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Feasibility analysis of nuclear–coal hybrid energy systems from the perspective of low-carbon development

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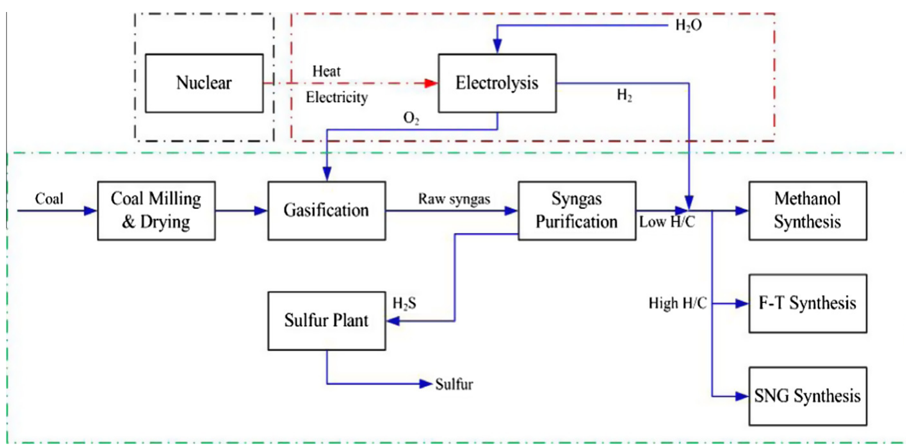
HIGHLIGHTS

- We report a nuclear–coal hybrid energy systems.
- We address the high-carbon energy resource integrating with a low-carbon energy resource.
- We establish a systematic techno-economic model.
- Improving both energy and carbon efficiency.
- A significantly lower CO_2 emission intensity is achieved by the system.

GRAPHICAL ABSTRACT



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ABSTRACT

Global energy consumption is expected to increase significantly due to the growth of the economy and population. The utilization of fossil resource, especially coal, will likely be constrained by carbon dioxide emissions, known to be the principal contributor to climate change. Therefore, the world is facing the challenge of how to utilize fossil resource without a large carbon footprint. In the present work, a nuclear–coal hybrid energy system is proposed as a potential solution to the aforementioned challenge. A high-carbon energy such as coal is integrated effectively with a low-carbon energy such as nuclear in a flexible and optimized manner, which is able to generate the chemicals and fuels with low carbon dioxide emissions. The nuclear–coal hybrid energy system is presented in this paper for the detailed analysis. In this case, the carbon resource required by the fuel syntheses and chemical production processes is mainly provided by coal while the hydrogen resource is derived from nuclear energy. Such integration can not only lead to a good balance between carbon and hydrogen, but also improve both energy and carbon efficiencies. More importantly, a significantly lower CO_2 emission intensity is achieved. A systematic techno-economic model is established, and a scenario analysis is carried out on the hybrid system to assess the economic competitiveness based on the considerations of various types of externalities. It is found that with the rising carbon tax and coal price as well as the decreasing cost of nuclear energy, the hybrid energy system will become more and more economically competitive with the conventional option, which make it a potential viable solution for the future carbon-constrained world.

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1. Introduction

Energy supply is vital to all aspects of modern society [1]. Over the past decade, global energy consumption is increasing constantly caused by the soaring demand from the developing countries, and the trend is expected to continue. The global energy consumption is predicted to increase by 56% from 2010 to 2040 [2]. In the meantime, global carbon emissions from energy consumption have risen by 1.9% (723 Mt CO_2) in 2012, which is even faster than primary energy consumption. The largest growth in 2012 came from China (548 Mt, 6%) and India (122 Mt, 6.9%), while Japan also recorded a significant increase (92 Mt, 6.7%) due to the suspension of nuclear energy supply [1]. Worldwide energy-related carbon dioxide emissions are predicted to rise to 36 billion metric tons by 2020 and 45 billion metric tons by 2040, which is a 46% increase from 2010 [2].

Carbon dioxide emission is considered to be a primary cause for climate change [3–5]. The world is facing dual pressure from both the growth of energy demand and the reduction of CO_2 emission. The consequences of carbon emission constrain the long-term usability of traditional fossil energy. Thus, it is urgent to find novel routes for the traditional energy industry to switch away from fossil resource utilization pattern.

Low-carbon energy, such as nuclear and renewable energy, is replacing fossil resource in electricity generation with reduced CO_2 emission [6–8]. However, fossil resource cannot be replaced entirely in the foreseeable future, as it is the primary source of carbon that is required for the bulk chemical and synthetic oil production. In recent years, low-carbon utilization of carbon-containing resources has been extensively investigated to maximize the utilization of carbon resources with minimal CO_2 emission. The concept of "Green Carbon Science" proposed by He and Sun optimized the transformation of carbon-containing compounds and the relevant processes involved in the entire carbon cycle from carbon resource processing, carbon energy utilization, and carbon recycling to use carbon resources efficiently and minimize net CO_2 emissions [9]. Huaman and Jun discussed the perspectives for development of carbon capture and storage (CCS) technologies in the global fight against climate change and proposed that the low-carbon technology was vital for future carbon emission reduction [10]. Chen et al. developed a conceptual design of H_2 coproduction from coal and biomass mixture in IGCC (Integrated Gasification Combined Cycle) with CCS, which has a high system efficiency with low CO_2 emission [11].

CO_2 emission from fossil fuel conversion processes usually comes from either fossil fuel combustion for supplying heat and power or chemical conversion processes [12]. If nuclear energy is used to supply heat and electricity, the consumption of fossil fuel will decrease as well as the corresponding CO_2 emission [13–16]. Meanwhile, for the chemical conversion process, such as the conventional coal-to-methanol process, most part of the CO_2 emission is from the water–gas shift reaction, which is necessary for increasing the H/C ratio of the syngas generated from coal. Due to the low hydrogen content of coal, most of carbon resources are converted to CO_2 via the water–gas-shift reaction. Therefore, CO_2 emission can be reduced by supplying hydrogen from either nuclear or renewable energy instead of relying on the water–gas shift reaction [17–21]. Moreover, the integration of renewable energy or nuclear energy with fossil resource was proposed, where hydrogen was obtained in the low-carbon process via water electrolysis, which could reduce the consumption of fossil fuels and also CO_2 emission [12,22–27].

Comparing to renewable energy such as wind and solar energy, the nuclear energy is acknowledged to be superior to integrating with fossil fuel in terms of technical feasibility for its stable and sustained energy throughput, which has attracted broad attention [28–35]. Nuclear energy has the potential to contribute a significant share of energy supply without negative impacts to global climate change [28]. Through a variety of options, such as electricity generation, heat and hydrogen supply in different industries, nuclear energy can ensure energy supply with minimal CO_2 emission [29]. The most promising nuclear reactors in the future are high-temperature reactors, such as the high-temperature gas-cooled reactor (HTGR) and the molten-salt reactor (MSR) [30]. The hydrogen can be efficiently obtained by the high temperature electrolysis (HTE) with the utilization of high temperature heat from the high-temperature nuclear reactors. The large-scale and low-cost hydrogen supply from HTGR or MSR improve the feasibility of nuclear-assisted coal-based hybrid energy system.

As mentioned above, the nuclear-assisted coal-based hybrid energy system is shown in Fig. 1, by which the very low CO_2

Table 1
Production scale and composition of final products.

	Final product	Scale	Composition	
System I	Methanol	427,800 tons/a	CH_3OH	99.97(mol%)
			H_2O	⩽0.03(mol%)
System II	Oil	183,500 tons/a	Solvent oil	41.55(wt.%)
			Diesel	21.82(wt.%)
			Wax	33.63(wt.%)
System III	Methane	2.2×10^8 N m^3/a	CH_4	95.45(mol%)
			N_2	1.54(mol%)
			H_2	2.53(mol%)
			CO	0.77(mol%)
			CO_2	0.48(mol%)

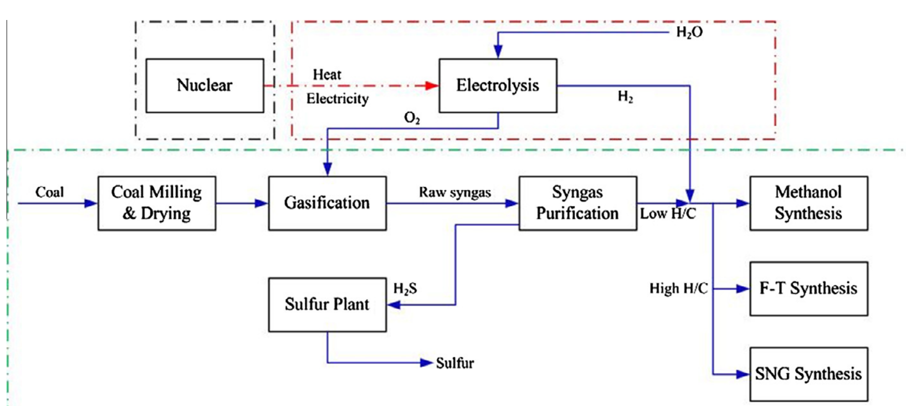

Fig. 1. Nuclear-assisted coal-to-fuel (methanol, oil and gas) production system.