Brandt A, Miller R. Global oil depletion: A review of the evidence. Energy Policy. 2010;**38**(9):5290-5295

[3] Nasruddin N et al. Potential of geothermal energy for electricity generation in Indonesia: A review. Renewable and Sustainable Energy Reviews. 2016;**53**:733-740

[4] Surjosatyo A, Haq I, Dafiqurrohman H, Gibran FR. Effect of rice husk ash mass on sustainability pyrolysis zone of fixed bed downdraft gasifier with capacity of 10 kg/hour. AIP Conference Proceedings. 2017;**1826**:020009

[5] Ould Amrouche S, Rekioua D, Rekioua T, Bacha S. Overview of energy storage in renewable energy systems. International Journal of Hydrogen Energy. 2016;**41**(45):20914-20927

[6] Wendel CH, Kazempoor P, Braun RJ. Novel electrical energy storage system based on reversible solid oxide cells: System design and operating conditions. Journal of Power Sources. 2015;**276**:133-144

[7] PwC. Power in Indonesia: Investment and Taxation Guide. Vol. 9. PwC Publ; 2017. p. 132

[8] Lasnawatin F, Indarwati F. Handbook of Energy and Economic Statistics of Indonesia 2017. Ministry of Energy and Mineral Resources Republic of Indonesia; 2018

[9] Zaini IN, Nurdiawati A, Aziz M. Cogeneration of power and H_2 by steam gasification and syngas chemical looping of macroalgae. Applied Energy. 2017;**207**:134-145

[10] Nikolaidis P, Poullikkas A. A comparative overview of hydrogen production processes. Renewable and Sustaiable Energy Reviews. 2017;**67**:597-611

[11] Aziz M. Combined supercritical water gasification of algae and hydrogenation for hydrogen production and storage. Energy Procedia. 2017;**119**:530-535

[12] Darmawan A, Ajiwibowo MW, Yoshikawa K, Aziz M, Tokimatsu K. Energy-efficient recovery of black liquor through gasification and syngas chemical looping. Applied Energy. 2018;**219**:290-298

[13] Chi J, Yu H. Water electrolysis based on renewable energy for hydrogen production. Chinese Journal of Catalysis. 2018;**39**(3):390-394

[14] Jensen SH, Sun X, Ebbesen SD, Knibbe R, Mogensen M. Hydrogen and synthetic fuel production using pressurized solid oxide electrolysis cells. International Journal of Hydrogen Energy. 2010;**35**(18):9544-9549

[15] Gómez SY, Hotza D. Current developments in reversible solid oxide fuel cells. Renewable and Sustainable Energy Reviews. 2016;**61**:155-174

[16] Zhang X, Chan SH, Li G, Ho HK, Li J, Feng Z. A review of integration strategies for solid oxide fuel cells. Journal of Power Sources. 2010;**195**(3):685-702

[17] Cinti G, Baldinelli A, Di Michele A, Desideri U. Integration of solid oxide electrolyzer and Fischer-Tropsch: A sustainable pathway for synthetic fuel. Applied Energy. 2016;**162**:308-320

[18] Luo Y, Wu X, Shi Y, Ghoniem AF, Cai N. Exergy analysis of an integrated solid oxide electrolysis cell-methanation reactor for renewable energy storage. Applied Energy. 2018;**215**:371-383

[19] Kezibri N, Bouallou C. Conceptual design and modelling of an industrial scale power to gas-oxy-combustion power plant. International Journal of Hydrogen Energy. 2017;**42**(30):1-9

[20] Aziz M. Power generation from algae employing enhanced process integration technology. Chemical Engineering Research and Design. 2016; **109**:297-306

[21] Aziz M, Oda T, Kashiwagi T. Integration of energy-efficient drying in microalgae utilization based on enhanced process integration. Energy. 2014;**70**:307-316

[22] Darmawan A, Hardi F, Yoshikawa K, Aziz M, Tokimatsu K. Enhanced process integration of black liquor evaporation, gasification, and combined cycle. Applied Energy. 2017;**204**:1035-1042

[23] Udagawa J, Aguiar P, Brandon NP. Hydrogen production through steam electrolysis: Model-based steady state performance of a cathode-supported intermediate temperature solid oxide electrolysis cell. Journal of Power Sources. 2007;**166**(1):127-136

[24] Guo Q, Zhang J, Tian H. Recent advances in $CaSO_4$ oxygen carrier for chemical-looping combustion (Clc) process. Chemical Engineering Communications. 2012;**199**(11):1463-1491

[25] Fan L. Chemical Looping System for Fossil Energy Conversions. John Wiley & Sons; 2010. pp. 143-214

[26] Song Q et al. Chemical-looping combustion of methane with CaSO4 oxygen carrier in a fixed bed reactor. Energy Conversion and Management. 2008;**49**(11):3178-3187