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Techno-economic analysis of direct coal-biomass to liquids (CBTL) plants with shale gas utilization and CO_2 capture and storage (CCS)

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HIGHLIGHTS

- BEOP is lower if hydrogen is produced from shale gas.
- Increase in BEOP strongly depends on the extent of CCS.
- Environmental credits can have strong effect on BEOP.
- Economic performance strongly depends on the shale gas price.

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ABSTRACT

In this paper, techno-economic analysis of direct coal biomass to liquids (CBTL) plants is performed in Aspen Process Economic Analyzer (APEA) using high fidelity process models developed in Aspen Plus for four different configurations of direct CBTL plants. Results from the economic model are validated with the data in the open literature, if available. Sensitivity studies are conducted to evaluate the impacts of key investment parameters, design parameters, and potential government-subsidized credits on the main economic measures including net present value (NPV), internal rate of return (IRR), break-even oil price (BEOP) and equivalent oil price (EOP). Using the North America 2015 pricing basis in APEA, this study shows that the BEOP of direct CBTL processes ranges from \$56.9/bbl to \$80.5/bbl for large scale (50,000 bbl/day) plants and from \$77.3/bbl to \$97.5/bbl for small scale (10,000 bbl/day) plants. It is observed that integrating a carbon capture and storage (CCS) unit to the direct CBTL process can increase the BEOP by about 10%, while utilization of the cheap and abundant shale gas (especially in the continental US) can make the direct liquefaction processes considerably more attractive than the indirect CBTL processes.

1. Introduction

Direct coal to liquids (DCL) process is technically feasible for producing alternative transportation fuels from coal, which has larger inventory than petroleum crude. With appropriate product upgrading, synthetic fuels produced from the DCL process can be directly used in the current motor engines. However, similar to other coal liquefaction processes, the DCL process has not been widely commercialized mainly because of economic uncertainty, high CO_2 emission, and high capital cost [1,2]. It is reported that the capital investment in and CO_2 emission from the Shenhua DCL plant with coal-derived hydrogen and a capacity of 16,300 bbl/day are about \$1.46 billion (reported in 2008) and 0.48 tonne CO_2 per barrel liquids [1–5]. The environmental footprint of coal liquefaction processes can usually be reduced by co-processing coal and biomass and applying CO_2 capture and storage (CCS) technology but at the cost of higher capital and operating investments [3,6–10]. Furthermore, instead of coal gasification, hydrogen can be produced from less expensive and more H_2-rich sources. For example, the recent boom of shale gas in the United States has opened a door for leveraging the shale gas as a source of H_2 [1,11,12]. Therefore, there is a need to reevaluate the potential of the DCL process. There is barely any study in the current open literature on the DCL technology at the systems level with shale gas and biomass utilization integrated with CO_2 capture and compression. Most published studies have focused on the indirect coal liquefaction (ICL) technology, mainly because the ICL technology is more mature and has adequate industrial experience, including several coal or gas to liquids plants recently constructed by Shell Qatar, Sasol, ExxonMobil and Yitai. [13–15] Due to the lack of commercial experience and literature in the area of process syn-

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Nomenclature

AGR	acid gas removal
APEA	Aspen Process Economic Analyzer
AUM	Analyzer Utility Modules
BEOP	break-even oil price
BFD	block flow diagram
BFW	boiler feed water
BOP	balance of plant percentage
CBTL	coal-biomass to liquids
CCS	CO_2 capture and storage
CEPCI	Chemical Engineering Plant Cost Index
COP	crude oil price
CTSL	catalytic two-stage liquefaction
CG	co-gasification
DCL	direct coal liquefaction
DIP	direct permanent investment
EDR	Exchanger Design and Rating
EIA	Energy Information Administration
EOP	equivalent oil price
FCI	fixed capital investment
FT	Fischer-Tropsch
GT	gas turbine
HHV	higher heating value
HRSG	heat recovery and steam generation
HTI	Hydrocarbon Technologies Inc.
ICL	indirect coal liquefaction
IGCC	integrated gasification combined cycle
IRR	internal rate of return
ISBL	inside battery limit
LHSV	liquid hourly space velocity
MOC	materials of the construction
NGCC	natural gas combined cycle
NPV	net present value
O&M	operating and maintenance
OSBL	outside battery limit
POX	partial oxidation
PSA	pressure swing adsorption
RON	research octane number
ROSE-SR	Residual Oil Supercritical Extraction-Solids Rejection
TPC	total project cost
SMR	steam methane reforming
WGS	water gas shift

thesis and systematic analysis of direct coal-biomass to liquids (CBTL) processes with or without shale gas utilization and CCS, development of plant-wide process and economic models will be useful for analyzing the feasibility of the modified DCL technology and for conducting further studies, such as optimization and life-cycle assessment.

In the DCL process, coal is directly converted to liquid fuels by adding hydrogen, as shown in Reaction (1) [1,2]. Because of low H/C ratio in the coal, even though very less CO_2 is generated in the direct liquefaction reactor, a significant amount of external hydrogen is required, generation of which leads to high amount of CO_2 release [1,3]. This hydrogen is needed not only to convert coal to partially refined syncrude in the liquefaction reactor, but also to bring the H/C ratio up to about 2 in the syncrude upgrading step. In the Shenhua DCL plants, the hydrogen demand is satisfied by coal gasification route with large capital investment and high level CO_2 emission [1,2,5,16]. Other than coal gasification, hydrogen can also been produced by partial oxidizing liquefaction residues or a mixture of residues, coal and biomass, and reforming natural gas or shale gas [1,17]. Residues partial oxidization (POX) can reduce the demand of external fuels for hydrogen production, while steam methane reforming (SMR) can produce hydrogen with less CO_2 emission and from cheaper energy sources. According to our previous studies, even though both POX and SMR technologies are considered for the DCL process, the CO_2 emission could only be reduced by about 20%, which is still significant compared with traditionally petroleum industries [1].

$$CH_{0.8} + 0.4H_2 \rightarrow CH_{1.6} \quad (1)$$

Similar to the studies conducted to the ICL processes [3,6–10], further reduction of CO_2 emission can be achieved by adding a small amount of biomass into the feedstock and applying CCS technology to capture the CO_2 produced in plant without substantially modifying current DCL technologies. It is widely accepted that biomass is a carbon-neutral energy source [18,19]. In addition, utilization of biomass in the DCL process can reduce the external hydrogen demand in the liquefaction reactors because of its higher H/C ratio, and therefore reduce the CO_2 emission from the hydrogen production plant [1,20]. Several experimental studies have been conducted for co-processing coal and biomass using direct liquefaction processes [10,20,21], but those processes have been barely modeled at either equipment-level or system-level. CCS technologies have been widely studied for the ICL [22], integrated gasification combined cycle (IGCC) [23], pulverized coal combustion and natural gas combined cycle (NGCC) processes [24], but there is still lack of such studies for the DCL processes.

In our previous study, detailed plant-wide models have been developed in Aspen Plus for direct CBTL plants of different configurations by considering different sources for hydrogen and different extent of CCS [1]. In that study, the focus was on conversion efficiency and CO_2 emission but not on economic performance. To analyze the commercial feasibility of those novel processes, techno-economic studies are required in addition to the technical analysis. It has been reported by several researchers that DCL processes may have better economic performance than ICL processes due to their higher thermal efficiency [1,3,25], while, as per Robinson et al., the economic performance of DCL and ICL processes are similar [4]. However, there is hardly any techno-economic study of the DCL technology conducted by using rigorous process and economic models especially while considering CO_2 capture, biomass co-processing and different H_2 sources. Most of the techno-economic studies in the open literature have been conducted for the ICL processes, IGCC plants and coal-firing power plants rather than DCL processes [6,7,18,24,26–29]. Due to the difference in the conversion mechanisms, CO_2 emission sources, and process configurations, the impact and penalty of adding biomass and CCS are expected to be different between ICL and DCL technologies. Therefore a rigorous techno-economic study of the direct liquefaction processes with CCS and different H_2 sources is very much desired.

As mentioned before, the carbon footprint of the energy conversion processes can be reduced by adding biomass and applying CCS technologies at the cost of higher operating cost and capital investment [3,6–10]. In order to promote biomass utilization and development and commercialization of CCS technologies, government subsidies, such as tax benefits, carbon tax and other environmental credits, are being offered in a number of countries or in various regions within a country [30]. For example, the federal government