Chemical looping technology in CHP (combined heat and power) and CCHP (combined cooling heating and power) systems: A critical review

Mahsa Rajabi, Mehdi Mehrpooya, Zhao Haibo, Zhen Huang

HIGHLIGHTS
• Chemical looping combustion method is used to prevent CO₂ emission.
• Integration of chemical looping technology in CHP and CCHP systems is studied.
• Structure of the processes integrated to chemical looping unit is discussed.
• Layout of the integrated processes are classified and explained.

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Chemical looping
Combined heat and power (CHP)

ABSTRACT
Chemical looping combustion (CLC) as an oxy-fuel combustion method with no contact between air and fuel, is one methods that can be used for combustion to prevent CO₂ emission in the atmosphere. Chemical looping reforming (CLR) and chemical looping hydrogen generation (CLHG) are procedures for hydrogen production with inherent CO₂ separation. Chemical looping technology is also used in other systems such as gasification and air separation called chemical looping gasification (CLG) and chemical looping air separation (CLAS). This technology can play an important role in controlling air pollution, fuel consumption and clean fuel production which are main concerns of the last century in the world. In this paper, chemical looping technology used in multi-generation systems is reviewed and investigated. The processes with power, heating and cooling production, called CHP (combined heat and power) and CCHP (combined cooling heat and power) systems are elaborated. They are categorized by their main product and main units for benefit outputs. The main feature of this paper is to show the overall structure of the units and likewise the inputs and outputs of them for a better understanding and comparison. Also consumed fuels, applied oxygen carriers, main conditions in chemical looping units, chemical reactions and resulted efficiencies, are considered and discussed. The presented results can be very useful for awareness, comparison and decision making for future modeling or experimental studies. The results show that fuel cell-based systems yielded higher efficiencies about 60–70%. Also the highest electrical efficiency (67%) is related to the SOFC-based power generation processes.

1. Introduction

With the fast social and economic development, especially in developing countries, the need for energy supply grows rapidly. Renewable resources cover 7% of the global energy supply, whereas fossil fuels provides 85% of that. Even until 2050, renewable percentage becomes double, and the fossil fuels still play the major role in future of universal energy security. Consequently attention to carbon emissions will be a global issue in the next two decades. Greenhouse gases (CO₂, NOx, SOx, CH₄) emissions is the main reason for global warming between them, CO₂ has the most emission rate. Power generation of the fossil fuels forms one third of the released carbon dioxide through combustion process. Therefore CO₂ capture is a key option. There are different ways to reduction the greenhouse gas emissions, for example energy consumption reduction, increasing in energy efficiency, using low carbon fuels, using renewable energy resources,
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<td>chemical looping combustion</td>
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<td>CLCS</td>
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<td>CLH</td>
<td>chemical looping hydrogen (generation)</td>
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<td>CLHP</td>
<td>chemical looping hydrogen production</td>
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<td>CLOU</td>
<td>chemical looping with oxygen uncoupling</td>
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<td>chemical looping oxy- combustor</td>
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<td>CLAS</td>
<td>chemical looping air separation</td>
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<td>ICLAS</td>
<td>integrated chemical looping air separation</td>
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<td>CLSA</td>
<td>chemical looping with saturated air</td>
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<td>ex-CLC</td>
<td>extended chemical looping combustion</td>
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<td>CLCCC</td>
<td>chemical looping combustion combined cycle</td>
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<td>TS-CLC</td>
<td>two stage chemical looping combustion</td>
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<td>TRCLR</td>
<td>three reactor chemical looping reforming</td>
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<td>BDCL</td>
<td>biomass direct chemical looping</td>
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<td>BDCLS</td>
<td>biomass direct chemical looping system</td>
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<td>DCCLS</td>
<td>direct coal chemical looping system</td>
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<td>BCCLC</td>
<td>biomass and coal co-fueled chemical looping combustion</td>
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<td>BGDCL</td>
<td>biomass gasification integrated with a dual chemical looping technology</td>
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<td>GCLC-CC</td>
<td>gasification chemical looping combustion with combined cycle</td>
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<td>CLSOM</td>
<td>chemical looping selective oxidation of methane</td>
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<td>HO-CLH</td>
<td>H₂ and O₂ combined cycle with CLH</td>
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<td>RHO-CLH</td>
<td>reheat H₂ and O₂ combined cycle with CLH</td>
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<td>IGCLSA</td>
<td>integrated gasification chemical looping combustion and saturation of air</td>
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<td>CLC-SE-SR</td>
<td>chemical looping combustion with sorption enhanced steam reforming</td>
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<td>SESMR</td>
<td>sorption enhanced steam methane reforming</td>
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<td>IGCC</td>
<td>integrated gasification combined cycle</td>
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<td>IGCCCP</td>
<td>integrated gasification combined cycle power plant</td>
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<td>NGCC</td>
<td>natural gas fired combined cycle</td>
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<td>STIG</td>
<td>steam injected gas turbine cycle</td>
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<td>CCPP</td>
<td>combined cycle power plant</td>
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<td>SOFC</td>
<td>solid oxide fuel cell</td>
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<td>PEMFC</td>
<td>proton exchange membrane fuel cell</td>
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<td>AFC</td>
<td>alkaline fuel cell</td>
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<td>DMFC</td>
<td>direct methanol fuel cell</td>
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<td>PAFc</td>
<td>phosphoric acid fuel cell</td>
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<td>MCFC</td>
<td>molten carbon fuel cell</td>
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<td>HRSG</td>
<td>heat recovery steam generator</td>
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<td>CASU</td>
<td>cryogenic air separation unit</td>
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<td>NGPH</td>
<td>natural gas preheating</td>
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<tr>
<td>CCHP</td>
<td>combined cooling, heating and power</td>
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<tr>
<td>UCCH</td>
<td>underground coal gasification</td>
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<tr>
<td>CCS</td>
<td>carbon capture and storage (or sequestration)</td>
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<td>CCU</td>
<td>carbon capture and utilization</td>
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<tr>
<td>DFB</td>
<td>dual fluidized bed</td>
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<td>DCFB</td>
<td>dual circulating fluidized bed</td>
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<td>HAT</td>
<td>humid air turbine</td>
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<td>HGD</td>
<td>high-temperature gas desulfurization</td>
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<tr>
<td>IPCC</td>
<td>Intergovernmental Panel On Climate Change</td>
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<td>GTCC</td>
<td>gas turbine combined cycle</td>
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<td>CFPP</td>
<td>coal fired power plant</td>
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<td>HPST</td>
<td>high pressure steam turbine</td>
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<td>LPST</td>
<td>low pressure steam turbine</td>
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<td>IPST</td>
<td>intermediate pressure steam turbine</td>
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<tr>
<td>SRC</td>
<td>Steam/conventional Rankine cycle</td>
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<td>Super-critical Rankine cycle</td>
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<td>KC</td>
<td>Kalina cycle</td>
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<td>ASU</td>
<td>air separation unit</td>
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<td>AGR</td>
<td>acid gas</td>
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<td>WGS</td>
<td>water-gas-shift</td>
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<td>PSA</td>
<td>pressure swing adsorption</td>
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<td>Oxy-PF</td>
<td>oxy-pulverized fuel</td>
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<td>ZEC</td>
<td>zero emission coal</td>
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<td>ATR</td>
<td>auto-thermal reformer</td>
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<tr>
<td>CHP</td>
<td>combined heat and power</td>
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<td>DCFB</td>
<td>dual circulating fluidized bed</td>
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<td>SHTCR</td>
<td>steam/hydrogen to carbon ratio</td>
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<tr>
<td>IBS</td>
<td>integrated boiler system</td>
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<td>IGS</td>
<td>integrated gasifier system</td>
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<tr>
<td>LCA</td>
<td>life cycle assessment</td>
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<tr>
<td>LNG</td>
<td>liquefied natural gas</td>
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<td>ZECA</td>
<td>Zero Emission Coal Alliance</td>
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<td>GHG</td>
<td>greenhouse gas</td>
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<td>COPROX</td>
<td>CO preferential oxidation reactor</td>
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<td>WHB</td>
<td>waste heat boiler</td>
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<tr>
<td>OSR</td>
<td>oil shale rotating</td>
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<td>TIT</td>
<td>turbine inlet temperature</td>
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<td>TOT</td>
<td>turbine outlet temperature</td>
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<tr>
<td>HHV</td>
<td>higher heating value</td>
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<td>LHV</td>
<td>lower heating value</td>
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<tr>
<td>NG</td>
<td>natural gas</td>
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<tr>
<td>FW</td>
<td>feed water</td>
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<tr>
<td>CaL</td>
<td>calcium looping</td>
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<tr>
<td>CW</td>
<td>cooling water</td>
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<tr>
<td>RED</td>
<td>reduction</td>
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<td>OXD, OXI oxidation</td>
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<tr>
<td>AR</td>
<td>air reactor</td>
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<tr>
<td>FR</td>
<td>fuel reactor</td>
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<td>SR</td>
<td>steam reactor</td>
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<td>RR</td>
<td>reduction reactor</td>
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<td>OR</td>
<td>oxidation reactor</td>
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<td>GT</td>
<td>gas turbine</td>
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<td>ST</td>
<td>steam turbine</td>
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<tr>
<td>AT</td>
<td>air turbine</td>
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<tr>
<td>OC</td>
<td>oxygen carrier</td>
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<td>HP</td>
<td>high pressure</td>
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<td>LP</td>
<td>low pressure</td>
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<td>MP</td>
<td>medium pressure</td>
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<td>IP</td>
<td>intermediate pressure</td>
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<td>HT</td>
<td>high temperature</td>
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<td>LT</td>
<td>low temperature</td>
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<tr>
<td>MT</td>
<td>medium temperature</td>
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<td>PO</td>
<td>partial oxidation</td>
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<td>P</td>
<td>pressure</td>
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<tr>
<td>T</td>
<td>temperature</td>
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<td>T&lt;br&gt;&lt;sub&gt;opt&lt;/sub&gt;</td>
<td>optimum temperature</td>
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<td>avg</td>
<td>average</td>
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<tr>
<td>vol%</td>
<td>volume percent</td>
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<tr>
<td>MeO</td>
<td>metal oxide</td>
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<tr>
<td>Me</td>
<td>metal</td>
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<tr>
<td>DME</td>
<td>dy-methyl-ether</td>
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<tr>
<td>CuO</td>
<td>copper oxide</td>
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<tr>
<td>CO₂</td>
<td>carbon dioxide</td>
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<tr>
<td>O₂</td>
<td>oxygen</td>
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**Standard ISO symbols**
- CuO: copper oxide
- CO₂: carbon dioxide
- O₂: oxygen
improvement in planting and CO₂ capture [1]. Atmospheric CO₂ concentration has been increased from 280 ppm in 1750 (before industrialization) to 400 ppm today which has been known as the main reason for global warming [2]. According to IPCC (Intergovernmental Panel on Climate Change), global temperature increasing more than 2°C will have severe effects on climate. In 2009 in Copenhagen, the countries presented the decisions for global warming limitation to 2°C up to 2100. It has been estimated that, to gain this aim, GHG emissions should be decreased to 40–70% and the zero emission should be implemented up to the end of this century [3]. Scientists express if the prompt decisions and proceedings had not been applied the target of global warming limitation to 2°C would be more difficult and more expensive than imagination [4].

There are two significant attitudes to avoid CO₂ emissions; CCS (Carbon Capture and Storage (or sequestration)) and CCU (Carbon Conversion and Utilization). CCS technologies may take the main amounts of separated CO₂ under treatment [5]. Then the resulted liquid may be sent to underground by pumping [6] or to be injected to the ocean depth. In CCU technologies, CO₂ is used as a low cost carbon source for many chemicals. These technological methods could consolidate large amount of CO₂ in products and be profitable [2]. There are three main approaches for CO₂ capture: oxy-fuel combustion process, pre-combustion capture and post-combustion capture. Oxy-fuel combustion uses pure oxygen instead of air as the primary oxidizer [7]. Pre-combustion capture is to convert a solid, liquid or gas fuel to a mixture of H₂ and CO₂ by using a number of processes such as reforming and gasification. Then CO₂ by some methods like physical and chemical absorption is separated, and results a H₂-rich fuel for use in some applications like boilers, gas turbines, fired heaters, fuel cells, etc. [8]. In post-combustion capture, CO₂ could be separated from the stack gas with a suitable method like absorption, adsorption/desorption, high pressure membrane filtration, and refrigerant separation processes, then separated CO₂ is compressed for transfer and storage [9]. Oxy-fuel combustion is based on the combustion in an oxygen-rich atmosphere. With elimination of nitrogen from combustion process, the stack gas mainly consists of CO₂ and H₂O. This, allows relatively low cost CO₂ separation which is done by only stack gas drying [9]. Chemical looping combustion is an oxy-fuel approach by using solid oxygen carriers as the oxygen-rich media. Until now, many studies and operations have been carried out on chemical looping technology and its related matters and parameters with any points of view, like oxygen carriers, reactor designs, operational conditions, chemical looping-based integrated processes and many others.

Several review papers with the basis of chemical looping technology have been published. M.M. Hossain and H.I. de Lasa provided [11] a vision of CO₂ capture and utilization, CLC combined power generations and CLC reactor systems. They also investigated chemistry and thermodynamics of CLC systems and kinetics of the reduction reactions. Another review paper, investigated two types of chemical looping technology application including CLR and CLHG, reactor engineering, reaction kinetics and oxygen carrier particles and their advancements [12]. Zeng et al. [13] provided a literature review about chemical looping systems in terms of reactor design and reaction mechanism. A review about application of chemical looping and ceramic membranes for hydrogen production systems and their developments was provided by Thursfield et al. [14]. In another review study, oxygen carrier characterizations and reactor designs were discussed [15]. Adanez et al. [16] in a review paper, investigate about different aspects of chemical looping technology. They discussed about used fuels, types of oxygen carriers, available layouts of using this technology like CLOU, iG-CLC and CLR. Also they expressed about reaction kinetics and modellings. Imtiaz et al. [17] in a review paper investigated the oxygen carriers in some points of view for CLOU systems. Li et al. [18] provided an overview of oxygen carriers applied in systems with the aim of converting methane to syngas by chemical looping processes briefly named CLSOM. A review study was carried out by Udomsirichakorn and Salam [19] which discusses biomass gasification, its types, and mechanisms, and the most effective parameters on its performance such as biomass characteristics, gasification temperature, Steam/Biomass ratio and equivalence ratio. Then CaO-based chemical looping gasification was discussed as a promising method with the aim of hydrogen production. Demirel et al. [20] analyzed chemical looping technology with CO₂ capture and hydrothermal processes, which these combined processes lead to conversion of fuel to power, heat and chemicals with decreased pollutant emissions. H. Rad et al. [21] reviewed the previous studies on aims to find the desired function and efficiency by investigation of oxygen carrier materials emphasizing on perovskite ones and reactor types for chemical looping systems. Tang et al. [22] reviewed the research works on oxygen carrier improvement in chemical looping reforming based on methane. A detailed review on recent developments in hydrogen production with chemical looping water splitting was done by Voitic and Hacker [23]. Protasova and Snijkers [24] provided a review on hydrogen production with various chemical looping systems by the perspective of specifications, performances and preparation of oxygen carriers. Nandy et al. [1] carried out a review study on CLC technology and its development in recent 10–15 years with the fuel, oxygen carrier and reactor systems view. In a review paper, Matzen et al. [25] investigated the natural ores applications as oxygen carrier in CLC systems. Some parameters such as stability, fuel conversion, carbon capture efficiency etc., were considered as the evaluation parameters. In a very recent review study, Adanez et al. [26] discussed chemical looping combustion performance and their characteristics with solid fuels. They categorized and studied CLC units in two scales (lab and small scale units and semi-industrial ones). In this study effective parameters on the system performance are reported. Also challenges of study in this field and techno-economical assessments are carried out. A review study about chemical looping-based hydrogen production was done by Luo et al. [27]. They discussed CLR and CLHP systems with metal oxides, support materials, preparation methods and reactor types. Also, they provided a summary of integrated systems with CLH. Differently, the present paper provides a comprehensive, detailed and updated review study on chemical looping- based CHP and CCHP systems. This paper has been prepared in six main sections. Each system consists of some subsystems by their own specific functions. A brief introduction of the major ones is presented. In the present review, the hybrid systems using chemical looping technologies are reviewed. The used fuels, conditions governing the process and the method of sub-systems integration are expressed. In addition type of products, and processes efficiencies are reported. A broad perspective on essentials and possible outcomes for researchers who follow integrated/multi-generation systems with environment friendly targets is provided. This, can help to proper selection of each item for future studies and designs.
1.1. Chemical looping

Chemical looping is a promising technology mainly contain CLC, CLR and CLHG by the goals of separation of CO₂ resulting from combustion, fuel reforming and hydrogen production respectively. Effective parameters in economy and efficiency of this technology mainly are reactor designs, kinds of the used fuel and applied oxygen carriers, and operating conditions [1,22,23,24,25].

1.1.1. Two reactor systems

CLC usually consists of using a metal-based oxygen carrier for supplying the required oxygen for oxidation reaction. After oxidation reaction in the fuel reactor, oxygen carriers are transferred to air reactor. They are reduced in the air reactor by means of pure oxygen or fresh air (see Fig. 1).

The bottom reaction occurs in the fuel reactor as follows:

\[(2n + m) \text{M}_x\text{O}_y + \text{C}_n\text{H}_{2m} \rightarrow (2n + m) \text{M}_x\text{O}_{y-1} + m\text{H}_2\text{O} + n\text{CO}_2\] (1)

After completing the fuel oxidation in FR, the metal oxide \(\text{M}_x\text{O}_{y-1}\) (or metal), is sent to AR for bottoming reaction as follows:

\[1/2 \text{M}_x\text{O}_{y-1} + 1/2\text{O}_2 \rightarrow \text{M}_x\text{O}_y + (\text{air: N}_2 + \text{unreacted O}_2)\] (2)

Generally, reduction and oxidation reactions are endothermic and exothermic, respectively. The heat of reactions depends on the fuel and oxygen carrier [11].

1.1.2. Three reactor systems

For hydrogen generation systems (CLHG), the loop is mainly contains three reactors (see Fig. 2).

Fuel enters fuel reactor and reacts with oxygen carrier:

\[(n + m/2)\text{M}_x\text{O}_y + \text{C}_n\text{H}_{2m} \rightarrow (n + m/2)\text{M}_x\text{O}_{y-2} + m\text{H}_2\text{O} + m\text{H}_2 + n\text{CO}_2\] (3)

When reactant was converted completely, pure CO₂ can be obtained after steam condensation. Then reduced OC (\(\text{M}_x\text{O}_{y-2}\)) enters the steam reactor and bottoming reaction occurs:

\[(n + m/2)\text{M}_x\text{O}_{y-2} + m\text{H}_2\text{O} \rightarrow (n + m/2)\text{M}_x\text{O}_{y-1} + m\text{H}_2\] (4)

Partially oxidized OC (\(\text{M}_x\text{O}_{y-1}\)) goes into the air reactor and become oxidized to its primary state:

\[(n + m/2)\text{M}_x\text{O}_{y-1} + \frac{1}{2}\text{O}_2 \rightarrow (n + m/2)\text{M}_x\text{O}_y\] (5)

Fully oxidized OC (\(\text{M}_x\text{O}_y\)) turns to the fuel reactor again, and new cycle starts [28].

1.1.3. More complex reactor systems

In some cases, more than one time reduction or oxidation would be needed in a loop. In such situations, more complex arrays of reduction and oxidation reactors are required. Reactors could be placed in parallel, series or combination of these states. In each reduction or oxidation step in a loop, a partial type is done, to be completed in a perfect loop. Some examples of such arrays are provided in Figs. 37–39 and 56–63. In rotating reactors, oxygen carriers are placed radially. Fuel, required air for OC reduction and inert gases, are placed in sectors of the circle. Because of rotational movements, these reactors have better mixing [1].

1.2. Air separation unit

Since the air consists of several elements and each of them, has a different property and applications, for example in chemical technologies; the air separation process, is an unavoidable operation. Medical, food processing, refining, steel, aeronautical and some other industries, require large amounts of high purity air elements like oxygen, nitrogen, argon etc. [29]. Depending on the required amount of purified air and so the percentage of desired purity, the proper way of air separation containing adsorption method, cryogenic air separation, membrane air separation and others could be applied [30]. In some chemical looping-based processes, pure oxygen and even pure nitrogen are required which are supplied by ASU.

1.3. Gasification

Gasification is a thermo-chemical process which converts carbon
containing fuels like biomass and coal to a combustible gas. Gasification occurs in high temperature conditions almost between 800 and 1200 °C [31] and can be explained in four steps; drying, pyrolysis, combustion [32] and reduction and contains several reactions that some of them are endothermic and others are exothermic [33]. Final resulted gas of gasification mainly consists of CO, H₂, H₂O and CO₂ with different properties. Gasification process needs a gasification agent which are commonly air, oxygen and steam. Briefly, gasifiers are categorized in three main groups containing packed bed (downdraft and updraft), fluidized bed (bubbling, circulating and pressurized) and pressurized entrained flow gasifiers [34]. The produced syngas of gasification process is used as a gaseous fuel and chemical looping combustion is one of approaches that prefers to apply gas-type fuels. So gasification (either in-situ or ex-situ) is an inevitable step at least when solid fuels are used.

1.4. Fuel cell

Fuel cell is a technology which converts fuel chemical energy to electricity, directly through electrochemical reactions. There are many kinds of fuel cells by their own advantages and disadvantages. A typical categorization method of fuel cells is attention on their electrolyte materials and used fuels [35]. They are classified in six main groups; AFC, PEMFC, DMFC, PAFC, MCFC and SOFC. Since fuel cells are silent, high efficient, with simple foundation and low emissions, gradually their applications become more common. Reforming and partial oxidation of hydrocarbons could be integrated with main process for hydrogen or syngas production for using as fuel in the fuel cells [36]. Due to their solid phase electrolyte and other advantages, the SOFCs and PEMFCs are the most appropriate type of fuel cells for integrating the high capacity power plants.

1.4.1. SOFC

Solid oxide fuel cells have were attractive because of their highly lighted advantages among power generator systems. They work at high temperature conditions, and are fuel flexible. They result high power density and high energy conversion efficiency [37] which their electrodes condition like their porosity have significant impact on their outcome [38,39]. Also, internal reforming of hydrocarbon fuels could be available because of high operating temperature in this device. Depending on the electrolyte material, this temperature can be varied between 600 and 1000 °C [40]. SOFCs are classified according to their operating temperatures and also the type of cell support [40]. SOFC can work with H₂, CO and CH₄. The hybrid application of SOFC/GT in CCPP has the highest output power and electrical efficiency in the fuel cell and conventional power generators and combination application of them [41]. This device can use CH₄/CO₂ with direct feeding to convert them to syngas and produce electricity [42]. A new concept of SOFC hybrid systems is combination of this device with gasification process. Effective parameters on syngas composition affect the cell performance [43]. It is demonstrated that a hybridization between gasifier, SOFC and gas turbine, can result the efficiency to about 50–60% [44].

1.4.2. PEMFC

Proton exchange membrane fuel cells or polymer electrode membrane fuel cells work with H₂ and O₂ as input streams. PEMFCs work at low temperature condition and have a long lifespan. They are high efficient and accordingly high power density [45]. High temperature PEMFCs have several benefits than low temperature ones. But warm up the cell with external heating is needed for providing high temperatures [46]. When PEMFCs work at high temperatures (100–200 °C), co-generation of power and heat will be possible [47].

1.5. Turbine power cycles

Power cycles and refrigerant cycles are of the two general categories in thermodynamic cycles. Depending on the phase of the working fluid, thermodynamic power cycles are classified to gas cycles and vapor (or steam) cycles. In gas cycles, the working fluid remains in gaseous phase throughout the cycle whereas the working fluid in steam cycles, changes between liquid and steam phases. Thermodynamic cycles also could be categorized in another point of view to open cycles and closed cycles. In open cycles, working fluid is renewed at the end of each cycle, but in closed cycles, at the end of cycle, working fluid is regenerated and returned to its initial state.

1.5.1. Steam power cycles

The most common working fluid for vapor power cycles is steam; because of its availability, low cost, high enthalpy for vaporization, etc. Steam power cycles are considered in external combustion engines class with heat supplying to working fluid by an external source such as furnaces, geothermal resources, nuclear reactors, solar based heat and some others. Since efficiency of these devices are low and they are high polluters, and because of limited fuel resources, the energy and exergy investigation and applying optimization methods for these plants seems to be necessary [48].

1.5.2. Gas power cycles

Gas turbines are very adaptable devices and can use a variety of fuels to burn. The increase in turbine inlet temperature, enhance in turbomachinery parts and modifying the simple cycle by adding reheating, intercooling and some other alterations, could help increasing the gas turbine cycle efficiency. Briefly, in a gas turbine system, air through compressor, reaches to higher temperature and pressure. Then the combustion occurs in combustor by entering the compressed air. Then the combustion mixture is sent to turbine for power generating [49]. Since temperature of the gas turbine may reach to higher than melting point of the applied materials for construction, cooling seems should be used [50]. Gas turbines operate in three classes namely open cycle, closed cycle and semi closed cycle [51]. Micro gas turbines have lower pollutant rather than small-scale internal combustion devices which has low cost and has been more common [52].

1.5.3. Combined power cycles

Since temperature of the exhaust gas of the gas turbine, is very higher than steam turbine operating temperature, embedding a bottoming steam turbine power plant, can lead to heat recovery of gas turbine stock to producing vapor in the steam turbine. The result is a combined cycle power plant which has higher efficiency rather than single gas turbine and steam turbine power cycles. Accompany of Bryton and Rankine cycles is commonly used in CHP systems which result efficiencies higher than 60% [53]. The performance of gas turbine is the most effective parameter in a combined cycle power plant for attainment to higher efficiencies [54].

1.6. Heat recovery

Due to thermodynamic restrictions in conventional power plants, almost only one third of fuel energy converts to electricity and remaining is released as heat to environment [55]. Waste heat recovery is an economical technology in power plants. Researches confirm achieving to a 10–25% thermal efficiency in compression ignition-ORC systems and an overall efficiency of combined system about 60–90% [56]. In HRSG systems, the hot streams are applied for steam generation from feed water. Produced steam usage, increases the plant efficiency. This steam could run a steam power plant or can be used as gasification agent or other applications. Operating temperature of the most of heat recovery systems, is in the ranges of high (350–500 °C) and medium (200–350 °C) [55]. The main heat recovery systems are Rankine cycle (ORC, SRC and SCRC), Kalina cycle (KC), exhaust gas turbine systems and thermo-electrical generators [57].

As mentioned, the aim of this review paper is focusing on the works
which in them hybrid chemical looping technology power production systems with, heat and cooling as outputs have been proposed and developed. Fig. 3 indicates the basic balance of a typical chemical looping-based process. As expected, each process consists of some subsystems with particular layout affected by inputs, facilities, opinions of the process designers, targets of the work and etc. Processes are categorized based on their useful and efficient outputs as are mentioned in the top. According to three significant products, processes must be categorized in three prime classes; but since the heat production and thereafter heat recovery units almost always is accompanied by power and cooling as specific products, we will have two categories: power and cooling production-based processes. At the first, power generation systems was placed in a class with the priority of non-combustible engines (here there is only fuel cells). Steam turbine cycles, gas turbine cycles and combined power cycles are the next groups which are included in second class. The three last subsystems would have existed in processes with fuel cell power generators but in those systems, the concern is non-combustible engines. Notwithstanding the existence of turbine power cycles in processes we put them in the first group of first class only (non-combustible engines power generators group). Likewise in cooling production class, besides cooling other products may be existed but we emphasize on cooling production to place in this class. Fig. 4 illustrates this categorization as well.

Some assumptions in the process overview and descriptions have been considered which are listed as follows:

- In each section based on the kind of the product, the relevant researches and studies are reviewed. Then the general schematics related to that section are provided.
- In all figures provided for the process description (Figs. 5–8, 11–13, 16–24, 27–39, 42–63 and 67) some simplifications has been applied. Only the main units (ASU, gasification, chemical looping reactors, turbine power plants, fuel cells, HRSG) are shown in gathered schematics.

**Fig. 3.** Necessary/possible inputs and outputs of a typical multi-generation chemical looping-based process.

**Fig. 4.** Classification of chemical looping-based processes with products point of view.
The figures prepared for processes are sorted from simple to complex structures in each class.

Some devices like compressors, pumps, heaters, coolers, heat exchangers, condensers, separators, AGR system, claus plant and tail gas treatment, syngas quench and cooling, saturator and some others are not shown in figures. Because the reference processes with same subsystems and same general schematics, are not exactly the same in the PFD and used devices. So for the generalization, the details are not mentioned in the figures; instead, detail of each related process is described below each figure.

Regardless kind of the fuel, kind of used gasification agent and oxygen carrier, entrance stream of the air or oxygen, content of the inlet and outlet currents to/from the reactors, turbines, gasifiers, fuel cells and chillers, all of them are shown the same in all figures with a same general label or no label. The exact stream contents are mentioned and explained in the process description below each figure.

Turbine power plants are shown with a single turbine. For example some processes apply steam turbine power plants in three pressure stages which one ST is used to show as a symbol. Also the combined cycle power plant with its wide tail and devices and any state of relation between gas cycle and steam cycle, is only shown by a GT and a ST next to each other.

Irrespective of the number and kind (for example air HRSG or CO₂ HRSG) of heat recovery systems, only a HRSG unit is shown. All CO₂-turbines and air turbines are shown by GT.

In process descriptions provided below of each figure, the oxygen carrier particles flow has not been described because their stream direction is constant and predefined between chemical the looping reactors.

Relation between the units and subsystems are shown by dark blue arrows. The detailed relevance connections are described for each reference.

Oxygen-carrier stream is specified by dashed lines, whereas other material streams are shown by continuous line.

Circulation of oxygen carrier between chemical looping reactors is not explained in the process descriptions.

2. Power generator/chemical looping-based systems

In this class, integrated power plants with the main product of power are discussed. They are classified in electro-chemical and thermo-mechanical power generation systems.

2.1. Electro-chemical power generation/chemical looping-based processes

Power plants by employing fuel cell- based power generation are studied. These processes may apply turbine- based power plants too, but as mentioned, the preference of classification, starts with non-combustible power generators.

2.1.1. SOFC/chemical looping-based systems

Chen et al. [58] developed a process consists of coal gasification, CLHG, SOFC and GT systems by means of power and hydrogen generation and CO₂ capture. They reached to net power efficiency of 45% and demonstrated that plant power efficiency rises up by increasing the system pressure and cell temperature. Also they approved that higher utilization factor of the fuel, results higher net power efficiency. The integration between chemical looping gasification and SOFC, leads to low exergy losses. Also it’s efficiency is significantly higher than conventional IGCC and CDCL–Combined Cycle [59]. Aghaie et al. [60] developed a combined cycle power plant integrated with SOFC which uses chemical looping technology for combustion. Their CLC system is based on Ca-looping and utilizes three reactors; carbonator, calcinator and hydrator. The SOFC efficiency, plant net power efficiency, hydrogen power efficiency and CO₂ capture efficiency are achieved.
54.2%, 55.8%, 87%, and 100% respectively. A trigeneration (power, heating and hydrogen) power plant using three reactor chemical looping system was developed by Ozcan et al. [61]. In this work, in addition to SOFC/GT system for power generation, a heat recovery system including steam cycle, organic Rankine cycle and space heating is considered. The overall energy and exergy efficiencies are obtained 56.9% and 45.05% respectively. The electrical efficiency with and without hydrogen production considering are found 23.47% and 37.3% respectively. It is concluded that higher SOFC pressure, results higher SOFC and overall efficiencies. It is showed that efficiency 5% increases when the pressure increases to 18 bar. Increasing the temperature is less effective than pressure. The ZECA process is one form of integration between chemical looping and SOFC systems. It has not been done experimentally ever. This process efficiency for a 600 MW plant is resulted 68.8% (HHV) with the SOFC efficiency of 59% (LHV) which are obtained from simulation with ASPEN PLUS and economic analysis [59]. A cooperation study between solid oxide fuel cell and chemical looping process has been done. A Fe-Ti-O carrier has been used for oxidation. The results showed 97mW S⁻² power density in its maximum value [62]. Chen et al. [63] introduced an integrated process, containing coal gasification and power generation with SOFC using chemical looping combustion. In this study net power efficiency based on the defined process characteristics is gained 49.8%. Also they reported that increasing the air reactor temperature increases the net power efficiency and increasing fuel reactor temperature, has opposite effect. Likewise, Fe₂O₃ and CuO presented better results for net power efficiency. Yan et al. [64] developed power generation based chemical looping and hydrogasification of coal and biomass process. This work, under the benchmark conditions, showed 43.6%, 41.2% and 99.1% for total energy efficiency, total exergy efficiency and carbon capture rate respectively. An integration between CLHG and power generation with SOFC was developed by Chen et al. [65]. Coal was fed directly to CLHG and net power efficiency reached to about 41.59%. Figs. 5–8 display four process layouts which apply chemical looping combustion technology and power generation with SOFC fuel cells. An ORC/HRSG integrated with SOFC/CLC process has been evaluated with thermodynamic concept by Spallina et al. [66] in small-scale and large-scale dimensions. The electric efficiencies (LHV) higher than 66%, was obtained in both scales. It was demonstrated that most effective parameter on plant efficiency and fuel cell size is SOFC voltage.

Fig. 5 illustrates a process that gasification product runs the SOFC and its output enters two reactors CLC. Output gases from CLC run a combined cycle power plant which exchanges heat with HRSG system.

In the process introduced by Chen et al. [63] the coal feed with gasification agents (CO₂ and O₂) enters the gasifier. Syngas after desulfurization and preheating follows to the anode, then the anode product enters the fuel reactor. On the other hand, compressed air reacts in the cathode then outlet oxygen depleted air is mixed fresh air and enters the air reactor. Fuel and air reactor exhaust gases after passing from the gas turbines, follows to the CO₂ HRSG and air HRSG which both import heat from the fuel reactor and waste heat boiler. Inlet water streams to the mentioned HRSGs, after converting to steam, then are compressed and condensed respectively.

Fig. 6 displays a layout of power generation with gasification, combined power plant and heat recovery system, which applies a three
reactors CLC system with the electricity generation by a SOFC stack.

In an integrated process, coal in addition to O₂ and steam enters the gasifier. Produced syngas after cleaning goes to the fuel reactor. The product of this reactor and steam enter the steam reactor. After reaction, partial oxidized carriers goes into the air reactor and produced H₂ enters the anode. Air reactor by means of outlet from the gas turbine, fully oxidizes particles and sends them to the fuel reactor. Output air enters the cathode. Fuel cell output stream is burnt in a combustor and enters the gas turbine. Output hot gases runs HRSG and then three steps steam turbine. Likewise outlet CO₂ from the fuel reactor is used in CO₂ HRSG and is separated from water in three steps [58]. In another suggested process, biomass after gasifying in the steam gasifier, preheats the incoming air to the cathode, then is divided into two parts. First part after reforming enters the anode and second part by combining anode output, goes into the carbonator. Carbonation solid product enters the calcinator and calcinator’s solid output goes into the hydrator and after the reaction with entranced steam to hydrator, completes the loop and enters the carbonator. H₂ after cooling in HRSG, is purified from the carbonator gas product, and CO₂ (calcinator gas product) after crossing the HRSG and compression, goes to the storage system. Hot steam entering the gasifier and reformer is a result of heating in HRSG. Also anode product after burning in gas turbine, passes HRSG. Again HRSG handles a three level steam turbine [60].

Fig. 7 shows a SOFC-CLC-GT- based power plant with supplying pure oxygen for AR and gasifier by means of ASU. Combustion occurs in a three reactors CLC system.

In a combined trigeneration system, a part of inlet air to the process after compression and intercooling, follows to the air separation unit. Oxygen part along with coal feed and steam, enter the gasification-island. Syngas enters the fuel reactor. Reduced particles enter the steam reactor and then air reactor and after being fully oxidized, return to the fuel reactor. Fuel reactor gas product containing CO₂ and H₂O is cooled in HRSG and after compression, is divided. A part of H₂/H₂O stream from steam reactor after passing through H₂ turbine enters the anode and remaining part, after cooling in HRSG, enters a splitter and purifies H₂. Beside reduced air from the air reactor enters the cathode. SOFC outputs, in addition to N₂ part of ASU output, after burning in GT follow to HRSG. HRSG supplies the required load in an ORC and a four level SRC power plants [61].

Fig. 8 illustrates a power generation system, using SOFC and steam turbine power plant. Chemical looping is provided by two separate two reactors systems. HRSG system provides a part of the required steam.

Yan et al. [64] proposed a power generation process which coal and biomass are gasified in a hydro-gasifier. Next CH₄-rich syngas after cleaning in a cleaner in addition to steam from steam generator goes into the reformer. A part of CaCO₃ produced in the reformer goes to calciner, and CaO returns and makes a loop. H₂-rich syngas with Fe₂O₃ coming from the combustor enter the reducer (fuel reactor) and its
product with H$_2$O goes to the oxidizer. Then Fe$_3$O$_4$ with air enter combustor and pure N$_2$ goes out. H$_2$ from the oxidizer with air enter SOFC then H$_2$O and N$_2$ are the outlet components. Recycled heat from the SOFC and other sections is used in the steam generator and supplies the required heat load in calciner too.

Fig. 9 indicates a typical layout of SOFC-based power generation using chemical looping system.

SOFC power generator processes, based on the chemical looping technology, have been analyzed from the efficiency point of view. Fig. 10 shows total energy and exergy efficiency, net power efficiency and electrical efficiency of the published records in this area.

Table 1 presents the main and highlighted operating conditions in SOFC/CLC-based power plants.

2.1.2. PEMFC/chemical looping- based systems

Lima da silva et al. [67] with analyzing performance of an integrated system of PEMFC and CLR, concluded that, the required power demand affects the overall efficiency of the PEMFC stack. Low loads result the efficiency around 45% while higher current values, lead to the efficiencies around 25%. Vairakannu and Kuamri [68] developed a process by means of power generation from underground coal resources. In this process, the produced hydrogen by CLR from UCG is used to power generation in a PEMFC system. The net efficiency of this system with carbon capture is obtained 43.6% whereas conventional reforming, leads to 37.95% of net electrical efficiency with carbon capture. A study of an integrated process (biogas sorption-enhanced chemical looping reforming (SECLR) and a high temperature PEMFC has been done. The results showed that heat integration, increases the exergetic efficiency from 16.6% to 26.72%. Also it is concluded that the total exergy destruction increases with cell temperature, whereas growing the current density, has opposite effect on the total exergy destruction [69].

Figs. 11–13 show a brief configuration of PEMFC-based power generation using chemical looping technology. Fig. 11 shows a power generation system with PEMFC which utilizes a water gas shift system and two CLC reactors.

In a suggested process, biogas with steam from steam generator goes to the heater, then enters the fuel reactor. Air after warming up follows to the air reactor. Air reactor output (N$_2$) passes a heat exchanger and fuel reactor output after crossing another heat exchanger, with a stream of steam from steam generator enters IT (intermediate temperature) water-gas-shift reactor. Its exhaust stream with O$_2$ stream goes into COPROX (CO preferential oxidation reactor). Then after crossing a heat exchanger enters the anode. Also an air stream enters the cathode [67].

Fig. 12 exhibits a three reactors CLC configuration with PEMFC-based electricity generation.

In Kasemanand et al. [69] syngas after preheating is fed to the fuel reactor. Solid product circulates between three fuel, calcination and air reactors respectively to regenerate oxygen carrier. Gas outputs of these reactors are used for preheating of the. H$_2$ outlet from the fuel reactor enters the anode and air enters the cathode of the PEMFC.

Fig. 13 illustrates power production with PEMFC and combined power cycle process configuration. With oxygen supplying by ASU and combustion in a three reactors CLH process by an integration of HRSG system to other parts of the overall process.

In a hybrid UCG, PEMFC and combined power plant process, air after compression enters the air reactor and its product with gas turbine exhaust follow to the fuel reactor. Produced syngas after preheating and power production in the gas turbine, crosses a HRSG then returns to the fuel reactor. Reduced particles in the fuel reactor goes to the steam reactor. Next fully oxidized particles return to the air reactor and gas.
outlet after passing a HRSG, goes into the anode. Pure O₂ from the air separation unit enters the cathode and excess O₂ is recycled. Air reactor discharged air, runs an air turbine, then crosses a HRSG. Produced steam runs a steam turbine [68].

Fig. 14 indicates a detailed PEMFC-based power generation system using chemical looping technology.

Fig. 15 shows the net efficiency, electrical efficiency, exergy efficiency and overall PEMFC stack efficiency in power generation processes with integration of PEMFC power generator and chemical looping system.

Table 2 exhibits some important parameters applied in PEMFC/chemical looping-based power plants.

2.2. Thermo-mechanical power generation/chemical looping-based systems

In this section, the processes using chemical looping technology,
based on the turbine power cycles are collected and discussed. First the processes with steam power plants are reviewed. Then gas turbine-based power generator processes are discussed. The last part of this section, investigates CLC-based power generator processes with combined cycle plants.

2.2.1. Steam turbine power plants/chemical looping-based systems

Cormos [70] evaluated the syngas-based chemical looping application for co-product (power and hydrogen) systems. Capacity of the process is 350–450 MW net electricity and a 0–200 MW hydrogen (based on LHV) production. Gasifier selection, gasifier feeding system, heat and power integration system, and some other potential ways to increase efficiencies, were investigated concepts. Tong et al. [71] offered a 25 KW th sub-pilot unit, using a three reactor chemical looping hydrogen generation with syngas as fuel. This work focus on scaling this technology for commercialization. And a comparison between simulation and experimental results for syngas conversion was done. The result show that moving bed reactors have advantages over fluidized bed ones. An evaluation of a 100 MW th CLC plant with integration of CLC reactors, steam cycle and heat recovery system, was done by Peltola et al. [72]. The net cycle efficiency is obtained 42.8% and it is found that a 2% decrement in fuel conversion, brings the net cycle efficiency about 1% down, so the reactor design is very important to achieving desirable efficiencies. Basavaraja and Jayanti [73] assessed fuel switching in a power plant with CLC technology. The kind of fuel specifies how the reaction in the fuel reactor to be (exothermic or endothermic). The temperatures of fuel and air reactors should slightly be varied to determine the nature of fuel oxidation reaction in terms of

<table>
<thead>
<tr>
<th>Year</th>
<th>Used fuel</th>
<th>Oxygen carrier type</th>
<th>Highlighted operational conditions</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>Natural gas</td>
<td>Ni, Fe and Cu-based</td>
<td>- SOFC - Anode Temperature: 800 °C - Cathode Temperature: 800 °C - CLC - Air reactor Temperature: 735 °C Pressure drop: 0.15 bar - Fuel reactor Pressure drop: 0.15 bar</td>
<td>[66]</td>
</tr>
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exothermic/endothermic. With some considerations for the system, it is concluded that it is feasible to switching between syngas and natural gas. Spinelli et al. [74] developed a CLOU power plant and optimization of effective items to efficiency, was done. The results was a 42% net electric efficiency with carbon capture more than 96%. In a project, application of inverted Brayton cycle with CLC was investigated. It was found that IBC, can show its benefits when is used with integration with other power generation systems. In a case study, 6% efficiency in a IBS with steam cycle was obtained in comparison with a simple steam cycle (39% versus 33%) [75]. Shah et al. [76] introduced a hybrid process called chemical looping oxy combustor. CLOC consist of CLAS unit with integration of oxy-fuel combustor which has many advantages than conventional systems. In this work, a comparison between the introduced collections of units with oxygen carriers against conventional processes, was done. It was found that energy penalty of CLOC system, is almost 3–4% and 50% less than CASU and about 4–5 times less than CLOU systems respectively. A 1500 MWth power plant based on the CLC is presented by Basavaraj and Jayanti [77] with considering CCS and syngas as the fuel. With considering CO$_2$ compression cost, the gross cycle efficiency and the net cycle efficiency is achieved 41.22% and 36.77% respectively. Cormos [78] evaluated the CLOU in a 100 MWth power plant with > 99% carbon capture efficiency. It was found that CLOU system has 5–15%, 10%, and 50% average lower costs on specific investment costs, electricity cost and CO$_2$ capturing cost respectively. A study about a 10 MWth power plant with CLC (DCFB type) and five-stage steam turbine in steam cycle is carried out. The net electrical efficiency is predicted 32.5–35.8% [79]. A study of two scenarios for power generation of natural gas with CLC is done. The real net efficiencies were obtained 38.34%-39.88% and it is found that by applying more advanced steam cycle, the efficiency could be higher than 40% [80]. Authier and Moullec [81] investigated a 250 MWth coal fired CLC power plant and presented 41.6% and 48.4% for net and gross electrical efficiency (LHV) respectively. A hydrogen and oxygen combined cycle with chemical looping hydrogen generation (HO-CLH) is developed. With TIT of 1300°C, the HO-CLC and RHO-CLC cycle efficiency can reach to 55.5% and 58.9% respectively that these values are expected to be reduced about 8–12% in the combined cycle with CO$_2$ capture [82]. Hanak et al. [83] modelled and studied solvent scrubbing and Ca-looping retrofits for CO$_2$ capture in a coal-fired power plant. It was demonstrated that CaL scenario is less complex and the efficiency penalties were found 6.7–7.9%, 9.0% and 9.5% for CaL, mono-ethanolamine and chilled ammonia scrubbing retrofits respectively. It was revealed that the most effective parameters on the net thermal efficiency and the net power output are sorbent make-up rate, CO$_2$ capture and O$_2$ content in the calciner fluidizing gas. Zhou et al. [84] investigated an integrated ICLAS process for oxy-fuel combustion for a presumptive coal- fired power plant with a capacity of 500 MW. They suggested to integrate ICLAS with steam cycle and methane firing or solar heating to avoiding the lower temperature of oxidation reactor, rather than reduction reactor, because of the impossibility of heat transfer from low temperature reactor to high temperature one. Also it was reported that the energy requirement for oxygen production in ICLAS is 75–80% lower than CASU. Shah et al. [85] developed an ICLAS process in a coal-fired power plant and reported that suggested path,
leads to much lower operating costs (1–10%) rather than an advanced CASU-based unit. A co-generation process was developed by Cebrucean [86] and it was demonstrated that in H₂ production section, using a moving bed reactor results higher efficiency than fluidized bed system (55.1% compared to 44.0%). Also in the electricity generation part, SCL-MB leads to higher efficiencies rather than SCL-FB systems (39.9% compared to 38.5%).

Figs. 16–24 provide an overview of the processes using chemical looping technology, with power generation based on steam cycle power plant. Fig. 16 shows a simple power generation with steam turbine, based on two reactors CLC system.

In a pre-commercial scale plant, fuel enters fuel reactor and its flue gas is being used for feed-water and air preheating which enter air reactor. Air reactor exhaust steam runs three continues steam reactor [72]. In a gas-fired power plant, fuel enters the fuel reactor. Its flue gas after preheating the turbine outlet water and producing steam, goes for H₂O condensing and CO₂ sequestration. Preheated steam and air, go into air reactor and its outlet steam runs a turbine [73]. In an integrated CLOU plant, coal enters fuel reactor and reduced oxygen carriers after carbon stripping and oxidation in the air reactor returns into the fuel reactor. CO₂ stream is used in fuel reactor and carbon stripper. Superheated and reheated water is sent to the air reactor and gas turbines which operates in three pressure levels for power generation. Gas turbine exhaust water after passing economizer, enters the fuel reactor [74]. In a process using inverted Bryton cycle for CLC process, natural gas and carbon dioxide enters the fuel reactor. After reaction of reduced particles and air in the air reactor, a part of discharged gas stream supplies the first steam cycle heating requirement, and remaining part goes into an inverted Brayton and then second steam cycle [75]. In the suggested process by Shah et al. [76] limestone and water besides coal enter an oxy-circulating fluidized bed combustor. The output steam runs a three step steam cycle and the flue gas after stripping the ash and sulfur in a cyclone, goes into the reduction reactor along with CH₄ as the feed. The output hot stream containing O₂, CO₂ and H₂O crosses a heat exchanger to heat up returned flue gas which enters the reduction reactor. Air and H₂O follows to the oxidation reactor. Produced gas heats the output steam up to drive a steam turbine.

Fig. 17 presents a steam cycle-based power generation, with two reactors CLC system which applies an oxy-firing combustor. In the CLAS process, studied by Zhou at al. [84] coal with a 26 vol% O₂ stream enter an oxy-pf furnace. The flue gas after preheating the inlet O₂ containing steam, ash and sulfur, is split into two parts. One part goes to CO₂ process unit and remaining is recycled to the reduction reactor. CH₄ stream enters this reactor too. Air acts in the reduction reactor·H₂O heated in the oxidation reactor, runs a steam turbine. Another H₂O stream passed oxy-pf, handles a three steps steam power plant. In another introduced process, the main structure of the process is the same as last explained one, but an addition part is applied. The solar heating is used in the reduction reactor heat supply system and particles temperature raising 90 °C between oxidation and reduction reactors [76,84]. In an ICLAS process introduced by Shah et al. [85] coal or natural gas enters an IBS or IGS. Produced CO₂ + H₂O with
steam at 560 °C goes into the reduction reactor. Its output stream along with coal feed goes into an oxy-furnace. H₂O from condenser passes a steam drum and then is sent to steam turbine. The flue gas enters cleaning and CO₂ processing unit, then CO₂ is stored. The required air for oxidation reactor is supplied by an air blower.

Fig. 18 shows a two reactor CLC with steam turbine power generation and heat recovery by HRSG system.

Basavaraj and Jayanti [77] presented a process in which fuel with air enter the fuel reactor and gas products after steam preheating follows to water condensing and carbon dioxide compression. Reduced particles are sent to the cyclone. Oxygen depleted air goes to steam preheating and solid part enters air reactor which reacts with input preheated steam and air. Superheated output steam from the air reactor enters the turbine and turbine’s output steam is preheated for entering the air reactor. In the power generation process with CLOU concept suggested by Cormos [78], fuel after conditioning (drying and grinding) enters the fuel reactor. Output steam goes to HRSG and power generation in the steam turbine. Condensates are separated and output CO₂ goes to drying and compression. In a 10 MWth power plant with CLC technology, natural gas enters the fuel reactor and flue gas follows to the steam generation unit and then is sent to CO₂ compression. Air after preheating enters the air reactor and exhausted gas is used for steam preheating.

![Flow Sheet of O₂/CO₂ blown UCG Integrated Conventional Syngas Reformer Based PEMFC Cycle Power Plant](image-url)

**Fig. 14.** A detailed flow sheeting of O₂/CO₂ blown UCG integrated conventional syngas reformer based PEMFC cycle power plant [64]. With permission of Elsevier, 2018.

![Bar Chart: Efficiency Comparison](image-url)

**Fig. 15.** Net efficiency, electrical efficiency and overall efficiency of PEMFC stack in PEMFC/chemical looping-based systems.
generating and then air preheating. HRSG output steam runs steam turbine unit [79]. In a process of CLC by NG, fuel enters the fuel reactor, then the outlet stream passes from the super heater, economizer and condenser as hot stream and then goes to CO2 compression. Preheated air and super-heated steam with reduced particles enter the air reactor. Depleted air from the air reactor crosses steam super heater, economizer, steam generator and low pressure steam generator. Super-heated steam and steam generated in HP and LP HRSG follows to a series of stages steam turbine power plant. Carbonator and calciner run primary and secondary super-heaters as HRSG.

Fig. 19 illustrates a two reactor chemical looping combustion with syngas generated from the gasification system integrated with steam cycle power generation and HRSG systems.

In a 250 MWe power system introduced by Authier and Moullec [81], syngas after fuel gasification, enter the fuel and air reactors respectively. Gas parts of each reactor’s product goes to HRSG and then produced steam runs respective steam cycles for power generation.

In the presented process by Zhang et al. [82] CH4 with H2O from the steam turbine enters reduction reactor. Output H2O and CO2 after cooling and condensation are separated. A part of the mentioned water follows to the oxidation reactor and the rest enters the combustor. Output H2 from the oxidation reactor along with the inlet water and O2 from the ASU, react in the combustor and produced H2O handles a steam turbine.

Fig. 20 displays a process configuration with carbonation/calcination reactions occurring in dual reactors with oxygen supplying by ASU and heat recovery steam generation system integrated with ST power generation.

A Ca-looping and chemical solvent scrubbing for CO2 capture was developed by Hanak et al. [83] in which flue gas from the coal-fired power plant CFPP (coal fired power plant) after preheating enters the carbonator. The output gas passes economizer then clean flue gas leaves the process. Fuel, O2 from ASU, recycled CO2 and Limestone make-up enter the calciner. Output CO2 enters CCU and output steam runs three stages steam turbine power plant. Carbonator and calciner run primary and secondary super-heaters as HRSG.

Fig. 21 shows three reactor chemical looping system with gasification and ST-based power generation.

In a co-generation process developed by Cormos [70], syngas from gasifier-island, steam and air streams enter fuel, steam and air reactors respectively. Solid particles circulate between these reactors to oxygen carrier regeneration. Steam part of the outputs go to the power generation section. CO2 from the fuel reactor after drying and compression goes to the storage system. A part of H2 from the steam reactor is used for power generation and the rest is sent to the compression and purification sections.

Fig. 23 explains an integrated process of gasification, three reactor chemical looping system, steam turbine power plant and heat recovery system.

Tong et al. [71] introduced a hydrogen and power generation system in that, syngas from the gasifier and H2-rich gas and unreacted gases from the MeOH goes into the reducer. Exhaust CO2, H2 and un-reacted gas from the reducer along with H2O and O2 after burning goes to the CO2 sequestration. Reduced particles are sent to the oxidizer. Produced gas is split to water and hydrogen. Then partially oxidized particles after fully oxidizing in the combustor returns to the reducer. Output depleted air enters turbine, then crosses a HRSG.

Fig. 24 shows a process similar to the process illustrated in Fig. 23, with difference in oxygen supplying.

In the process provided by Cebrucean et al. [86] coal + transport

<table>
<thead>
<tr>
<th>Year</th>
<th>Used fuel</th>
<th>Oxygen carrier type</th>
<th>Highlighted operational conditions</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>Biogas</td>
<td>Nickel-based</td>
<td>• CLR</td>
<td>[67]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(consisting of 20 wt% NiO and 80 wt% Al2O3)</td>
<td>• Air reactor</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Temperature: 949 °C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Fuel reactor</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• Temperature: 800 °C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Preheat of reactants (biogas, steam, air)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Temperature: 400 °C</td>
<td></td>
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<tr>
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<td></td>
<td></td>
<td>• Reformer (SR, PO, ATR) or Fuel reactor (CLR)</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• H2O/CH4 molar ratio: 3:2</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>Coal</td>
<td>Iron-based (Fe2O3 (hematite)/FeO (wustite))</td>
<td>• Reforming reactor</td>
<td>[68]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Temperature: 800 °C</td>
<td></td>
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<tr>
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<td></td>
<td></td>
<td>• Water-gas shift reactor</td>
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<td></td>
<td>• Temperature: 350 °C</td>
<td></td>
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<td></td>
<td>• Fuel reactor</td>
<td></td>
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<td></td>
<td></td>
<td>• Temperature: 700 °C</td>
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<td></td>
<td></td>
<td></td>
<td>• Steam reactor</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• Temperature: 700 °C</td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td>Biogas</td>
<td>Nickel- and Calcium-based (Ni/NiO and CaCO3/CaO)</td>
<td>• Fuel reactor</td>
<td>[69]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Temperature: 500 °C</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>• Calcination reactor</td>
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<td>• Temperature: 900 °C</td>
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<td></td>
<td>• Air reactor</td>
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<td></td>
<td></td>
<td></td>
<td>• Operating pressure: 1 bar</td>
<td></td>
</tr>
</tbody>
</table>
gas, steam and O₂ from ASU enter the gasifier. Raw syngas after scrubbing and cooling, goes for H₂S removing. Clean syngas enters the fuel reactor (reducer). Steam and air enter the steam reactor (oxidizer) and air reactor (combustor) respectively. Hot streams CO₂ + H₂O, H₂ + H₂O and depleted air (N₂) from the fuel, steam and air reactors respectively follows to the heat recovery steam generation. Generated steam, runs steam cycle power plant and output water is recycled to the HRSG. CO₂ and H₂ discharging from HRSG are purified from water as the target products. Fig. 25 shows a typical process with integration of steam cycle power generation and chemical looping system. Fig. 26 shows efficiencies reported in the steam turbine-based power generator processes which apply chemical looping system. Gross and net electrical efficiencies, net cycle efficiencies and net power
efficiencies are shown with different colors.

Table 3 provides the substantial conditions and parameters for ST-based power generator processes with chemical looping application.

2.2.2. Gas turbine power plants/chemical looping-based systems

Two process alternatives (ex-CLC and CLC3) beside a conventional CLC system were considered and evaluated from energy and economics point of view. It is demonstrated that efficiency of the proposed system is about 54% whereas a conventional system with the same conditions, offers a 46% efficiency [87]. An integrated biomass-fired process is introduced which recovers the released heat from the LNG vaporization. Energy efficiency of the process is 57.3% and produced H₂ is about 166.8 kmol/h with 100% CO₂ capture [88]. Wang and Fu [89] investigated a solar-hybrid trigeneration system and reported a 67% energy efficiency and 55% exergy efficiency which is 7% and 4% higher than the conventional trigeneration system. A solar CCHP system is provided by He et al. [90] by estimation of thermal efficiency of 96.7% and exergy efficiency of 35%. Exergy destruction of this system is almost 10.3% lower than the conventional one. An evaluation for CLC in a power plant was done and it was found that the overall efficiency is highly affected by oxidation inlet and outlet temperature and with considering the compression of CO₂ (1–100 bar), efficiency would be decreased 2% [91]. In this study total efficiency is obtained 45.1%–55.9%. An analysis for exergy loss in a LNG power plant using CLC with thermal efficiency of 50.2% (LHV) was done and it is demonstrated that preheating the reactants reduces the exergy loss in the reaction part [92]. Also intercooling the air during the compression and methane saturating with water, helps the heat recovery. Co-generation of power and H₂ is considered and after evaluation of the process, it is concluded that, the overall efficiency of the complete cycle depends on the oxidizer pressure and optimum value is obtained 75% [93]. Ishida and Jin [94] introduced an integrated process called CLSA with the expecting of 55.1% (LHV) power plant efficiency with water recovery and 56.7% without it, which these values are 7–8% higher than
They inferred that using combination of both saturated air using and CLC technologies, results lower exergy destruction in all temperatures. Whereas the first, is effective in low and middle temperature regions and the latter, shows its performance in middle and high temperature regions. Han and Bollas [95] in an optimization work for maximizing the energy efficiency on integrated CLC power generation systems, illustrated that batch fixed bed reactor utilization would show better results. Hassan and Shamim [96] evaluated a CLC power plant about the fuel and OCs. The results revealed that Fe- and Ni-based OCs offer maximum thermal efficiencies. Cu-based particles result highest reduction reactor temperatures and Fe-based materials require larger mass flowrates of OC, rather than two other particles. Although it is illustrated that NG offers higher thermal efficiencies (50%), whereas syngas-fueled power plants due to greater fuel heat capacities and higher air feed flowrates, show lower efficiencies (44%). The performance of two configurations for CLC power generation was assessed by Hamers et al. [97]. They reported a 41.1% net electric efficiency (LHV) in IG-CLC system and efficiencies between 40.3% and 40.8% for TS-CLC system were obtained. Co-production of hydrogen and electricity with chemical looping was introduced by Cleeton et al. [98]. They showed for a fully heat integrated process, the peak exergy efficiency for 1 atm and 10 atm conditions, would be obtained 48.4% and 58.3% respectively. Also it was inferred that by adding a bottoming steam cycle, these values could be increased to 53.7% and 59.7% respectively. An analysis on a CLC-based power plant was done by Iloege et al. [99]. They illustrated that by preventing the temperature difference between two reactors of CLC system and accordingly the presence of thermal equilibrium between air and fuel sides (by using a rotary CLC reactor), the cycle efficiency will improve up to 2% points. The maximum values are obtained 51% at 1000 °C, 3 bar and 60% at 1400 °C, 4 bar. A tri-generation exCLC-STIG process was studied by Wolf and Yan [100]. It was inferred that by optimizing
Fig. 23. Steam turbine power plant, gasification, chemical looping system with three reactors, HRSG.

Fig. 24. Steam turbine power plant, ASU, gasification, chemical looping system with three reactors, HRSG.
the power efficiency and consideration of 95% CO₂ capture, the power efficiency and thermal efficiency would reach 24% and 47% respectively. On the other hand, by maximizing the hydrogen production, almost 40% hydrogen efficiency and about 54% thermal efficiency could be obtained. Zerobin et al. [101] studied and evaluated a DCFB design on a scale of 10 MW power plant for a pressurized natural gas-fueled CLC. They reported that using CLC technology, may reduce the net electric efficiency rather than conventional GTCC processes (38.47–40.34% versus about 60%). The reasons of this decrease are low TIT (AR operating temperature), required steam for fluidization, higher pressure drop rather than conventional systems and limited pressure ratio. A CLC-based co-production of hydrogen and electricity from coal was investigated [102]. The results indicated that by SR temperature of 815 °C and steam conversion rate of 37%, the system efficiency can reach 57.85%. It was showed that by increasing the steam conversion rate from 28 to 41%, the system efficiency increase from 53.17% to 58.33%. Also exergy efficiency of the proposed system, was obtained 54.25%.

Figs. 27–39 show simplified CLC-based power generation processes by means of gas turbine cycles. Fig. 27 illustrates a simple power generation based on gas turbine system using two reactors chemical looping combustion.

In a simulation study of CLC-based power plants, a process was discussed in which, MEO and NG enter reduction reactor and air after compression enters oxidation reactor. Output CO₂ from the reducer goes for power generation and the oxidizer exhaust enters gas turbine [87]. In the NG-fired power plant offered by Brandvoll and Bolland [91], air after compression preheats the CH₄ stream then, after crossing saturator is heated by gas turbines output hot streams in three steps, next enters the oxidation reactor. Preheated CH₄ goes into the reduction reactor. Both reactors exhaust runs a distinct gas turbine. In an exergy analysis study, a process was proffered that at first, natural gas after preheating, crosses saturator and contacts with hot water. Then after heating, enters reduction reactor. Exhaust gas after heating in two continues heat exchangers, enters GT which its hot output is used for air and fuel preheating in addition to heating GT entrance stream. Air at environment condition is compressed and preheated then goes for oxidation. Oxidation exhaust handles two gas turbines and heats transient particles between reduction and oxidation [92]. In a H₂ and power co-generation system submitted by McGlashan et al. [93] CH₄ enters reduction reactor. Air is compressed then goes into the oxidizer. Output flue gas from oxidation reactor runs a gas turbine. In another power generation system based on the CLC, CH₄ after preheating enters the reduction reactor and its exhaust enters a gas turbine [94]. Output of the GT is used for fuel preheating. Air after compression and heating in several stages goes for saturating then is used for oxidation in the oxidation reactor.

Fig. 28 displays a power generation by gas turbine with heat recovery system, which applies chemical looping combustion.

In an optimization study of CLC integrated with thermal power plants, Han and Bollas [95] discussed a process in that; air, inert gas and fuel that is considered CH₄ or syngas enter CLC system. A part of hot output gas enters gas turbine and other is used for heat recovery.

Fig. 29 shows a two reactor CLC system with GT cycles with using
<table>
<thead>
<tr>
<th>Year</th>
<th>Used fuel</th>
<th>Oxygen carrier type</th>
<th>Highlighted operational conditions</th>
<th>Reference</th>
</tr>
</thead>
</table>
| 2010 | Methane           | Iron-based (Fe$_2$O$_3$/Fe$_3$O$_4$)                    | - Air reactor  
Temperature: 1000 °C  
- Fuel reactor  
Temperature: 890 °C | [75]       |
| 2011 | Methane           | Nickel- and Manganese-based (Ni/NiO- Support materials Al$_2$O$_3$ + MgO NiO content 41.3 wt%) | - Fuel reactor  
Temperature: 900 °C  
Pressure drop: 0.185 bar (Real conversion) 0.183 bar (Ideal conversion)  
- Air reactor  
Temperature: 980 °C  
Pressure drop: 0.048 bar (Real conversion) 0.048 bar (Ideal conversion) | [79]       |
| 2012 | Coal and syngas   | Iron-based (magnetite (Fe$_3$O$_4$))                     | - Gasification  
Temperature: > 1400 °C  
- Fuel reactor  
Temperature: 750–900 °C  
Pressure: 30.5 bar  
Pressure drop: 1 bar  
- Steam reactor  
Temperature: 500–700 °C  
Pressure: 29.5 bar  
Pressure drop: 1 bar  
- Turbine outlet temperature (TOT): 588 °C  
- ASU  
Oxygen and nitrogen delivery pressure: 2.37 bar  
- Reducer  
Temperature: 900 °C  
- Oxidizer  
Temperature: 800 °C  
- Combustor  
Temperature: 700 °C | [70]       |
| 2013 | Syngas            | Iron-based (Fe$_2$O$_3$/Fe$_3$O$_4$/FeO)                 | - Fuel reactor  
Temperature (target): 900 °C  
Temperature (average): 900 °C  
Temperature (flue gas): 885 °C  
- Air reactor  
Temperature (average): 927 °C  
Temperature (flue gas): 916 °C  
Operating pressure: ∼ 1 bar | [71]       |
| 2013 | Methane           | Nickel-based (Ni-based (40 mass%) and Al$_2$O$_3$ supported) | - Fuel reactor  
Temperature (target): 900 °C  
Temperature (average): 900 °C  
Temperature (flue gas): 885 °C  
- Air reactor  
Temperature (average): 927 °C  
Temperature (flue gas): 916 °C  
Operating pressure: ∼ 1 bar | [72]       |
| 2013 | Coal              | Manganese-based (Mn$_2$O$_3$/MnO The pulverized oxygen carrier is supported by natural magnesium aluminate (MgAl$_2$O$_4$ ∼ 30% mass)) | - Fuel reactor  
Temperature: 985 °C  
- Air reactor  
Temperature: 1000 °C  
- MnO$_2$/Mn$_2$O$_3$ system  
Operating temperature: 350–450 °C  
- CuO/Cu$_2$O system  
Operating temperature: 850–1050 °C  
- CoO/Co$_3$O$_4$ system  
- Reduction  
Temperature: 927 °C  
- Oxidation  
Temperature: 797 °C  
(leads to higher oxygen concentration (∼ 90 wt%)) | [81]       |
| 2013 | Coal              | Manganese-, Copper- and Cobalt-based                     | - HO-CLH system  
Temperature: 650 °C  
Pressure: 40 bar  
Turbine inlet temperature: 1300 °C  
Turbine inlet pressure: 40 bar  
- RHO-CLH system  
Temperature: 760 °C  
Pressure: 40 bar  
Turbine inlet temperature: 1300 °C  
Turbine inlet pressure: 40 bar  
- Copper oxide system  
- Oxidation reactor  
Temperature: 950 °C  
- Reduction reactor  
Temperature: 1025 °C  
- ICLAS unit  
Oxidation reactor  
Temperature: 950 °C  
- Reduction reactor  
Temperature: 1025 °C  
- Copper oxide system  
- Reduction reactor  
Temperature: 950 °C  
- Reduction reactor  
Temperature: 1025 °C | [76]       |

(continued on next page)
<table>
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<tr>
<th>Year</th>
<th>Used fuel</th>
<th>Oxygen carrier type</th>
<th>Highlighted operational conditions</th>
<th>Reference</th>
</tr>
</thead>
</table>
| 2015   | Natural gas or syngas          | Nickel-based (NiO/NiAl₂O₄ as support)                    | Temperature: 1040 °C  
- Manganese oxide system  
- Reduction reactor  
Temperature: 915 °C  
- Cobalt oxide system  
- Oxidation  
Temperature: 845 °C  
- Reduction  
Temperature: 895 °C  
- CLAS/CLOU  
- Oxidation reactor  
Temperature: 800–950 °C  
Pressure: 1 bar  
- Reduction reactor  
Temperature: 900–1042 °C  
Pressure: 1 bar  
- Air reactor  
Temperature: 1000 °C (natural gas) 900 °C (syngas received)  
- Fuel reactor  
Temperature: 900 °C (natural gas) 908 °C (syngas received) | [73]       |
| 2015   | Syngas                         | Nickel-based (NiO)                                       | Temperature: 900 °C  
Pressure: 1 bar  
- Air reactor  
Temperature: 900 °C  
Pressure: 1 bar  
- Fuel reactor  
Temperature: 908 °C  
Pressure: 1 bar | [77]       |
| 2015   | Coal                           | Calcium-based                                            | Temperature: 650 °C  
- Carbonator  
Temperature: 900 °C  
Pressure: 1 bar  
- Calciner  | [83]       |
| 2016   | Coal                           | Copper-based (a 50:50 mixture (weight basis) of active CuO/Cu₂O and supporting TiO₂) | - Air reactor  
Temperature: 899.8 °C  
Pressure: 1.01 bar  
- Fuel reactor  
Temperature: 921.3 °C  
Pressure: 1.01 bar | [74]       |
| 2016   | Natural gas                    | Manganese-based                                          | - Reactors  
Temperature: 900 °C  
Pressure: 1 bar  | [80]       |
| 2016   | Coal and Natural gas           | Copper-based (CuO – SiO₂ Cu oxide particles on the SiO₂ support) | - Oxidation reactor  
Temperature: 950 °C  
Pressure:1.0 bar  
- Reduction reactor  
Temperature: 1040 °C  
Pressure: 1 bar | [84]       |
| 2016   | Syngas                         | Iron-based (Fe₂O₃)                                       | - Gasification  
Temperature: 1450 °C  
Pressure: 42 bar  
- Fuel reactor  
Temperature: 900 °C  
Pressure: 30 bar  
- Steam reactor  
Temperature: 800  
Pressure: 30 bar  
- Air reactor  
Temperature: 1200 °C (max.)  
Pressure: 30  
- HPST inlet  
Temperature: 565 °C  
Pressure: 125 bar  
- IPST inlet  
Temperature: 565 °C  
Pressure: 30 bar  
- LPST inlet  
Temperature: 290 °C  
Pressure: 4.5 bar | [86]       |
| 2017   | Fossil and Renewable fuels     | Copper-based (CuO/Cu₂O: TiO₂)                            | - Fuel reactor  
Temperature: 925–950 °C  
- Air reactor  
Temperature: 910–940 °C  
- Operating pressure: 28 bar (for natural gas system)  
atmospheric (for solid fuels systems) | [78]       |
additional combustion chamber.

In a GT-based power plant, natural gas is divided to two streams. First part by combination of fluidization steam enters fuel reactor, second part with output of the air reactor goes into optional combustion chamber. Compressed air after combination with a portion of fluidization steam, enters air reactor. Exhaust of the combustion chamber runs a gas turbine which is coupled with compressor [101].

An integrated process, is introduced in Fig. 30, Gasifier supplies the syngas for chemical looping combustion system which works by two reactors. The gas cycle uses hot stack gases for power generation and HRSG supplies the needed steam.

Zerobin et al. [102] studied reactor design for CLC of NG and used a process which in that, coal is gasified by oxygen agent. Syngas enters fuel reactor. Its outlet gas after running a gas turbine goes for heat recovery and next goes for CO2 separation. Exhaust from steam reactor goes into a turbine, then enters HRSG. H2 is purified from this output by condensation and compression. Generated steam of HRSG is sent to the steam reactor.

Fig. 31 demonstrates a GT power generation system that uses a two reactors chemical looping combustion integrated with solar thermal system and steam generation by heat recovery.

In a thermodynamic analysis of a solar-hybrid trigeneration system, a process has been evaluated in which, CH4 and air after compression enter the reduction and oxidation reactors respectively. Solar heat...
supplies the required heat for both reactors. Outlet gas of each reactor handles a gas turbine. Gas turbine exhaust is cooled in an adsorption chiller. Cooled streams go to the heat exchanger for water heating. Then cooled reduction reactor exhaust, goes for H2O and CO2 separation [89]. In the process suggested by He et al. [90] Air after compression and DME after preheating enter the oxidation and reduction reactors respectively. Solar thermal energy is used in fuel preheater and reduction reactor. Oxidation and reduction reactors exhausts enter two discrete gas turbines. Turbines outputs cross absorption cooling subsystem which recovers heat in an absorber and a condenser by cooling water as cold stream and in an evaporator by chilled water cold stream. Then cooled exhaust streams enter heating subsystem for heating the water. After this step, CO2 and H2O are separated by a condenser. Fig. 32 shows an integration of ASU, gasification, two reactors CLC system and gas turbine power generation.

In process introduced in reference [103], coal feed stock with O2 from ASU and steam enter the gasifier. After ash separation and produced syngas cleaning (sulfur recovery), clean gas goes into the reduction reactor. Its exhaust gas runs a GT then preheats the air and goes for CO2 separation by condensation. Air is preheated and is compressed in several steps and after crossing a saturator, enters oxidation reactor. Its output gas after power generation in a gas turbine is used in one of the air preheaters.

Fig. 33 presents a chemical looping hydrogen generation with three reactors, by power generation based on GT power plant.

In a proposed power generation system based on the chemical looping, MeO and natural gas enter the reduction reactor. Output Me goes into the steam reactor and CO2 goes for power generation. Air after compression and steam recovered from the compression section enter steam reactor. Output flue gas goes into the burner and its exhaust,
enters the gas turbine. Partially oxidized particles along with compressed air follows to the air reactor. Its output gas enters the mentioned burner and output particles are recycled and added to the inlet MeO [87]. Fig. 34 shows a three reactor chemical looping system with heat recovery and GT- based power generation.

In a tri generation process studied by Wolf and Yan [100], methane enters the fuel reactor. H$_2$/H$_2$O output stream enters district heating and H$_2$ is purified. A part of the compressed air enters air reactor and its exhaust (N$_2$/O$_2$/H$_2$O) with combining with remaining part of air enters GT. Solid particles are in circulation between air, fuel and calcination reactors. CO$_2$/H$_2$O stream from the calciner after heat recovery and compression goes for CO$_2$ separation. Hot streams are used for steam
generation in HRSG unit. Fig. 35 exhibits a Ca-looping based hydrogen generation with three reactors in loop which is integrated with gasification process, power generation with gas turbine power cycle and LNG vaporization system.

In an integrated co-generation process developed by Mehrpooya et al. [88] produced syngas from the biomass gasifying by steam agent, enters the carbonator. Carbonation reaction product goes into the cyclone. Gas part follows to H₂ separation and solid part enters the calcination reactor. Next calciner solid output enters the hydrator. Hydration occurs with cooperation of entrance steam. Discharge particles return to the carbonator. Calcinator hot gas output after mixing with O₂ stream splits to two parts. First part after burning with NG goes for power generation in GT and second part is used for heating in three heat exchangers. LNG at −162.3°C after pumping, is split to three streams which each of them plays cold stream role in the mentioned heat exchangers. Three heated streams which have been converted to natural gas are mixed. A portion goes for burning before gas turbine and remain part is sent to the pipeline.

Fig. 36 shows a rotary reactor chemical looping combustion, integrated with GT- based power generation.

In the suggested process for power generation with carbon capture, air and fuel after compression, enter air side and fuel side regenerator respectively which are fed with H₂O stream. Purge steam from each regenerator enters CLC reactor. Output streams from each side (fuel and air sides) of CLC reactor runs a distinct gas turbine which outputs of each of them, passes air side and fuel side regenerators [99]. A power

---

**Fig. 33.** Gas cycle power plant, chemical looping system with three reactors.

**Fig. 34.** Gas cycle power plant, chemical looping system with three reactors, HRSG.

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generator process coupled with chemical looping combustion system, containing two FRs and two ARs in series and also gasification system is shown in Fig. 37.

A process is developed for H2 and electricity co-generation [98]. In this process, syngas produced by coal gasification by steam agent enters a reduction reactor. The outlet gas goes into another reduction reactor which its exhaust, runs a gas turbine. The outlet of this turbine (CO2 + H2O) is sent for cooling and condensing. Water with a pump is sent to a heat exchanger, then a part of resulted saturated steam enters first oxidation reactor and remaining goes into the gasifier. Output gas of this oxidation reactor (H2 + H2O) goes for H2 purification by cooling and condensing. Second oxidation reactor uses compressed air and its outlet gas runs a turbine then output N2 goes for cooling.

Fig. 38 illustrates a four reactor chemical looping system with FRs in parallel and ARs in series. Power generation with gas turbine power plant and heat recovery steam generator system are used in this process. A two stage CLC power generation process is investigated by Hamers et al. [97]. Syngas at 600 °C enters two parallel reduction reactors. A part of the compressed air passes air blower then goes into two continues oxidation reactors and remaining part of the air with combination of exhaust gas of second oxidation reactor, goes into the heat removal system. Then combines with compressed N2 from ASU runs a gas turbine. Output gas of GT enters heat recovery seam cycle.

Fig. 39 shows an arrangement of two stages CLC, GT power generator and steam generator with heat recovery.

Hassan and Shamim [96] expressed a process for evaluation of the oxygen carriers. In this process compressed fuel enters the first reducer. Its output gas after crossing an inter cell heat exchanger (heat exchanging with hot particles from first oxidizer), runs a gas turbine, then with combination by heated outlet gas of the second reducer, runs another gas turbine. Inlet air after compression follows to the first oxidizer. Output gas after running a gas turbine, is sent to second oxidizer. Its output gas is sent to another gas turbine. A part of the exhaust of this turbine passes second reducer, then first reducer. Remaining part is used for heat recovery.

Fig. 40 presents a typical detailed process with power generation by gas turbine integrated to chemical looping system.

The efficiencies calculated for power generation systems with gas turbine power plants and application of chemical looping technology is reported in Fig. 41. Energy, exergy, electrical, thermal and system
efficiencies has been provided and shown with particular colorful columns. Related references are presented in horizontal axis and efficiency values, are reported in vertical axis.

Table 4 presents the highlighted and substantial parameters which are most effective on the process performance like efficiencies, amount of recovered heat and hydrogen production content for GT/CLC based processes.

2.2.3. Combined cycle power plants/chemical looping-based systems

A techno-economic evaluation of a co-generation (hydrogen and power) CLC system with the capacity of 500 MW net electricity and hydrogen output of about 0–100 MW (LHV) is done [104]. It has been found that direct solid fuel CLC has a 5.7 net percent points and a 4.5 net percent points performance rather than gas-liquid and syngas-based looping systems respectively. A study on a co-production of hydrogen and power for a process with 300–450 MW net electricity and hydrogen production in a range of 0–200 MW (LHV) is done [105]. It is illustrated that direct coal CLC has lower oxygen consumption and offers higher energy efficiency (3–4% higher net electrical efficiency) in comparison with syngas- and solvent-based systems. Cormos [106] evaluates a BDCL co-product system performances in a 400–500 MW net power and a hydrogen output up to 200 MW. It was inferred that the BDCL system has 5.7% and 4.5% higher net energy efficiency (lower energy penalty) in comparison with gas-liquid adsorption and syngas-fueled CLC systems respectively. The cost of electricity for BDCL is 3.7% lower than gas-liquid system and about 5.7% higher than syngas-based CLC. Yang et al. [107] develop a techno-economic evaluation on hydrogen production of integrated process of oil shale retorting with chemical looping technology. The results indicate that exergy destruction is about 15.8% lower than conventional systems. Although OSR-CLH requires higher capital and production investment, instead more hydrogen is produced. An IGCLC process is assessed by Zhang et al. [108]
and it was found that setting the SHTCR on “2”, results the highest hydrogen production. The proposed power plant (IGCLC system) shows a better performance than conventional systems (80% and 36% higher efficiency with CCS consideration and without it respectively). A study on a CLC3 power generation system was carried out and it was inferred that, efficiency of the proposed system is higher than ATR one (up to 51.5% vs 49.5%) and CO2 is almost fully captured whereas its value in ATR is about 90.7% [109]. Khan and Shamim [110] did an exergoeconomic study for H2 and power generation on a CLR unit. They inferred that increase in mass flow rate of fuel, increases the thermal and exergetic efficiency and increase in steam, air and OC mass flow-rate, decrease it. Also it was found that CLR has a high exergy destruction which affects the cost rate and exergoeconomic factor. The specific costs of H2 and net power are obtained 2.9 $/GJ and 26.7 $/GJ respectively. Alvaro et al. [111] carried out a thermodynamic study on a syngas-fueled CLHG system. They reported a 63–67% overall efficiency with proposed considerations and they concluded that with no extra firing, the power yield is very low but the overall efficiency is the highest possible. A coal-fired co-production power plant is studied and the results reveals that with increasing the AR temperature via using a

[Diagram of a gas cycle power plant, gasification, chemical looping system with four reactors, HRSG.]
supplementary firing from 1000 °C to 1300 °C, the electric efficiency and H₂ efficiency change 10.13% to 14.34% and 41.51% to 36.93% respectively (total energy efficiency from 59.98% to 61.66%). The increase in supplementary temperature makes the electrical efficiency, the total energy efficiency and CO₂ emission higher and decreases the hydrogen efficiency and CO₂ capture. Also by the increase in oxygen carrier circulation the electric efficiency and plant total energy efficiency go up and CO₂ capture becomes lower slightly [112]. Xiang and Wang investigated performance of a combined cycle CLC power plant and reported a thermal efficiency of 44.4% (LHV) and 90.1% CO₂ capture efficiency [113]. Energetic performance of a CLC-based power plant with CCS was analyzed by Alvaro et al. [114]. They concluded that with a simple gas turbine, thermal efficiency would be better 2.1–2.9% and by considering the benefits of CCS, the efficiency improvement could be reach to the range between 4.5 and 5.9%. Also it was proved that because of reduction of exergy destruction in CLC systems, the optimal pressure would be lower than conventional systems. In a work, Petralopoulou et al. [115] performed a comparative study between a CLC power plant with 100% CO₂ capture and a reference plant without carbon capture, from the exerGO-economic and exergo-environmental points of view. The results indicated that produced electricity by CLC method, has lower environment impacts and diminish the exergy destruction in main components, would result better environmental effects. Additionally the fixed capital cost of CLC plant reported 71% higher than the reference plant which 35% of this value is related to CLC reactors and 13% of that, refers to newly added equipment for CCS. An exerGO-economic evaluation on a CLC-based power plant with CCS was done by Petarakopoulou et al. [116]. It was demonstrated that the reactor, expander and compressor of the main gas turbine, are the most important components for avoidable investment cost and exergy destruction cost. An assessment on the performance of a CLC-NGCC was done [117]. It was understood that the proposed power plant has comparable or higher efficiency in comparison with NGCC layout without CCS. Additionally, it was demonstrated that LP-HRSG configuration has better performance than HP-HRSG (about 10 MW higher power and around 2% higher net plant efficiency). In a work about CLC-based combined cycles, Stefano et al. [118] showed by increasing the temperature from 850 °C to 1200 °C, by a supplementary firing, the plant efficiency will grow from the range of 43–48% to about 52%. A CLC-based DME-fueled power generation system is studied [119]. The proposed system thermal efficiency reaches to 58.6%, which indicates 8.5% better performance, in comparison with DME-fueled combined cycle with CO₂ capture. A methanol-fueled CLC-based power plant is designed and developed by Jin et al. [120]. It was demonstrated that exergy destruction decreases and CO₂ is captured without energy penalty in comparison with conventional reference power plant. Also with a TIT of 1300 °C, thermal energy efficiency and CO₂ recovery were reported 60.6% (8% improvement rather than reference plant) and 70% respectively. In a comparison study between conventional and CLC-based IGCC system with three types of oxygen carriers (Ni-based, Fe-based and Mn-based) the Fe-based OCs exhibit higher output from GT and lower output from ST [121]. Shijaz et al. [122] carried out an analysis on an IGCCPP with Indian coal as fuel. The reported efficiencies were 42.69%, 40.2% and 35.8% for the system without capture, with looping combustion and with pre-combustion capture, respectively. An integrated process was developed by Fan et al. [123]. Coal and biomass enter as fuel and after gasification, syngas is consumed in the combined cycle power generation integrated with chemical looping combustion and heat recovery steam generation. The obtained energy and exergy efficiencies are 53.19% and 50.81% respectively. A study about benefits and limitations of a CLC coupling with gas turbine power plant was done [124]. The results shows that TIT is controlled by oxygen carrier material, and the required work for air compression goes up, because of CLC pressure drop. Likewise efficiency of the steam cycle decreases because of gas-sealing between FR and AR. These limitations decreases net electric efficiency under 45% versus 60% in commercial gas turbine system. A techno-economic evaluation of a CH₄-fueled power plant containing chemical looping combustion, combined power plant and heat recovery systems by several oxygen carriers is done [125]. It was demonstrated that nickel-based oxygen carriers, result the best performance in power efficiency point of view, followed by ilmenite-based and copper-based one’s. The related values obtained 50.14%, 48.02% and 45.59% respectively. In an integration of CLC with packed bed reactors, CLOP and IGCC with coal as fuel, the electric efficiency reaches to about 45.4%. It is shown that using the technology named hot gas cleaning, improves the plant efficiencies by 2% rather than cold gas commercialized cleaning [126]. An integrated power and hydrogen generation process is developed by Aziz and Zaini [127]. The used fuel and oxygen carrier were algae and iron oxide respectively. It was demonstrated that lower moisture content in dried algae and higher pressure of chemical looping, results better performance for system. The power generation efficiency, hydrogen generation efficiency and total efficiency reaches to achieved 14.46%, 57.25% and 71.71% respectively. In a natural gas-fueled process, two concepts were considered for techno-economic evaluation [128]. In the first, a power generation system is utilized for waste heat recovery which improves the system efficiency by 12%. In the second one, absorption chilling technology is used by 9 MW cooling capacity. The second approach, resulted higher economic performance. Kuo et al. [129] developed an integrated process for hydrogen and electricity production with chemical looping technology. They implemented modelling of moving bed reducer and oxidizer to reach optimum performance. They concluded that steam velocity has an important effect between oxidizing reactor parameters. In a combined power plant developed by Luo et al. [130], two approaches were applied by coal as fuel; coal direct chemical looping combustion (CD-CLC) and coal gasification chemical looping combustion (CG-CLC). The CD-CLC presented better performance in power efficiency, carbon capture efficiency and exergy efficiency. Circulation ratio of the oxygen carrier in CG-CLC was smaller than the first process.
<table>
<thead>
<tr>
<th>Year</th>
<th>Used fuel</th>
<th>Oxygen carrier type</th>
<th>Highlighted operational conditions</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986</td>
<td>Natural gas</td>
<td>Nickel- and Iron-based (NiO, FeO, Fe₂O₃)</td>
<td>- Ni/NiO system&lt;br&gt;- Reduction reactor&lt;br&gt;Temperature: 300 °C&lt;br&gt;- FeO/Fe₂O₃ system&lt;br&gt;- Reduction reactor&lt;br&gt;Temperature: 550 °C&lt;br&gt;- Fe/Fe₂O₃ system&lt;br&gt;- Reduction reactor&lt;br&gt;Temperature: 900 °C</td>
<td>[92]</td>
</tr>
<tr>
<td>2004</td>
<td>Natural Gas</td>
<td>Nickel-based (NiO/Al₂O₃)</td>
<td>- Oxidation&lt;br&gt;Inlet temperature: 520 °C (base case in 6 cases)&lt;br&gt;Outlet temperature: 1200 °C (base case in 6 cases)&lt;br&gt;- Fuel&lt;br&gt;Inlet temperature: 465 °C (base case in 6 cases)&lt;br&gt;- Reduction&lt;br&gt;Outlet temperature: 560 °C (base case in 6 cases)&lt;br&gt;- Gas turbine&lt;br&gt;TIT: 900 °C (base case in 6 cases)&lt;br&gt;Reactor pressure: 20 bar (base case in 6 cases)</td>
<td>[91]</td>
</tr>
<tr>
<td>2005</td>
<td>Methane</td>
<td>Calcium- and Nickel-based (CaO and NiO)</td>
<td>- ex-CLC&lt;br&gt;- Fuel reactor&lt;br&gt;Temperature: 750 °C&lt;br&gt;- Air reactor&lt;br&gt;Temperature: 1000 °C</td>
<td>[100]</td>
</tr>
<tr>
<td>2007</td>
<td>Coal</td>
<td>Iron-based (FeO/Fe₂O₃)</td>
<td>- Gasification&lt;br&gt;Temperature: 1400 °C&lt;br&gt;Pressure: 40 bar&lt;br&gt;Pressure loss: 5%&lt;br&gt;- Steam reactor&lt;br&gt;Temperature: 815 °C&lt;br&gt;Pressure loss: 6%&lt;br&gt;- Fuel reactor&lt;br&gt;Temperature: 788 °C&lt;br&gt;Pressure loss: 6%</td>
<td>[102]</td>
</tr>
<tr>
<td>2009</td>
<td>Coal</td>
<td>Iron-based (hematite (Fe₂O₃))</td>
<td>- Gasifier&lt;br&gt;Temperature: 900 °C&lt;br&gt;- O₂ reaction&lt;br&gt;Temperature: 920 °C (h)</td>
<td>[98]</td>
</tr>
<tr>
<td>2009</td>
<td>Methane</td>
<td>Zinc-based (ZnO)</td>
<td>- Reducer&lt;br&gt;Temperature: –1377–1587 °C&lt;br&gt;- Oxidizer&lt;br&gt;Temperature: 1027–1127 °C</td>
<td>[93]</td>
</tr>
<tr>
<td>2011</td>
<td>CH₂OH</td>
<td>Iron-based (FeO)</td>
<td>- Reduction&lt;br&gt;Temperature: 150 °C&lt;br&gt;- Oxidation&lt;br&gt;Temperature: 1315 °C</td>
<td>[103]</td>
</tr>
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<td>2011</td>
<td>Dimethyl Ether</td>
<td>Cobalt-based (CoO)</td>
<td>- Air reactor&lt;br&gt;Temperature: 1000 °C</td>
<td>[90]</td>
</tr>
<tr>
<td>2013</td>
<td>Natural and synthesis gas fuels</td>
<td>Nickel-, Copper- and Iron-based</td>
<td>- Fuel reactor&lt;br&gt;Temperature: 761–1937 °C (in 6 cases)&lt;br&gt;- Air reactor&lt;br&gt;Temperature: 986–1231 °C (in 6 cases)&lt;br&gt;- High pressure CLC loops&lt;br&gt;Pressure: 30 and 18 bar&lt;br&gt;- Low pressure CLC loops&lt;br&gt;Pressure: 15 and 9 bar</td>
<td>[96]</td>
</tr>
<tr>
<td>2015</td>
<td>Methane</td>
<td>nickel-based (NiO/Ni) Bulk layer (inert solid material: Boron nitride (BN))</td>
<td>- Oxidation reactor&lt;br&gt;Temperature: 1200 °C&lt;br&gt;Pressure: 10 bar&lt;br&gt;- Reduction reactor&lt;br&gt;Temperature: 1192 °C&lt;br&gt;Pressure: 10 bar</td>
<td>[99]</td>
</tr>
<tr>
<td>2015</td>
<td>Coal</td>
<td>Copper- and Manganese-based</td>
<td>- One stage CLC&lt;br&gt;- Reduction reactor&lt;br&gt;Temperature (in): 600 °C&lt;br&gt;Temperature (out, avg): 832 °C (During the reduction reaction, the temperature inside the reactor is 450–550 °C)&lt;br&gt;- Oxidation reactor&lt;br&gt;Temperature (in): 449 °C&lt;br&gt;Temperature (out, avg): 970 °C (When the reduction is completed, two different temperature plateaus can be observed: the first reactor is mainly at 700 °C and the second reactor mainly at 900 °C)&lt;br&gt;- TS-CLC with reduction in parallel (TS-CLC parallel)&lt;br&gt;- Reduction reactor&lt;br&gt;Temperature (in): 600 °C&lt;br&gt;Temperature (out, avg): 801 °C&lt;br&gt;- Reduction reactor&lt;br&gt;Temperature (in): 600 °C&lt;br&gt;Temperature (out, avg): 994 °C&lt;br&gt;- Oxidation reactor&lt;br&gt;Temperature (in): 448 °C&lt;br&gt;Temperature (out, avg): 915 °C</td>
<td>[97]</td>
</tr>
<tr>
<td>2016</td>
<td>Methane</td>
<td>Calcium-based (CaS and CaSO₄)</td>
<td>- Oxidation reactor&lt;br&gt;Temperature: 900 °C&lt;br&gt;Pressure: 20 bar&lt;br&gt;- Reduction reactor&lt;br&gt;Temperature: 1300 °C&lt;br&gt;Pressure: 20 bar</td>
<td>[89]</td>
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</table>

(continued on next page)
part of the compressed air is sent to the air reactor. Its gas output runs a
gas turbine and its hot output is submitted to HRSG system. In a hy-
drogen fueled gas CLC power generation, H₂ enters fuel reactor. Output
steam runs a steam turbine. Compressed air after saturation goes into
the air turbine and its exhaust enters a gas turbine [132]. For a techno-
economic investigation of a CLC passed power plant, in the considered
process, preheated CH₄ goes into the fuel reactor. Its gas output after
running a gas turbine enters HRSG system, then goes for CO₂ separation
by several condensation and compression. Compressed air goes into the
air reactor and its exhaust is used in a gas turbine which its outlet
stream is used in a HRSG. Generated steam of both HRSG systems is
used in two distinct IP steam turbine [133]. For investigation a co-
product process, based on the chemical looping technology; wet brown
coal after preheating, enters fluidized bed dryer. Dryed brown coal after
mixing with a part of produced CO₂, goes into the reducer. Output gas
(CO₂ + H₂O) is sent to gas turbine. Steam enters oxidizer and H₂ is
produced. A combustor is embedded for providing the required heat for
reduction. Produced H₂ is sent to hydrogenation which in it, H₂ is
chemically bounded with toluene for MCH production [134]. In a
process for power generation of gaseous fuels, natural gas enters the
fuel reactor. Its exhaust gas runs a gas turbine. Compressed air goes into
fuel reactor and its gas outlet goes for power generation in the air
turbine. Exhaust of GT and AT are sent for heat recovery. Generated
steam in HRSG is used for power generation in steam turbine power
plant H₂O and CO₂ outlet from FR are separated by a series of com-
pression and condensation [135].

Fig. 43 shows a simplified configuration of power generation with
combined cycle power plant with HRSG system based on the chemical
looping combustion with two reactor.

It is necessary to mentioning that in all processes explained in this
part, the hot output of AR or some when FR, runs a gas turbine. Then,
the output of gas turbine, supplies the required heat for steam gen-
eration in a HRSG system coupled with Steam turbine power plant as
a series of steam turbines or a single one. But to avoid of repeating too
much, the explanation of this part of process, has not been stated for
most processes.

Xiang and Wang [113] discussed a process in which, coal slurry
with sorbent cross air reactor for heating. Then after ash separation,
enters the fuel reactor. Its exhaust goes into a HRSG system which
supplies the required steam for a steam turbine system. Then the FR
output after several compression and water condensation goes out as
the purified liquid CO₂. Output of the air reactor runs another gas
turbine. The output gas goes for steam generation in the second HRSG
which is coupled with a steam turbine system. Both ST systems work in
three levels pressures. In the considered process by Alvaro et al. [114]
air after compression and preheating enters oxidation reactor. Produced
gas goes for power generation in a gas turbine. Its output after crossing
reduction reactor for heat exchanging enters a HRSG. Syngas is com-
pressed then follows to the reduction reactor. And its exhaust runs
another gas turbine. The output of the reduction reactor which contains
CO₂ and H₂O goes for several compression and condensation. Then
purified CO₂ goes for the storage. In an exergoeconomic and ex-
ergoenvironmental analysis [115] of a combined cycle power plant with
CLC system, a process was offered in which, natural gas after preheating
and air after compression enter chemical looping combustion system. In
a process considered for evaluation of a power plant with exergy and
economy points of view, natural gas is preheated and enters the fuel
reactor [116]. Output heat load of gas turbine is used in reheater, su-
perheater, and evaporator. In a gas-fueled power plant evaluation, a
process was proposed in which, fuel and compressed air enter the fuel
and air reactors respectively [117]. Output gas from the fuel reactor
goes into the expander and produces power and its flue gas enters
HRSG. CO₂ after separation from H₂O follows to the compression. In
a proposed CLC-based power plant, natural gas after preheating enters
the reduction reactor [118]. Also compressed air goes into the oxidation
reactor. CO₂ + H₂O stream from the reduction reactor goes to the

General schematics for the processes using combined cycle gas
turbine power plants used chemical looping technology are collected in
Figs. 42–63.

A simple two reactor CLC system with combined cycle power gen-
eration is shown in Fig. 42.

In a proposed process for oxygen carriers comparison in chemical
looping combustion, preheated methane enters fuel reactor [131]. Its
exhaust interact with heat recovery system for steam generation. Steam
is used for power generation in three pressure levels of steam turbine. A

### Table 4 (continued)

<table>
<thead>
<tr>
<th>Year</th>
<th>Used fuel</th>
<th>Oxygen carrier type</th>
<th>Highlighted operational conditions</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>Methane and syngas</td>
<td>Copper- and Nickel-based (CuO and NiO)</td>
<td>- CuO system TIT set-points: 1000, 900 °C - NiO system TIT set-points: 1100, 1000 °C</td>
<td>[95]</td>
</tr>
<tr>
<td>2016</td>
<td>Natural gas</td>
<td>Iron- and Nickel-based</td>
<td>- CLC Reducer - Air reactor Temperature: 1049 °C Pressure: 20 bar - Oxidizer Temperature: 1200 °C Pressure: 20 bar - exCLC Fuel reactor Temperature: 750 °C Pressure: 20 bar - Air reactor Temperature: 1049 °C Pressure: 20 bar - CLC3 &amp; HAT model - Fuel reactor Temperature: 447 °C Pressure: 20 bar - Steam reactor Temperature: 498 °C Pressure: 20 bar - Air reactor Temperature: 651 °C Pressure: 20 bar (The simulation exercise involves 9 different sub-cases for each configuration. These sub-cases consider 3 levels of pressure for the CLC reactors (10, 20 and 30 bar) and three levels of turbine inlet temperature (TIT; 1050, 1020 and 1350 °C))</td>
<td>[87]</td>
</tr>
<tr>
<td>2017</td>
<td>Biomass</td>
<td>Calcium-based (CaO)</td>
<td>- Gasification Temperature: 950 °C Pressure: 22 bar - Carbonation reactor Temperature: 800 °C - Calcination reactor Temperature: 850 °C - Hydration reactor Temperature: 600 °C Pressure: 22 bar</td>
<td>[88]</td>
</tr>
<tr>
<td>2017</td>
<td>Natural gas</td>
<td>Manganese-based (Mn₂O₃/MnO (CaMnO))</td>
<td>- Fuel reactor Exhaust temperature: 900 °C - Air reactor Exhaust temperature: 900 °C - Gas turbine Inlet temperature: 900 °C</td>
<td>[101]</td>
</tr>
</tbody>
</table>
For an exergetic analysis of a CLC-based power plant, natural gas after preheating and air after compression enter the CLC system. Output gas of both reduction and oxidation reactors is used for power generation in two distinct gas turbines. CO₂ as a product of reduction is separated by several continues condensation, cooling and compression stages. Outlet hot gas of the turbine which is burned after reduction reactor, crosses HP, IP and LP super heaters, evaporators and economizers. Generated steam is used in the steam turbine power cycle [136]. For evaluation of a power plant with chemical looping combustion; a process layout is offered that coal after preparation and steam as gasification agent enter the fuel reactor [137]. Air is compressed then goes into the air reactor. A carbon stripper is embedded between AR and FR. Produced steam of HRSG runs three steps steam turbine system. Purified CO₂ from FR goes...
for storage.

In a process suggested by Jafarian et al. [138] for evaluation of a high temperature CLC, fuel with combination of steam enters the fuel reactor. Produced gas after steam preheating goes into a gas turbine. Its output crosses a conventional CLC and heat recovery, then goes for water condensing. Mentioned preheated steam runs a steam turbine. Air stream is compressed and is preheated. Then goes into the air reactor. Depleted air of this reactor after preheating the entrance air runs

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**Fig. 44.** CCPP, solar thermal, chemical looping system with two reactors, HRSG.

**Fig. 45.** CCPP, ASU, gasification, chemical looping system with two reactors.
a gas turbine. In the considered process by Naqvi et al. [139] natural gas after preheating enters the reduction reactor. Its exhaust goes into CO₂ turbine and its output is used for fuel preheating then follows to water condensing and CO₂ separation. Air stream is sent to the compressor. A part of this stream runs an air turbine and its output gas enters HRSG. Produced steam of this system is delivered to a steam turbine in two pressure levels. Zhang at al. [140] considered a CLC-based power plant for power generation in which methanol enters the reduction reactor and output CO₂/H₂O stream goes for H₂O separation by condensation. Compressed and preheated air follows to the oxidation reactor. Naqvi and Bolland [141] suggested a process in that, natural gas after preheating enters the reduction reactor. Produced CO₂/H₂O goes into CO₂-turbine which its exhaust after fuel preheating is sent for several compression and condensation stages. Compressed air is divided into two parts. First part, goes to the air turbine which its exhaust goes into the HRSG system. Second part, is sent to the oxidation reactor. Its produced gas enters the mentioned air turbine. Generated steam of HRSG system is sent to steam turbine for power generation in two pressure levels. In the integrated process introduced by Chen et al. [142] fuel after preheating enters the reduction reactor which its hot exhaust is used in the economizer, evaporator. Produced steam is used in HP and LP steam turbines. Ambient air after preheating and compression goes into the oxidation reactor which its exhaust gas is used in second HRSG system. In a NG-fired process presented by Naqvi et al. [143] preheated fuel enters the reduction reactor. Its output is used for power generation in a gas turbine. Next after crossing the fuel preheater goes for compression and condensation for CO₂ capturing. Zerobin et al. [101] proposed a process for NG- fueled chemical looping combustion for study on reactor design. In this process, natural gas enters the fuel reactor and its output is used as the hot stream for steam generation. Produced steam runs the steam turbine system. On the other hand, compressed air after depletion in air reactor runs a gas turbine which is coupled with air compressor. In a polygeneration process introduced by Salkuyeh and Adams II [144], hydrogen from SCL (syngas chemical looping) enters the fuel reactor. Compressed air enters the air reactor. An exergy analysis is done on a CLC-based combined cycle in that, syngas after compression enters reduction reactor. Compressed air after preheating goes for particle’s oxidation in the oxidation reactor. Hot output enters a gas turbine and its exhaust crosses reduction reactor and HRSG for heat exchanging. CO₂ and H₂O, two main components in reduction reaction, are separated by compression and condensation [145]. In a near-zero emission power plant presented by Petrakopoulou

**Fig. 46. CCPP, ASU, gasification, chemical looping system with two reactors (calcination/carbonation).**

**Fig. 47. CCPP, ASU, gasification, chemical looping system with two reactors (calcination/sorbent enhanced WGS).**
preheated natural gas and compressed air enter the fuel and air reactors respectively. The exhaust of gas turbine dependent to FR, is sent to CO\textsubscript{2} separation and compression. Generated steam of HRSG system, supplies the required steam for steam turbine power cycle in different pressure levels.

Fig. 44 illustrates a simplified hybrid solar thermal and a two reactor chemical looping combustion, integrated with steam generation with heat recovery and combined cycle power plant.

Like the previous part (Fig. 43 section) in this part the exhaust of CLC system goes for power generation in gas turbine and then heat recovery and steam generation for steam power cycle. For preventing repetition, theses explanations has been eliminated. In a process introduced for study on oxygen carriers in a hybrid CLC system, CH\textsubscript{3}OH and DME enter fuel reactor which receives solar heat. Its exhaust goes for condensation and CO\textsubscript{2} separation. A part of the air stream after compression enters air reactor which its outlet gas stream runs a gas turbine. The output of gas turbine is combined with remaining part of the air stream and follows to the HRSG [147]. In an evaluation of a solar-hybrid chemical looping combustion [148], CH\textsubscript{4} goes into solar fuel reactor which receives solar heat by means of heliostat field. Exhaust gas enters FR-HRSG, after dehydration, separated CO\textsubscript{2} is compressed. Air after compression along with a stream of CH\textsubscript{4} enter the after-burner. Its exhaust, goes for power generation in a gas turbine. The exhaust gas goes into AR-HRSG. Generated steam in two levels run a steam turbine. Steam from FR-HRSG runs another steam turbine. There are two reservoirs to store the hot and cold particles. In another hybridization of solar thermal system and CLC [149], methanol is preheated then enters the reduction reactor. Air after compression and heating with hot particles goes into oxidation reactor. The output gas goes for combustion with a stream of methanol. The required heat in fuel preheater and reduction reactor is supplied by solar thermal energy. C\textsubscript{2}H\textsubscript{5}OH in an ethanol-fueled solar-hybrid power plant introduced

![Diagram of hybrid solar thermal and chemical looping system with two reactors.](image1)

**Fig. 48.** CCPP, ASU, gasification, chemical looping system with two reactors, HRSG.

[146], [147], [148], [149].
by Hui et al. [150], after preheating with concentrated solar energy is fed to reduction reactor. Compressed air is preheated then is sent to oxidation reactor. Exhaust after preheating the compressed air goes into HRSG. In a CLC study by Jin and Zhang [103], CH3OH after passing the regenerator enters the reduction reactor. The exhaust stream (CO2/H2O) runs a gas turbine. Output gas after regeneration goes to HRSG system, then after condensation, CO2 and H2O are separated. Compressed air after crossing the second regenerator is sent to oxidation reactor. Hong et al. [151] discussed a solar-CLC power plant in which reduction reactor is fed by methane stream and receives thermal energy from the concentrated solar radiation. Produced gas after crossing a gas-solid heat exchanger goes into a gas turbine. Its exhaust enters HRSG, then goes for CO2 separation by means of a condenser. Preheated compressed air goes into oxidation reactor. Its exhaust runs a gas turbine and its output after preheating the air stream goes to HRSG system. Generated steam by both HRSG systems is sent to steam turbine power cycles.

Fig. 45 illustrates an integrated process containing gasification, ASU, combustion with two reactors and power generation in the combined cycle.

In a process introduced by Anheden and Svedberg [121], compressed CO2 and syngas from the gasifier enter reduction reactor. Its exhaust gas after passing through gas turbine, enters bottoming steam cycle. Compressed air after combination with N2 from ASU goes to oxidation reactor and its output gas runs a gas turbine then enters the steam cycle.

Another layout of process equipment mentioned in Fig. 45, is shown in Fig. 46. The difference between these two configurations is that the produced oxygen in ASU in the first layout, enters air reactor, but ASU in the second configuration, supplies the required oxygen for

Fig. 50. CCPP, chemical looping system with three reactors, HRSG.

Fig. 51. CCPP, gasification, chemical looping system with three reactors.
Cormos et al. [152] for assessing a co-generation plant, suggested a layout of process in which coal with transport gas (N₂) and a stream of O₂ from ASU and a steam stream enter gasification-island. After syngas quenching and cooling, acid gas removal is done. Then the produced syngas goes for power generation in a combined cycle power plant. Exhaust gas enters carbonation reactor. It interacts with calcination reactor which is fed by coal and oxygen streams. Clean flue gas follows to the carbonation reactor. Outlet CO₂ after drying and compression goes for storage. In another layout [152], coal with transport gas (N₂/CO₂) is gasified by steam and oxygen from ASU. Syngas after quenching, cooling and AGR enters fuel reactor. Steam reactor is fed by a steam stream and its output after condensate separation with N₂ stream of ASU enters combined cycle gas turbine.

In a process by the aim of co-production of electricity and hydrogen and CCS, coal and biomass with steam and O₂ from ASU as the gasification agent enter gasification section. Water stream is used for syngas quenching and cooling, then syngas goes for AGR with communication with claus plant and tail gas treatment. Desulphurised syngas follows to fuel reactor and steam enters the steam reactor. Exhaust of FR after

**Fig. 52.** CCPP, gasification, chemical looping system with three reactors, HRSG.

**Fig. 53.** CCPP, ASU, chemical looping system with three reactors.
condensate separation, goes for CO₂ drying, compression and storage. Outlet stream of SR after condensate separation and H₂ purification, enters combined cycle gas turbine which its other inlet stream is N₂ from ASU [153]. In a power plant with gasification using Ca-looping, steam and O₂ from ASU streams are used for gasification of coal which is accompanied transport gas (N₂) [154]. Syngas after quenching and cooling of the AGR enters combined cycle gas turbine. Its exhaust enters carbonation reactor and interact with calcination reactor. Oxygen and coal are fed into calcination reactor. Output CO₂ after drying and compression goes for storage. Exhaust of SR after H₂ compression enters combined cycle gas turbine. In other configuration of the same work [70], coal with transport gas (N₂) is gasified by O₂ from ASU and steam. Desulphurised syngas enters fuel reactor and air goes into the air reactor. Steam from AT, FR, and syngas after quenching and cooling enter ST. Petrescu and Cormos [155] developed an IGCC power plant for assessing with environment point of view. In their considered process, a part of coal feed enters gasification section by steam from ST and O₂ from ASU unit. Syngas after quenching and cooling and AGR along with steam stream goes into sorbent enhanced WGS reactor and carbonation reactor interacting with calcination reactor. A stream of coal enters calcination reactor too. Exhaust of this reactor enters ST and output gas of other one, goes into GT.
Fig. 47 illustrates a combined cycle power generation system using a loop containing calcination and WGS. Pure oxygen as gasification agent, is supplied by air separation unit. In a CLC-based study by Cormos [154], coal and transport gas (N₂) enters gasification section by O₂ from ASU and steam agents. Syngas after quenching and cooling crosses AGR and claus plant and tail gas treatment units. Then with a steam stream enters sorbent enhanced WGS reactor which completes a loop with calcination reactor. Two streams of coal and oxygen are fed into this reactor. Outlet CO₂ of this reactor after drying and compression goes for storage. H₂ reach stream of sorbent enhanced WGS reactor goes for power generation in a combined cycle gas turbine. In other layout introduced by Cormos and Cormos [152], coal with transport gas (N₂) and a stream of O₂ from ASU and steam stream, enters gasification-island. After syngas quench and cooling, acid gas removal is done. The gained syngas with a steam stream enters sorbent enhanced WGS reactor. It is interacting with calcination reactor which is fed by coal and oxygen streams. The output of sorbent enhanced WGS reactor goes into gas turbine combined cycle. Outlet CO₂ of calcination reactor after drying and compression is sent to storage.

Fig. 48 shows a two reactor chemical looping combustion with syngas fueled from gasifier and oxygen supplying by ASU. Hot gases run combined cycle power plant and heat recovery system. Zhu et al. [156] developed a process of coal fired IGCC power plant using chemical looping technology. In this process, coal is gasified by O₂ from ASU. Steam from gasifier enters HRSG system and slag is taken out. Produced syngas after quench and cooling enters expander, then goes into chemical looping process. Produced H₂-rich gas with compressed air enters gas turbine. The exhaust of this turbine and produced CO₂ of CLP goes into heat recovery system. Generated steam runs a three stage steam turbine system. In an IGCC power plant based on CLC which is introduced for energy analyzing, coal is gasified by O₂ from ASU and CO₂. Produced syngas after cooling and treatment enters fuel heater then goes into reduction reactor. The produced gas after crossing HP and LP evaporator, super heater and economizer, is sent to H₂O condensation and CO₂ compression. A part of compressed air after passing through air blower enters oxidation reactor and remaining, by combination with exhaust of oxidation reactor and first purge system, goes for heat removal. Then it combines with purge outlet and goes into gas turbine. Its output enters HRSG system [97]. In CLC-based IGCC presented by Alvaro et al. [157] fuel enters a co-gasifier of coal and biomass. Produced syngas after cooling and de-sulfurizing, with oxygen from ASU goes to CLC unit. Hot outputs run combined power plant and hot flue gases are used for heat recovery steam generation. In the power plant proffered by Prabu [158] based on chemical looping combustion; CO₂, CO, H₂ and CH₄ from production well by underground coal gasification system enter fuel reactor. The produced flue gas after pre-heating the fuel, output steam from MP steam turbine and inlet air to air turbine goes to CO₂ compression unit. Steam from production well and air follows into the air reactor. Output steam handles three steps steam turbine with midway heating. Compressed CO₂ from CO₂ compression unit and O₂ from ASU are injected to injection well.

Fig. 49 displays a simple power plant using three reactor CLC and power generation with combined cycle. Co-generation power plant based on BDCLS is investigated [104]. In this process biomass with fluidization gas (steam, CO₂) enters fuel reactor. Steam from outlet stream of fuel reactor goes into steam reactor and for power generation in steam turbine. Condensates are separated.
Fig. 57. CCPP, two chemical looping systems (Fe-based & Ni-based), HRSG.

Fig. 58. CCPP, two chemical looping systems (AR/FR & reformer/calciner), HRSG.
and CO₂ after drying and compression goes to storage. Air is fed to the air reactor. A part of steam and air reactor's output joins to steam stream to ST and SR. The exhaust of steam reactor goes for power generation in the combined cycle gas turbine and H₂ separation. In a study of co-generate power plant introduced by Cormos and Cormos [105], coal along with steam and CO₂ goes into the fuel reactor. Steam and air are fed to steam reactor and air reactor respectively. Output steam from fuel reactor goes to power block and then, condensate separation. Steam reactor outlet, after condensate separation goes for power generation in the combined cycle gas turbine and H₂ purifica-

Cormos [106] developed a BDCLS for co-production of power and hydrogen. In this system, biomass with fluidization gas, steam and air are fed to the fuel reactor, steam reactor and air reactor respectively. Fuel reactor outlet, after condensate separation goes for CO₂ storage. Steam reactor exhaust after condensate separation runs a combined cycle gas turbine and goes for H₂ compression. A hydrogen production system based on CLC integrated with oil shale retorting process was developed by Zhang et al. [108] in which syngas from coal gasification enters fuel reactor. Its flue gas goes to gas the turbine combined cycle. Outlet air from the turbine cycle is used in air reactor and the outlet of this reactor enters power generation system. Required steam for steam reactor is supplied by this system. A portion of the exhaust of steam reactor (H₂/H₂O) after compression acts as gasification agent in the gasifier and the remaining enters a combined cycle. A combined power plant integrated with three reactor chemical looping system is shown in Fig. 51.

A chemical looping combustion of solid fuels with gasification system was evaluated by Xiang et al. [112] in which syngas from coal gasification enters fuel reactor. Its flue gas goes to gas the turbine combined cycle. Outlet air from the turbine cycle is used in air reactor and the outlet of this reactor enters power generation system. Required steam for steam reactor is supplied by this system. A portion of the exhaust of steam reactor (H₂/H₂O) after compression acts as gasification agent in the gasifier and the remaining enters a combined cycle. A combined power plant integrated with three reactor chemical looping system is shown in Fig. 51.

In the system introduced by Xiang et al. [112] coal is gasified by steam and O₂ agents, then the produced syngas goes for quenching. After crossing syngas cleaning equipment, a portion of syngas is delivered to the supplementary firing and another portion enters fuel reactor. Air after compression enters air reactor and its output gas is submitted to SF (supplementary firing). Exhaust of SF runs a gas turbine

and CO₂ after drying and compression goes to storage. Air is fed to the air reactor. A part of steam and air reactor's output joins to steam stream to ST and SR. The exhaust of steam reactor goes for power generation in the combined cycle gas turbine and H₂ separation. In a study of co-generate power plant introduced by Cormos and Cormos [105], coal along with steam and CO₂ goes into the fuel reactor. Steam and air are fed to steam reactor and air reactor respectively. Output steam from fuel reactor goes to power block and then, condensate separation. Steam reactor outlet, after condensate separation goes for power generation in the combined cycle gas turbine and H₂ separation. Cormos [106] developed a BDCLS for co-production of power and hydrogen. In this system, biomass with fluidization gas, steam and air are fed to the fuel reactor, steam reactor and air reactor respectively. Fuel reactor outlet, after condensate separation goes for CO₂ storage. Steam reactor exhaust after condensate separation runs a combined cycle gas turbine and goes for H₂ compression. A hydrogen production system based on CLC integrated with oil shale retorting process was developed by Yang et al. [107]. In this process, oil shale after preparation goes for retorting. Retorting gas after condensation and recovery enters the fuel reactor. Product CO₂ with H₂O stream and oxygen depleted air from the air reactor which is fed by air, goes into the power generation system.

Fig. 50 represents a power generator system based on three reactor CLC integrated with HRDG system.

In an electricity generation power plant with three reactors developed by Lozza et al. [109] natural gas after preheating enters the reduction reactor. A portion of the output gas of this reactor (CO₂/H₂O) is used for fuel preheating and the remaining after crossing the economizer, joins the first portion preheater outlet. Outlet stream after water condensing goes for CO₂ compression and liquid CO₂ storage. Air stream after compression goes into the air reactor which its exhaust gas is delivered to gas turbine combined with air compressor. A CLR plant for hydrogen production was studied from the exergy and economy points of view [110]. In this system, natural gas enters fuel reactor. A portion of output CO₂ of this reactor returns for fuel preheating and remaining goes into the HRSG. Air after compression enters air reactor and outlet gas, runs a gas turbine. Its exhaust is used in HRSG. Produced H₂ and CO₂ in this process, go for compression and storage. Alvaro et al. [111] did an analytical study on a CLC-based co-product system. In this process, syngas after compression enters fuel reactor. Produced stream (CO₂/H₂O) of this reactor along with compressed air enter the air reactor. Exhaust of this reactor with syngas stream goes into an extra-firing combustor which its output gas runs a gas turbine. CO₂/H₂O output of AR is delivered to another gas turbine. Outlet of both gas turbines are used for steam generation in HRSG. Produced steam in this unit goes into steam reactor. CO₂ and H₂ are sent for separation and storage.

A combined power plant integrated with three reactor chemical looping and gasification system is shown in Fig. 51.

A chemical looping combustion of solid fuels with gasification system was evaluated by Zhang et al. [108] in which syngas from coal gasification enters fuel reactor. Its flue gas goes to gas the turbine combined cycle. Outlet air from the turbine cycle is used in air reactor and the outlet of this reactor enters power generation system. Required steam for steam reactor is supplied by this system. A portion of the exhaust of steam reactor (H₂/H₂O) after compression acts as gasification agent in the gasifier and the remaining enters a combined cycle. A combined power plant integrated with three reactor chemical looping system is shown in Fig. 51.

A chemical looping combustion of solid fuels with gasification system was evaluated by Zhang et al. [108] in which syngas from coal gasification enters fuel reactor. Its flue gas goes to gas the turbine combined cycle. Outlet air from the turbine cycle is used in air reactor and the outlet of this reactor enters power generation system. Required steam for steam reactor is supplied by this system. A portion of the exhaust of steam reactor (H₂/H₂O) after compression acts as gasification agent in the gasifier and the remaining enters a combined cycle. A combined power plant integrated with three reactor chemical looping system is shown in Fig. 51.

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which is coupled with air compressor. Gas turbine outlet enters first HRSG system. The exhaust of fuel reactor after expansion goes into second HRSG. After several condensation and compression, H₂ and CO₂ goes for storage as purified outputs. In another process layout by Yang et al. [107] oil shale enters pyrolysis reactor. The gas output after super heating and purification splits to two streams. The first part, goes into the fuel reactor and the second part with a stream of air, enters heating furnace. Furnace output as the thermal cycle gas enters oil shale. Output stream of the fuel reactor (N₂, CO₂) runs a gas turbine. Tail gas from the GT is submitted to HRSG. The exhaust of steam reactor enters a steam turbine and its output, goes into second HRSG. Shale oil is other product of this process.

Fig. 53 illustrates a combined power cycle integrated to three reactor chemical looping system, using generated oxygen from ASU.

A process layout introduced by Cormos and Cormos [105], represents a system in which coal with O₂ from ASU and fluidization gas (e.g. steam, CO₂) enters fuel reactor. Steam and air goes into the SR and AR respectively. Steam of FR goes to power generation and CO₂ goes for drying and compression. Condensate of SR’s outlet is separated, and remaining, goes for power generation in a combined cycle gas turbine and H₂ compression and purification. In [152] a process configurations is offered for Co-generation, Coal + transport gas (CO₂) runs a gas turbine. Tail gas from the GT is submitted to HRSG. The exhaust of steam reactor enters a steam turbine and its output, goes into second HRSG. Shale oil is other product of this process.

Fig. 53 illustrates a combined power cycle integrated to three reactor chemical looping system, using generated oxygen from ASU.

A layout of co-production has been offered in which O₂ from ASU and steam enters gasifier for coal gasification [105]. Produced syngas after quench and cooling crosses AGR plant interacting with Claus plant and tail gas treatment. Resulted syngas, steam and air, enter FR, SR and AR respectively. CO₂ of FR after condensate separation goes for drying and compression. Outlet stream of FR after condensate separation is sent to H₂ compression and purification then with N₂ stream of ASU, enters combined cycle gas turbine. In a co-generation process configuration [106], coal + biomass (sawdust) with steam and O₂ stream of ASU enters gasification. Produced syngas after quenching and cooling is sent to AGR unit which is interconnected to the Claus plant and tail gas treatment that is fed by O₂ from ASU. The produced syngas goes into FR and steam and air are fed into steam and air reactors respectively. Exhaust of FR after condensate separation is sent to CO₂ drying and compression. Condensate of SR’s output gas is separated too. Then H₂ separation and compression is done and remaining gas with N₂ stream from ASU is used for power generation in a combined cycle gas turbine.

Fig. 55 illustrates a combined cycle using syngas from gasifier with three reactors chemical looping system with heat recovery system and oxygen supplying from ASU.

In an IGCC power plant based on SCL [159], coal after drying and milling operations enters a gasifier. O₂ from ASU and steam from HRSG are gasification agents. Produced syngas crosses syngas cooler, HGD desulphurizer and HGD regenerator, then enters reducer. Compressed air goes into air reactor. Depleted air runs a gas turbine which its exhaust enters HRSG. Outlet steam of this reactor enters HRSG. Output gas of the reducer after heat releasing in another HRSG system, goes for...
Fig. 61. CCPP, three chemical looping systems (HP, LP & reformer/calciner), HRSG.

Fig. 62. CCPP, chemical looping system with four reactors, HRSG.
condensation and CO₂ separation. A part of generated steam of this system is sent to steam reactor. Remaining steam runs a steam turbine power plant and supplies the required steam for gasification.

Fig. 56 shows a combined cycle power generation system with two steps chemical looping combustion provided in HP and LP conditions respectively. A steam generator system has been integrated to power cycle for recovery of released heat.

In a multi-stage CLC process introduced by Naqvi and Bolland [141], fuel after preheating is divided into two streams, and enters reduction reactors. Produced CO₂/H₂O of second CLC system, goes into CO₂-turbine which its exhaust after fuel preheating goes for CO₂ dehydration and compression. Compressed air is divided into two streams. First, goes to air turbines as cooling air, which exhaust of the second AT, goes into the HRSG system. Second part of the compressed air, goes for first oxidation reactor. Its produced gas enters the first air turbine, then goes into the second air reactor. Produced steam from HRSG is sent to the steam turbine with two pressure levels.

Fig. 57 represents a syngas-fueled two stages CLC integrated with

Fig. 63. CCPP, gasification, two chemical looping systems, HRSG.

Fig. 64. A schematic diagram of a double-stage CLC-SE-SR [157]. With permission of Elsevier, 2018.
gasification, combined cycle power plant and heat recovery steam generation.

In a co-production power plant presented by Chen et al. [160] coal with O₂ and CO₂ enters a gasifier. Produced syngas after quenching and crossing super heater and reheater, goes into Fe-FR and steam from HP-ST enters Fe-SR. Output gas from Fe-SR after crossing an expander, enters H₂-HRSRG system, containing super heater, evaporator and economizer. HRSRG outlet passes several continues compressors and condensers to produce pure H₂. Output gas of Ni-FR goes into expander, then enters CO₂ HRSG. Its output crosses several continues compressors and condensers to separate CO₂. Compressed air enters Ni-AR. Its exhaust, goes into an optional supplementary firing then goes for power generation in a GT. Its exhaust enters air HRSG system. Fig. 58 shows a two stage chemical looping process. First stage consists of AR and FR. Second stage contains reformer and calciner. A combined cycle power plant integrated to a HRSG system was considered.

In [161] natural gas is compressed to 15 bar and then enters FR. Outlet gas of this reactor is sent to gas turbine and then, for heat recovery, goes to CO₂ dehydration and compression. Compressed after reaction in the air reactor, enters air turbine, then goes for HRSG and power generation on steam turbine. On the other hand a stream of NG after compression and a stream of steam from ST enter reformer. Dissipated heat of reformer H₂ stream is used in HRSRG and ST systems. Output stream from the calcinator, after heat recovery goes to CO₂ compression plant. The required heat of the reformer and calcinator is supplied by AR. In the process developed for hydrogen production by Alam et al. [162] a part of preheated CH₄ enters FR. The remaining part, with exhaust of FR and a steam stream from HRSRG system goes into SMR (steam methane reformer). Its gas outlet (H₂) preheats CH₄, then is delivered to the HRSRG. The outlet N₂ stream runs a GT, then enters HRSRG. Generated steam, supplies the required steam for ST and SMR.

Fig. 59 exhibits an integrated process for co-production of hydrogen and power. A gasification system, two stages chemical looping systems, combined cycle power plant and heat recovery steam generation system has been applied in this process.

Zhu et al. [163] studied a polygeneration system based on the chemical looping system. In this process, coal after pyrolyzing, with an O₂ + CO₂ stream enters calcinator. Syngas from HRSRG after desulfurization with steam from HP-ST enters WGS reactor. CO₂ from calcinator and shift gas from WGS reactor go into HRSRG system. On the other hand, coal after drying with steam from HP-ST and O₂ + CO₂ stream enters the gasifier. Produced syngas after crossing syngas quenching, goes into HRSRG. Combustor exhaust, goes into the GT then its heat is used for air preheating. Preheated air enters AR and a part of CO₂ from the calcinator after passing the HRSRG and dehydration and compression enters reduction reactor. Steam from HRSRG runs HP, MP and LP-ST respectively.

Fig. 60 shows a power plant using multi-stage chemical looping with power generation and heat recovery system.

In a three stage CLC-based process discussed by Naqvi and Bolland [141], preheated fuel is divided and enters HP, IP and LP-CLC systems reduction reactors. The exhaust of each mentioned reactors is sent to CO₂ turbine for power generation. A part of compressed air goes into oxidation reactor of HP-CLC system and remaining part, with depleted air of oxidation reactor of each stage, run an AT and its exhaust, goes into oxidation reactor of the next stage. Outlet of last AT enters HRSRG. Generated steam, runs steam cycle in two pressure levels.

Fig. 61 demonstrates two chemical looping system in two pressure levels and a naturel gas steam reforming. A combined cycle for power generation and a heat recovery system are embedded in this process.

In the thermodynamic investigation of CLC-based power plants, Zhu et al. [161] studied a process in which a part of fuel (NG) after compression enters FR and compressed air goes into AR of HP-CLC system. Depleted air from AR after running an AT, enters AR of LP-CLC system and exhaust gas of FR of HP-CLC after running a GT goes for heat generation.
Table 5

Used fuel, OC and operational conditions for CLC-based processes with power generation by CCPP.

<table>
<thead>
<tr>
<th>Year</th>
<th>Used fuel</th>
<th>Oxygen carrier type</th>
<th>Highlighted operational conditions</th>
<th>Reference</th>
</tr>
</thead>
</table>
| 1996  | Coal      | Nickel-, Iron- or manganese-based (NiO, Fe₂O₃ or Mn₃O₄) | **Gasifier**  
- Temperature: 1335 °C  
- Pressure: 50 bar  
- MnO system  
- Oxidation  
- Temperature: 1280 °C  
- Pressure: 17 bar  
- Reduction  
- Temperature: 1280 °C  
- Pressure: 17 bar  
- FeO system  
- Oxidation  
- Temperature: 1180 °C  
- Pressure: 17 bar  
- Reduction  
- Temperature: 1230 °C  
- Pressure: 17 bar  
- NiO system  
- Gas Turbine  
- Maximum turbine inlet temperature: 1280 °C  
- Maximum pressure: 17 bar  
- Pressure drop: have not been considered for the different system components, except for turbines and compressors | [121] |
| 2000  | Hydrogen  | Nickel-based (NiO) | **Combustion**  
- Temperature: 1350 °C  
- Turbine inlet temperature: 1200 °C | [132] |
| 2004  | Natural gas | Nickel-based (NiO) | **Fuel reactor and air reactor: Adiabatic Reactors**  
- Pressure drop: 5%  
- TIT: 1050–1200 °C | [143] |
| 2005  | Natural gas | Nickel- and Iron-based  
(in the cases with Fe₂O₃ stabilised with 40 wt% Al₂O₃ (cases C and D)  
the cases with NiO stabilised with 50 wt% NiAl₂O₄ (cases E-G)) | **Air reactor**  
- Temperature: 1200 °C  
- CLC (Seven cases)  
- Pressure : 9 and 13 bar  
- Gas turbine  
- Pressure ratio: 13  
- TIT: 1000 and 1200 °C | [131] |
| 2006  | Natural gas | Iron-based  
(FeO/Fe₂O₃/Fe₃O₄) | **Reduction reactor**  
- Temperature (RR to SOR): 697.4 °C  
- Steam reactor  
- Temperature (SOR to AOR): 728 °C  
- Air reactor  
- Temperature (AOR to RR): 832 °C | [109] |
- Iron-based system  
- Oxidation reactor  
- Outlet temperature: 1050 °C  
- Reduction reactor  
- Outlet temperature: 986.2 °C  
- Nickel-based system  
- Oxidation reactor  
- Outlet temperature: 1050 °C  
- Reduction reactor  
- Outlet temperature: 707.5 °C  
- Gas turbine inlet temperatures ranging: 1000–1200 °C | [118] |
| 2006  | Methane   | Nickel-based (NiO) | **Reduction**  
- Temperature: 530 °C  
- Oxidation  
- Temperature: 1200 °C  
- Solar reactor  
- Pressure: 15 bar  
- Turbine inlet temperature (TIT): | [151] |

(continued on next page)
Table 5 (continued)

<table>
<thead>
<tr>
<th>Year</th>
<th>Used fuel</th>
<th>Oxygen carrier type</th>
<th>Highlighted operational conditions</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>Natural gas</td>
<td>Metal oxide is not defined</td>
<td>1200 °C • Air reactor: Temperature: 1200 °C</td>
<td>[139]</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• Fuel reactor: Temperature: 980 °C</td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Air turbine: Turbine inlet temperature: 1140 °C</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• TET: 492 °C</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• Reduction: Temperature: 980 °C</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>• TIT: 900–1000 °C</td>
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<td></td>
<td></td>
<td></td>
<td>• TET: 645 °C</td>
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<tr>
<td>2008</td>
<td>Coal</td>
<td>Nickel-based (NiO)</td>
<td>950 °C • Gasification: Temperature: 950 °C</td>
<td>[113]</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• Pressure: 25 bar</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• Syngas temperature: 870 °C</td>
<td></td>
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<tr>
<td>2009</td>
<td>Methanol</td>
<td>Iron-based (Fe2O3)</td>
<td>100–200 °C • Oxidation: Temperature: 980 °C</td>
<td>[120]</td>
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<td>• Pressure: 1 bar</td>
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<td>• Reduction: Temperature: 411 °C</td>
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<td></td>
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<td>• Press: 15.2 bar</td>
<td></td>
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<tr>
<td>2009</td>
<td>Methanol</td>
<td>Iron-based</td>
<td>100–200 °C • Oxidation: Temperature: 1200 °C</td>
<td>[140]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Pressure: 1 bar</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>Biomass and Coal</td>
<td>Iron-based (((Fe3O4))</td>
<td>&gt; 1400 °C • Oxidation: Temperature: 40 bar</td>
<td>[148]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Fuel reactor: Temperature: 750–900 °C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Pressure: 30.5 bar</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>Methanol</td>
<td>Iron-based ((Fe2O3/FeO))</td>
<td>1000 °C • Oxidation: Temperature: 1000 °C</td>
<td>[149]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Reduction: Temperature: 150 °C</td>
<td></td>
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<tr>
<td></td>
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<td></td>
<td>• Solar reactor: Pressure: 1 bar</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• TIT: 1400 °C</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>Coal</td>
<td>Iron-based (Fe2O3/FeAl2O4)</td>
<td>• Oxidation: Temperature: 1000 °C</td>
<td>[112]</td>
</tr>
</tbody>
</table>

(continued on next page)
Table 5 (continued)

<table>
<thead>
<tr>
<th>Year</th>
<th>Used fuel</th>
<th>Oxygen carrier type</th>
<th>Highlighted operational conditions</th>
<th>Reference</th>
</tr>
</thead>
</table>
| 2011 | Natural gas (100% CH₄) | Nickel-based (NiO/Ni) | - Fuel reactor  
Temperature: 930 °C  
Air ratio: 2.9  
Inlet pressure: 17 bar  
Pressure drop: 3%  
- Air reactor  
Temperature: 1200 °C  
Inlet pressure: 17 bar  
Pressure drop: 3%  | [115] |
| 2011 | DME (dimethyl ether) | Iron-based (Fe₂O₃/FeO) | - Oxidation reactor  
Temperature: 1288 °C  
- Reduction reactor  
Temperature: 180 °C  
- Turbine inlet temperature of 1288 °C  | [119] |
| 2011 | Ethanol | Nickel-based NiO | - Reduction reactor  
Temperature: 150–200 °C  
- Oxidation reactor  
Temperature: 1288 °C  
TIT: 1288 °C  | [150] |
| 2012 | Coal | Iron-based | - Gasification  
Temperature: − 797 °C  
- Fuel reactor (i.e., combustor) Temperature: 867 °C  
- Steam/hydrogen to carbon ratio (SHTCR): 2  | [108] |
| 2012 | Di-methyl ether (DME) | Iron-, Nickel- and Cobalt-based (Fe₂O₃, NiO, and CoO as solid reactants and Al₂O₃, MgAl₂O₄, and YSZ as binders) | - CoO system  
- Reduction  
Temperature: − 450 °C  
- H₂O/DEM optimal range: − 1.5–2.0  | [147] |
| 2012 | Natural gas | Nickel-based | - Air reactor  
Temperature: 1200 °C  
- Fuel reactor  
Temperature: 930 °C  
The air ratio (the ratio between the oxygen included in the air and the oxygen needed for stoichiometric combustion): 2.9  | [146] |
| 2012 | Coal | Iron- and Nickel-based | - Gasification  
Temperature: 1371 °C  
Pressure: 32 bar  
Pressure loss: 5%  
- Fe looping unit  
- Fuel reactor  
Temperature: 815 °C  
Operation pressure: 17 bar Pressure loss: 8%  
- Steam reactor  
Temperature: 815 °C  
Operation pressure: 17 bar Pressure loss: 8%  
- Ni looping unit  
- Fuel reactor  
Temperature: 900 °C  
Operation pressure: 17 bar Pressure loss: 8%  
- Air reactor  
Temperature: 1050 °C  | [160] |

(continued on next page)
<table>
<thead>
<tr>
<th>Year</th>
<th>Used fuel</th>
<th>Oxygen carrier type</th>
<th>Highlighted operational conditions</th>
<th>Reference</th>
</tr>
</thead>
</table>
| 2013         | Natural gas        |                             | Operation pressure: 17 bar Pressure loss: 8%  
- Gas turbine  
- Discharge pressure: 1.047 bar  
- Stream existing the CLC  
Temperature: < 1200 °C (Due to material limitations) | [136]     |
| 2013         | Coal               | Calcium-based (CaO/CaCO₃)   | - Gasification  
Temperature: > 1400 °C  
Pressure: 40 bar  
Pressure drop: 1.5 bar  
- Carbonation reactor:  
Temperature: 650–700 °C  
- Calcination reactor:  
Temperature: 900–950 °C | [154]     |
| 2013         | Biomass and Coal   | Iron-based (ilmenite-based ilmenite - FeTiO₃) | - Gasifier  
Pressure: 40 bar  
- Water gas shift (Case 3) Steam/CO ratio: > 2 | [104]     |
| 2014         | Coal               | Iron-based (hematite Fe₂O₃) | - Fuel reactor  
Temperature: 650–900 °C  
Pressure: 38 bar  
- Steam reactor  
Temperature: 650–750 °C  
Pressure: 36 bar  
- Air reactor  
Temperature: 800–1000 °C  
Pressure: 34 bar  
- Gas turbine  
Pressure ratio: 21  
Turbine outlet temperature (TOT): 588 °C | [105]     |
| 2014         | Syngas             | Iron-based (FeSO₃/FeO)      | - Oxidation reactor  
Temperature: 1127–1277 °C  
Pressure: 14.29 bar  
- Reduction reactor  
Temperature: ∼ 537 °C  
Pressure: 14.29 bar | [114]     |
| 2014         | Coal and Natural gas | Nickel- and Iron-based (nickel-oxide for power generation iron-oxide for H₂ production) | - Slurry gasifier  
Temperature: 1370 °C  
pressure: 55 bar  
- Gasifier  
Temperature: 1400 °C  
pressure: 40 bar  
- Iron-oxide loop  
- Reducer  
Temperature: 750 °C  
Pressure: 55 bar  
- Oxidizer  
Temperature: 560 °C  
Pressure: 55 bar  
- Combustor  
temperature: 950 °C  
Pressure: 55 bar  
- NiO loop  
- Reducer  
Temperature: 860 °C  
Pressure: 34.5 bar  
- Oxidizer  
Temperature: 1250 °C  
Pressure: 34 bar  
- Gas turbine  
Temperature: 1260 °C  
Inlet pressure: 35 bar  
Outlet pressure: 1.05 bar | [144]     |
| 2014         | Methane            | Not specified               | - Air reactor  
Temperature: 950 °C  
Pressure: 15 bar  
Pressure variation range: 10–20  
- Fuel reactor  
Temperature: 750 °C | [148]     |
<table>
<thead>
<tr>
<th>Year</th>
<th>Used fuel</th>
<th>Oxygen carrier type</th>
<th>Highlighted operational conditions</th>
<th>Reference</th>
</tr>
</thead>
</table>
| 2014 | Coal              | Iron-based \((\text{magnetite (Fe}_3\text{O}_4))\) | - Gasification  
Temperature: \(\geq 1400^\circ\text{C}\) (slagging conditions)  
Pressure: 40 bar  
Pressure drop: 1.5 bar  
- Chemical looping unit  
- Fuel reactor  
Temperature: 750–900 °C  
Pressure: 30.5 bar  
Pressure drop: 1 bar  
- Steam reactor  
Temperature: 500–700 °C  
Pressure: 29.5 bar  
Pressure drop: 1 bar  
- Gas turbine  
Pressure ratio: 21  
Turbine outlet temperature (TOT): 588 °C | [152] |
| 2014 | Coal              | Iron-based \((\text{iron oxide (Fe}_3\text{O}_4))\) | - Gasification  
Exit temperature: 1550 °C  
Pressure: 40 bar  
- Air reactor  
Temperature: 1000 °C  
- Gas turbine  
Pressure ratio: 19.5 | [159] |
| 2015 | Biomass and Coal  | Iron-based \((\text{ilmenite (FeTiO}_3))\) | - Fuel reactor  
Temperature: 650–900 °C  
Pressure: 38 bar  
Pressure drop: 1 bar  
- Steam reactor  
Temperature: 650–750 °C  
Pressure: 36 bar  
Pressure drop: 1 bar  
- Air reactor  
Temperature: 800–1000 °C  
Pressure: 34 bar  
- Gas turbine  
Pressure ratio: 21  
- Turbine outlet temperature (TOT): 588 °C | [106] |
| 2015 | Oil shale         | Iron-based                      | - Gasification reactor  
Temperature: 850 °C  
Pressure: 1 bar  
- Fuel reactor  
Temperature: 870 °C  
Pressure: 30 bar  
- Steam reactor  
Temperature: 720 °C  
Pressure: 30 bar  
- Air reactor  
Temperature: 1250 °C  
Pressure: 1 bar | [107] |
| 2015 | Coal              | Nickel- and Calcium-based \((\text{CLC: Ni-based CLP: Ca-based})\) | - Gasification  
Temperature: 1400 °C  
Pressure: 30 bar  
- CLC  
- Fuel reactor  
Pressure: 15 bar  
Heat duty: 0 kW  
- Air reactor  
Temperature: 1200 °C  
Pressure: 15 bar  
- Air turbine  
TIT: 1200 °C  
Discharge pressure: 1.03 bar  
- CO\text{2} turbine  
Discharge pressure: 1.03 bar  
- CLP  
- Carbonation reactor  
Temperature: 650 °C  
- Calciner | [156] |
<table>
<thead>
<tr>
<th>Year</th>
<th>Used fuel</th>
<th>Oxygen carrier type</th>
<th>Highlighted operational conditions</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>Coal</td>
<td>Nickel-based</td>
<td>Temperature: 950 °C</td>
<td>[158]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Air reactor</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Temperature: 916 °C Subcritical condition: 1100 °C Supercritical condition: 1200 °C Ultra supercritical condition: 1100 °C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Fuel reactor</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Temperature: Subcritical condition: 885 °C Supercritical condition: 1000 °C Ultra supercritical condition: 1100 °C</td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>Biomass and Coal</td>
<td>Iron-based</td>
<td>- CLC reactors</td>
<td>[157]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Fe$_2$O$_3$/FeO)</td>
<td>Optimal pressure: around 20 bar</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>- Reduction reactor</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Temperature: 447-542 °C</td>
<td></td>
</tr>
<tr>
<td>2015</td>
<td>Natural gas</td>
<td>Iron-based</td>
<td>- Fuel reactor</td>
<td>[110]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Fe$_2$O$_3$/Fe$_3$O$_4$)</td>
<td>Temperature: 728 703 689 676 °C</td>
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<td></td>
<td></td>
<td></td>
<td>- Air reactor</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Temperature: 864 852 840 831 °C</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>Natural gas</td>
<td>Nickel-, Iron- and copper-based</td>
<td>(Among the three OC materials, Ni-OC systems gave slightly better performance than the Fe-OC and Cu-OC systems) Ni-OC(40%NiO,60%Al$_2$O$_3$)) (CuO(10%CuO,90%Al$_2$O$_3$)) (Fe$_2$O$_3$ (60%Fe$_2$O$_3$,40%Al$_2$O$_3$))</td>
<td>[117]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- NiO system</td>
<td></td>
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<td></td>
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<td></td>
<td>- Air reactor</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Temperature: 1100 °C Pressure drop: 0.14 bar</td>
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<td></td>
<td>- Fuel reactor</td>
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<td></td>
<td></td>
<td>Temperature: 945 °C Pressure drop: 0.20 bar</td>
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<td></td>
<td>- CuO system</td>
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<td></td>
<td>- Air reactor</td>
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<td></td>
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<td></td>
<td>Temperature: 950 °C Pressure drop: 0.30 bar</td>
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<td></td>
<td>- Fuel reactor</td>
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<td></td>
<td></td>
<td></td>
<td>Temperature: 974 °C Pressure drop: 0.14 bar</td>
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<td></td>
<td></td>
<td></td>
<td>- Fe$_3$O$_4$ system</td>
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<td>- Air reactor</td>
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<td></td>
<td>Temperature: 1100 °C Pressure drop: 0.19 bar</td>
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<td></td>
<td></td>
<td></td>
<td>- Fuel reactor</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Temperature: 1029 °C Pressure drop: 0.52 bar</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>Natural gas</td>
<td>Copper- and Nickel-based</td>
<td>Gas turbine inlet temperature: 1100 °C</td>
<td>[142]</td>
</tr>
<tr>
<td>2016</td>
<td>Syngas</td>
<td>Iron-based</td>
<td>- Reduction reactor</td>
<td>[145]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(FeO/Fe$_2$O$_3$, YSZ (yttria-stabilized ZrO$_2$) a mass of 0.27 mol of ZrO$_2$ per mol of FeO)</td>
<td>Temperature: 540.8 °C (T$_{opt}$: ~ 457–557 °C) Pressure: 27 bar</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Oxidation reactor</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Temperature: 1277 °C Pressure: 27 bar TIT: 1127–1327 °C</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>Natural gas (assumed 100% CH$_4$)</td>
<td>Nickel-based</td>
<td>- Combustion chamber:</td>
<td>[133]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(NiO (supported with Al$_2$O$_3$))</td>
<td>Temperature: 1200 °C Pressure: 10.1 bar aire turbine inlet temperature: 1200 °C</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>Coal</td>
<td>Iron-based</td>
<td>- Reduction</td>
<td>[134]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Fe$_2$O$_3$, Fe$_3$O$_4$, Fe, FeO)</td>
<td>Temperature: 800 °C Operating pressure: 3 MPa</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>Natural gas</td>
<td>Nickel-based</td>
<td>- Fuel reactor</td>
<td>[161]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Temperature: &gt; 600 °C Pressure: 15 bar</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>- Air reactor</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Temperature: 120 °C Pressure: 15 bar</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>- Reformer &amp; calcinatory</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pressure: 15 bar</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>Coal</td>
<td>Manganese- and Calcium-based</td>
<td>- Gasification</td>
<td>[163]</td>
</tr>
</tbody>
</table>
|              |                | (CLAS: Mn-based (Mn$_2$O$_3$) Water-gas shift integrated with calcium looping (WGS-CaL): Ca- | Pressure: 40 bar Temperature: 1400 °C - Chemical looping air separation (CLAS)                       |           | (continued on next page)
<table>
<thead>
<tr>
<th>Year</th>
<th>Used fuel</th>
<th>Oxygen carrier type</th>
<th>Highlighted operational conditions</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>Biomass</td>
<td>Iron- and Manganese-based (CLC: Fe-based Fe₂O₃, CLAS: Mn-based Mn₂O₃)</td>
<td>- Oxidation/reduction Temperature: 867 °C Operation pressure: 1 bar Water-gas shift integrated with calcium looping (WGS-CaL): Operation pressure: 30 bar Heat recovery steam generator (HRSG) and steam cycle (Rankine): Pressure level: 120 bar</td>
<td>[164]</td>
</tr>
<tr>
<td>2017</td>
<td>Gaseous fuels, such as natural gas</td>
<td>a perovskite-type oxygen carrier based on calcium-manganese with the formal composition CaMn₀.₇₇₅Ti₀.₁₂₅Mg₀.₁₀₃₋₈</td>
<td>Fuel reactor Temperature: 850 °C Air reactor Temperature: 850 °C TIT: ∼ 900 °C</td>
<td>[135]</td>
</tr>
</tbody>
</table>

(continued on next page)
<table>
<thead>
<tr>
<th>Year</th>
<th>Used fuel</th>
<th>Oxygen carrier type</th>
<th>Highlighted operational conditions</th>
<th>Reference</th>
</tr>
</thead>
</table>
| 2017 | Methane       | Calcium- and Nickel-based (CaO/CaCO₃ NiO/Ni) | - Air Reactor  
Temperature: 1050 °C  
Steam Reactor  
Temperature: 600 °C  
Fuel Reactor  
Adiabatic  
Pressure: 15.19 bar  
Air Reactor  
Adiabatic  
Temperature: 1000 °C  
Pressure: 15.19 bar  
SESMR (steam methane reforming)  
Temperature: 655 °C  
Adiabatic  
Pressure: 15.19 bar  
Regenerator  
Temperature: 900 °C  
Pressure: ~ 1 bar   | [162]     |
| 2017 | Natural gas   | Ni-based                                    | - Air reactor  
Temperature: 850 °C  
Fuel reactor  
Temperature: 850 °C  
TIT: 900 °C   | [128]     |
| 2017 | Natural gas   | Not specified                               | - Gasification  
Temperature: 700 °C  
Pressure: 1.0133 bar  
Combustion  
Temperature: 850 °C  
CLC   | [126]     |
| 2018 | Coal          | Not specified                               | - Gasification  
Temperature: 1371 °C  
Pressure: 42.2 bar  
Air reactor  
Temperature: 950 °C  
Fuel reactor  
Temperature: 900 °C   | [130]     |
| 2018 | Methane       | Ni, Cu and ilmenite-based                   | - Gasification  
Temperature: 950–1200 °C  
Pressure: 15.19 bar  
Fuel reactor  
Temperature: 870–900 °C  
Pressure: 15.19 bar   | [125]     |
| 2018 | Biomass and coal | Not specified                      | - Gasification  
Pressure: 28.5 bar  
CLC  
Pressure drop: 0.5 bar  
Air reactor  
Temperature: 1200 °C  
Fuel reactor  
Adiabatic  
Temperature: 900 °C  
Pressure: 1.013 bar   | [123]     |
| 2018 | Biomass       | Fe-based                                    | - Gasification  
Temperature: 900 °C  
Pressure: 1.013 bar  
CLHP  
Reducer  
Temperature: 900 °C  
Pressure: 1.013 bar   | [129]     |
recovery. Remaining part of the fuel is compressed and enters FR of LP-CLC system. Its exhaust goes for power generation GT, then is sent for heat recovery. Output gas of AT enters HRSG and ST system. Generated steam with a compressed stream of natural gas enters reformer and pure output H2 goes for heat recovery. Output CO2 from calcinator after heat recovery goes to CO2 compression plant. First and second air reactors supply heat of reforming and calcination respectively.

Fig. 62 shows a power plant using a CLC-based system which uses two fuel reactors and two air reactors. A HRSG system has been applied in integration with combined cycle gas turbine.

Hamers et al. [97] investigated a two stage chemical looping system integrated with power generation system by energy analysis. Syngas at 600 °C enters two continues reduction reactors and the produced CO2/H2O goes out from the second reactor. First and second air reactors supply heat of reforming and calcination respectively.

Fig. 62 shows a power plant using a CLC-based system which uses two fuel reactors and two air reactors. A HRSG system has been applied in integration with combined cycle gas turbine.

Fig. 67. Absorption chiller/refrigerator, ASU, gasification, chemical looping with two reactors, CCPP, HRSG.

In the co-generation process suggested by Zhu et al. [164], biomass after dehydration, enters gasifier with a steam stream. Raw gas after cooling, ash separating and cleaning (H2S removing), follows to FR in Fe-CLC unit. Also compressed air and steam from HRSG enter AR and

Fig. 68. Exergy and overall energy efficiencies for cooling/chemical looping-based systems.
Table 6
Used fuel, OC and operational conditions for CLC-based processes with cooling generation.

<table>
<thead>
<tr>
<th>Year</th>
<th>Used fuel</th>
<th>Oxygen carrier type</th>
<th>Highlighted operational conditions</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>Coal</td>
<td>Nickel-based (NiO/Al2O3)</td>
<td>- Gasifier</td>
<td>[165]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Operating temperature: varied</td>
<td>- Fuel reactor</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Pressure: 30 bar</td>
<td>- Temperature: 1285 °C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Fuel reactor</td>
<td>- Heat duty: adiabatic</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Temperature: 5 bar</td>
<td>- Air reactor</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Operating temperature: 1200 °C (air cooling)</td>
<td>- Air inlet pressure: 5 bar</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Biomass and Coal</td>
<td>Nickel-based (NiO (as active component) and Al2O3 (as inert component to enhance physical strength)) (NiO (40 wt%)/Al2O3)</td>
<td>- Gasifier</td>
<td>[166]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Temperature: variant</td>
<td>- Pressure: 28.5 bar</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Pressure: 28.5 bar</td>
<td>- Temperature: 1023 °C</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Pressure drop: 15% of inlet</td>
<td>- Pressure: 4.25 bar</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Heat duty: adiabatic</td>
<td>- Air reactor</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Temperature: 1000 °C (air cooling)</td>
<td>- Air inlet pressure: 5 bar</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Pressure drop: 15% of inlet</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5 illustrates the main applied materials and conditions for chemical looping-based power generation processes with combined power plants.

3. Cooling generator/chemical looping-based processes

Fun et al. [165] studied a CCHP-CLC system. They proved that the optimum conditions of 0.05 and 0.75 for S/C and O/C ratios respectively and 5 bar operating pressure for CLC. Overall energy efficiency was achieved 58.20% for summer and 60.34% in winter. The reduction potential for coal consumption was estimated 23.23% and 27.20% for summer and winter respectively. In another work, an evaluation of a BCCLC-CCHP system was done by Fan et al. [166] from the thermodynamics and environmental points of view. It was demonstrated that energy efficiency of this system can reaches to 60.16% and 57.46% in summer and winter respectively. Also it was found that temperature increase of AR causes increase in power production, energy efficiency, exergy efficiency and primary energy saving ratio (PESR), but decreases the cooling and/or heating production. It was reported that by increasing the corn ratio in the fuel from 10% to 50%, the GHG emissions will be reduced from 97.91% to 123.38% in summer and from 98.06% to 121.66% in winter.

Fig. 69. An overview of used fuel for chemical looping-based CHP and CCHP systems.

SR of this unit. A part of the flue gas of FR, and output stream of SR (H2 + steam) is used for heat recovery in the HRSG system. Depleted gas of AR, runs a GT and enters HRSG. On the other hand, biomass with a portion of output gas of reduction reactor of CLAS unit, goes into the combustor. Exhaust gas enters a gas turbine, then after crossing a heat exchanger, enters HRSG system. Preheated air is used for oxidation reactor in the CLAS unit. Generated steam of HRSG runs a three stage steam cycle power plant.

Fig. 64 provides a detailed view of a combined cycle power generator process which employs chemical looping system.

Figs. 65 and 66 show electrical, thermal, energy, exergy, net power, hydrogen and plant efficiencies for integrated systems using combined cycle power plants and chemical looping system. Vertical axis presents the efficiency values and horizontal axis shows related references. Efficiency types are distinct with different colors. The provided figures could present an acceptable overview and comparison between the gained efficiencies in different studies and works.
<table>
<thead>
<tr>
<th>Oxygen carrier type</th>
<th>Reduction and oxidation reactions</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe-based</td>
<td>Fe₂O₃ + CH₆H₆O₂₉O₂₀ → CO₂ + 0.42H₂O + 1.13FeO + 0.87FeO</td>
<td>[134]</td>
</tr>
<tr>
<td></td>
<td>Fe + H₂O → FeO + H₂</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3FeO + H₂O → Fe₂O₃ + FeO + H₂</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4Fe₂O₃ + O₂ → 6Fe₂O₃</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4Fe₂TiO₅ + 4TiO₂ + CH₄ → 8FeTiO₃ + CO₂ + 2H₂O</td>
<td>[26]</td>
</tr>
<tr>
<td></td>
<td>Fe₂TiO₅ + TiO₂ + CO → 2FeTiO₃ + CO₂</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe₂O₅ + TiO₂ + H₂ → 2FeTiO₃ + H₂O</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe₂O₅ + Al₂O₃ + (CₓHₙₐₐ, CH₄, CO, H₂) → Fe₃Al₂O₆ + CO₂ + H₂O</td>
<td>[167]</td>
</tr>
<tr>
<td></td>
<td>4Fe₂Al₂O₄ + O₂ → 2Fe₃O₄ + 4Al₂O₃</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4Fe₂ + C + 0.21O₂ → 1.185Fe + CO₂</td>
<td>[15]</td>
</tr>
<tr>
<td></td>
<td>3Fe + 4H₂O → Fe₃O₄ + 4H₂</td>
<td>[86,155]</td>
</tr>
<tr>
<td></td>
<td>1.202Fe₃O₄ + CO ↔ 3.807Fe₀.₉₄₇O + CO₂</td>
<td>[98,160]</td>
</tr>
<tr>
<td></td>
<td>1.202Fe₃O₄ + H₂ ↔ 3.807Fe₀.₉₄₇O + H₂O</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe₀.₉₄₇O + CO ↔ 0.947Fe + CO₂</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe₀.₉₄₇O + H₂ ↔ 0.947Fe + H₂O</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.807Fe₀.₉₄₇O + H₂O ↔ 1.202Fe₃O₄ + H₂</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3Fe₂O₃ + CO → 2Fe₃O₄ + CO₂</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3Fe₂O₃ + H₂O → 2Fe₃O₄ + H₂O</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3Fe + 2O₂ → Fe₃O₄</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6Fe₂O₃ + CH₃OH → 12FeO + 2CO₂ + 3H₂O</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12FeO + 3O₂ → 6Fe₂O₃</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12Fe₂O₃ + CH₄ → 8FeO + CO₂ + 2H₂O</td>
<td>[108,112]</td>
</tr>
<tr>
<td></td>
<td>4.808FeO₃ + CH₄ → 15.23Fe₂O₅ + CO₂ + 2H₂O</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.947Fe₂O₃ + 0.788CO → 3FeO + 0.788CO₂</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.947Fe₂O₃ + 0.788H₂O → 3FeO + 0.788H₂O</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3FeO + CO → 2Fe₂O₄ + CO₂</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3Fe₂O₄ + H₂O → 2Fe₃O₄ + H₂O</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12Fe₂O₃ + CH₄ → 2Fe₃O₄ + 8FeO + 2H₂O</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3FeO + H₂O → Fe₂O₄ + H₂</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4FeO + 3H₂O → 4Fe + 3H₂O</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2Fe₂O₃ + 2H₂O → 2Fe₃O₄ + H₂O</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3Fe₂O₄ + H₂O → 3FeO + H₂O</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3FeO + H₂O → Fe₂O₄ + H₂</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3Fe + 2O₂ → Fe₃O₄</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12Fe₂O₃ + CH₄ → 8FeO + CO₂ + 2H₂O</td>
<td>[92,109,169,170]</td>
</tr>
<tr>
<td></td>
<td>4FeO + CH₄ → 4Fe + CO₂ + 2H₂O</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2Fe₂O₃ + CH₄ → 2FeO + CO₂ + 2H₂</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3Fe₂O₃ + H₂ → 2Fe₃O₄ + H₂O</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8FeO + 8/3H₂O → 8/3Fe₂O₄ + 8/3H₂</td>
<td></td>
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</tbody>
</table>

(continued on next page)
<table>
<thead>
<tr>
<th>Oxygen carrier type</th>
<th>Reduction and oxidation reactions</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni-based</td>
<td>7NiO + C + H₂ → 7Ni + 2CO₂ + 3H₂O</td>
<td>[11,16,27,73,77,82,92,94,99,100,113,118,122,125,128,131,133,144,156,158,161,162,165,166,173]</td>
</tr>
<tr>
<td>Ni-based</td>
<td>7NiO + C + H₂ → 7Ni + 2CO₂ + 3H₂O</td>
<td>[11,16,27,73,77,82,92,94,99,100,113,118,122,125,128,131,133,144,156,158,161,162,165,166,173]</td>
</tr>
<tr>
<td>Cu-based</td>
<td>4CuO + CH₄ → 4CO₂ + 2H₂O + 4Cu</td>
<td>[11,92]</td>
</tr>
<tr>
<td>Ca-based</td>
<td>CaO + CO₂ → CaCO₃</td>
<td>[100,152,154,155,156,163]</td>
</tr>
<tr>
<td>Cu-based</td>
<td>4CuO + CH₄ → 4CO₂ + 2H₂O + 4Cu</td>
<td>[11,92]</td>
</tr>
</tbody>
</table>
evaluation. In this process, air after compression crosses is sent to the PSA. Separated O₂ is compressed and with steam from HRSG and ST system enters gasifier for coal and biomass gasification. Produced syngas enters WHB, then after gas conditioning, cooling and sulfur removal, is heated and enters FR. The produced CO₂ + H₂O is used for power generation in a gas turbine. FR and AR exhaust go into the WHB with interact by a LiBr refrigerator. After three stage intercooling compressor, CO₂ of flue gas of FR is ready to transport.

The reported efficiencies for cooling production integrated with chemical looping technology, is presented in Fig. 68. The results of two references are presented in different colors. Horizontal axis, explains reported efficiencies (overall efficiency in winter and summer and energy efficiency) and vertical axis demonstrates the related values.

Table 6 shows characteristics of chemical looping-based processes with the cooling as main product.

Fig. 69 shows dispersion of the used fuel for power, heating, and cooling production using chemical looping technology with studies and researches reviewed in the current paper. It is inferred that coal, methane, natural gas and syngas were the most popular fuels in the mentioned processes.

In Table 7, the reactions occurring in the fuel reactors, steam reactors and air reactors for chemical looping systems in CHP and CCHP units are presented briefly. The reactions have been categorized according to the applied oxygen carrier in the system. At first, reactions occurring in the fuel reactors, have been mentioned. The fuels which are shown in the reactions, are syngas (CO and H₂) and CH₄ mainly.
<table>
<thead>
<tr>
<th>Year</th>
<th>Brief title</th>
<th>Used fuel</th>
<th>Oxygen carrier type</th>
<th>Highlighted operational conditions</th>
<th>Reference</th>
</tr>
</thead>
</table>
| 2005 | Co-production of power and hydrogen with CLR in an integrated process | Natural gas | Nickel-, Copper-, Manganese- and Iron-based (Metal oxides of Ni, Cu, Mn, and Fe were prepared by impregnation on a SiO₂ support (NiO, Fe₂O₃, Mn₂O₃, and CuO on a SiO₂ carrier)) | -Reformer: Temperature: 800–850 °C  
-Oxidizing and reducing Temperature: 700–950 °C | [177] |
| 2009 | An up-scaling of CLC technology with a 10 kW prototype and 120 kWth scaled-up unit for CO₂ capture goals | Natural gas and syngas | Nickel-based | Temperature difference between air reactor and fuel reactor: 5–20 °C | [178] |
| 2010 | A 140 kWth pilot plant with CLR equipped with cooling system | Natural gas | Nickel-based | -Three experimental campaigns Temperature: 747 °C , 798 °C and 903 °C, respectively | [179] |
| 2010 | Investigation of effect of ambient temperature on performance of a combined cycle chemical looping power generation system | Natural gas | Nickel-based (NiO/NaAl₂O₄) | -Oxidation Temperature: 1200 °C  
-Reduction Temperature: 967 °C  
Pressure drop: 14.7 kPa  
-Turbine inlet temperature (TIT): 1116 °C | [176] |
| 2011 | A chemical looping-based system for production of power and H₂ by application of combined cycle gas turbine and WGS reactor | Hydrocarbon-based fuels | Na-based (Liquid Na₂O) | -Oxidizer Temperature: 1577 °C  
-Reducer Temperature: 1177 °C | [179] |
| 2013 | Analyzing the effective variables on the performance of a 200 MW thermal power plant using chemical looping combustion | Methane | Iron-based (Fe₂O₃/Al₂O₃) | -Air reactor Temperature: 1000 °C  
Pressure drop: 11.08 kPa  
-Fuel Reactor Temperature: 979.7 °C  
Pressure drop: 6.92 kPa | [180] |
| 2014 | Evaluation of oxygen carrier composition on performance of a 300 Wth chemical looping combustion unit | Syngas and Natural gas | Manganese-based (manganese and silica-oxide (Mnsi) manganese and silica-oxide and titania (MnSiTi)) | -Fuel reactor Temperature(full conversion): 950 °C (syngas) and 900 °C (natural gas) | [181] |
| 2014 | A 100 kW DFB gasifier coupled with a 100 kWth DCFB chemical looping combustion pilot plant | Solid biomass | Copper-based | -Gasifier Temperature: 850 °C  
Steam/fuel ratio: 1.6 kg/kg dry biomass  
-Fuel reactor Temperature: 850 °C and 900 °C  
(Two operating conditions)  
-Oxidation Temperature: 1200 °C  
-Reduction Inlet temperature: 530 °C  
-Air reactor Design temperature: 1050 °C  
Operating temperature: 1000 °C and 1030 °C  
-Fuel reactor: Design temperature: 970 °C  
Operating temperature: 900 °C and 930 °C | [182] |
| 2014 | Process simulation and economic analysis of an integrated system of CLC and HAT | Natural gas | -Air reactor Temperature: 530 °C  
-Fuel reactor Temperature: 970 °C  
Operating temperature: 900 °C | [173] |
| 2015 | Investigation of a 1 MWth CLC pilot plant | Coal | Iron-based (Ilmenite) | [184] |
| 2015 | Investigation the performance of a 120 kW CLC pilot plant | Natural gas | Copper-based (A copper based oxygen carrier prepared by impregnation on a highly porous alumina support (14.2 wt% active CuO)) | [185] |
| 2015 | A 1 MWth auto-thermal CLC pilot plant using two interconnected CFB reactors | Coarse Hard Coal | Iron-based (Ilmenite) | [186] |
| 2017 | A 1 KWth CLC unit with liquid fossil fuels | Diesel, Mineral lubricant oil and Synthetic lubricant oil | Iron-based support (γ-Al₂O₃) | [167] |

(continued on next page)
Reactor between the fuel and solid oxides in the fuel reactors, the partial oxidation in the steam reactors, and oxidation in the air reactors, has been presented respectively for each reference. A comparison between the abundance applied oxygen carrier types in the chemical looping systems. Has been carried out. As shown in Fig. 70, iron- and nickel-based particles are the most used oxygen carriers in the chemical looping-based units with heating, cooling and power generation.

Some studies has been carried out around the chemical looping-based systems with power or heat generations. In these systems, configuration of the process structure and connection of components of the process, has not been identified. A brief Characteristics of them are explained in Table 8.

4. Conclusion

Chemical looping integration in CHP (combined heat and power) and CCHP (combined cooling, heating and power) systems, with the aim of hydrogen generation (CLHG (chemical looping hydrogen generation), CLR (chemical looping reforming)), air separation (CLA (chemical looping air separation)), gasification (CLG (chemical looping gasification)) and combustion (CLC (chemical looping combustion)) with inherent CO₂ capture reveals many advantages than conventional systems. The most important advantage of using chemical looping technology is discarding the cost of separation of impurities and pollutants before and after combustion. Based on the discussed integrated processes, chemical looping power plants can be categorized into thermo-electrical and thermo-mechanical processes. Thermo-electrical power plants have higher efficiency, but because of using fuel cells for conversion of the fuel to electricity, they use more advanced and developing technology. Thermo-mechanical processes use conventional methods for production of electrical power and their efficiency is lower. Proposed processes for CHP and CCHP systems with application of chemical looping technology and studies about them, has been demonstrated that some units are crucial in integrated systems. For instance, application of gasification unit for solid-fueled processes and ASU for supplying the pure oxygen when is required, are inescapable. Due to biomass as a renewable resource and coal, have high portion in fuel supplying in chemical looping-based power plants, special attention to gasification process is needed. So in such processes for increasing the efficiency and decreasing the cost, adjustment of the operating conditions and using efficient equipment seems essential. It is obvious that performance improvement of the units and modification of the subsystems, leads to growth in integrated process function and useful products. As well as power generation subsystems (selection of the most appropriate type, subject to existing conditions and improvement in their operation) have very outstanding role in performance of the integrated systems. Performance of the discussed processes configurations are compared by comparative figures and tables.

Total, net, electrical, energy and exergy efficiencies were reported in the bar graph figures. With the study on yields of the power plants using chemical looping technology, the highest electrical efficiency was gained 67% for SOFC-based power generation processes. The lowest electrical efficiency is related to a combined cycle power plant with the value of 11.36%. The energy efficiency is in the range of 39–70%. Both the lowest and highest values are attributed to the combined cycle power plants. The minimum value reported for exergy efficiency was 22.16% for cooling-based power plants and the highest value was 73.25% relevant to combined cycle power plants. Despite the limitation created by chemical looping employment in the power plants, the wide range of reported efficiencies, shows that many parameters can affect each section and overall system performance. Chemical looping application, imposes some energy consumption and equipment utilization on the power plant. But as mentioned with various resulted efficiencies, applying the appropriate condition and system characteristics, has the most impact on results. Oxygen carrier type has an important role in chemical looping systems and overall system performance. Fe-based and Ni-based solid oxides have had the most usage in CHP, CCHP/chemical looping systems. Fe-based oxygen carriers are relatively inexpensive, chemically stable, non-toxic, and low temperature is required for sintering. Ni-based ones because of their strong catalytic properties, have been appeared attractive for chemical looping systems.

References


[39] Dick FP, Mu IL, Lima A. Performance of a PEMFC system integrated with a biogas chemical looping reforming processor: a theoretical analysis and comparison with other fuel processors (steam reforming, partial oxidation and auto-thermal re-


