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Current Opinion in Chemical Engineering

Integrated biomass and fossil fuel systems towards the production of fuels and chemicals: state of the art approaches and future challenges

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Volatility of crude oil prices and dependence of the United States on petroleum imports make the development of alternative refineries inevitable. Recent work has focused on developing and simulating such alternative processes from integrated biomass/natural gas and biomass/coal feedstocks to produce fuels and chemicals. These process simulations provide invaluable information on the performance and capability of the specific process alternative considered. However, the development of many alternative technologies, along with multiple feedstock and product possibilities, made the superstructure based optimization methods the natural approaches to be pursued. These process superstructures can be efficiently optimized to provide insights into topological, economic, and environmental trade-offs by simultaneously weighing the strengths and weaknesses of each alternative. Despite the development of these powerful tools, several outstanding challenges need to be systematically addressed. These challenges include the implementation of different conversion technologies and feedstock types, investigating the production of a superset of fuels and chemicals, systematically addressing price uncertainties for robust refinery designs, and synthesizing a supply network optimization to potentially displace the petroleum demand. This perspective article reviews the current work on integrated biomass/natural gas and biomass/coal refineries, highlights the major advances in these fields, and discusses future directions.

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Current Opinion in Chemical Engineering 2015, **9**:66-74

This review comes from a themed issue on **Energy and environmental engineering**

Edited by **Rakesh Agrawal** and **Vasilios I Manousiouthakis**

http://dx.doi.org/10.1016/j.coche.2015.08.005

Introduction

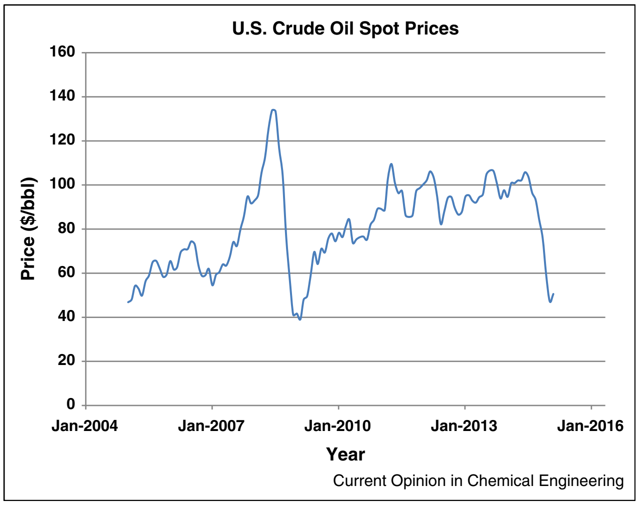
The United States demands about 19.03 million barrels of petroleum products per day [1], of which 38.6% (7.34 million) are supplied via imports [1]. As Figure 1 illustrates, recent market trends make crude oil prices extremely volatile. Additionally, petroleum industries in the United States accounted for 2254 million metric tons of CO_2 emissions in 2012 [2]. This motivates the development of processes that utilize domestically available coal, biomass, and natural gas for fuels production to reduce dependence on crude oil imports and mitigate greenhouse gas (GHG) emissions.

Biomass is an attractive feedstock that is abundantly available in the United States [4] and can reduce lifecycle GHG emissions. Coal is an abundantly available feedstock with low delivered cost ($2.0–$2.5/MM Btu) [5], but has a high carbon content that can trigger higher conversion to CO_2 [6–9]. Natural gas is an attractive feedstock with a high hydrogen to carbon ratio and a low price (7.97$/TSCF in 2008 to 2.66$/TSCF in 2012 [10]). Therefore, integrating biomass with coal or natural gas can provide reduced GHG emissions and attractive process economics. A recent review highlighted key developments for the processes that utilize these feedstocks towards the production of fuels [11••]. Figure 2 presents a flow diagram that spans all the process alternatives that are considered in the literature. In this article, we present the existing alternatives, state-of-the-art approaches, new directions, and outstanding challenges towards the integrated biomass and fossil fuel systems for the production of fuels and chemicals.

Integration of biomass and natural gas

The combination of biomass and natural gas within an integrated refinery provides a synergistic advantage compared to single feedstock systems. Borgwardt considered biomass and natural gas to be the feedstock of such hybrid refineries in 1997 [12]. Despite utilizing a fixed topology and producing a single product (methanol), the techno-economic analysis revealed a savings of $4.28 per gigajoule of gasoline displaced [12]. Borgwardt's environmental analysis also showed that the net CO_2 emissions avoided were superior than the equivalent single feedstock counterparts [12]. Dong and Steinberg [13] studied a process design where the gasification effluent is directed into the steam reformer along with natural gas that has high hydrogen

Figure 1



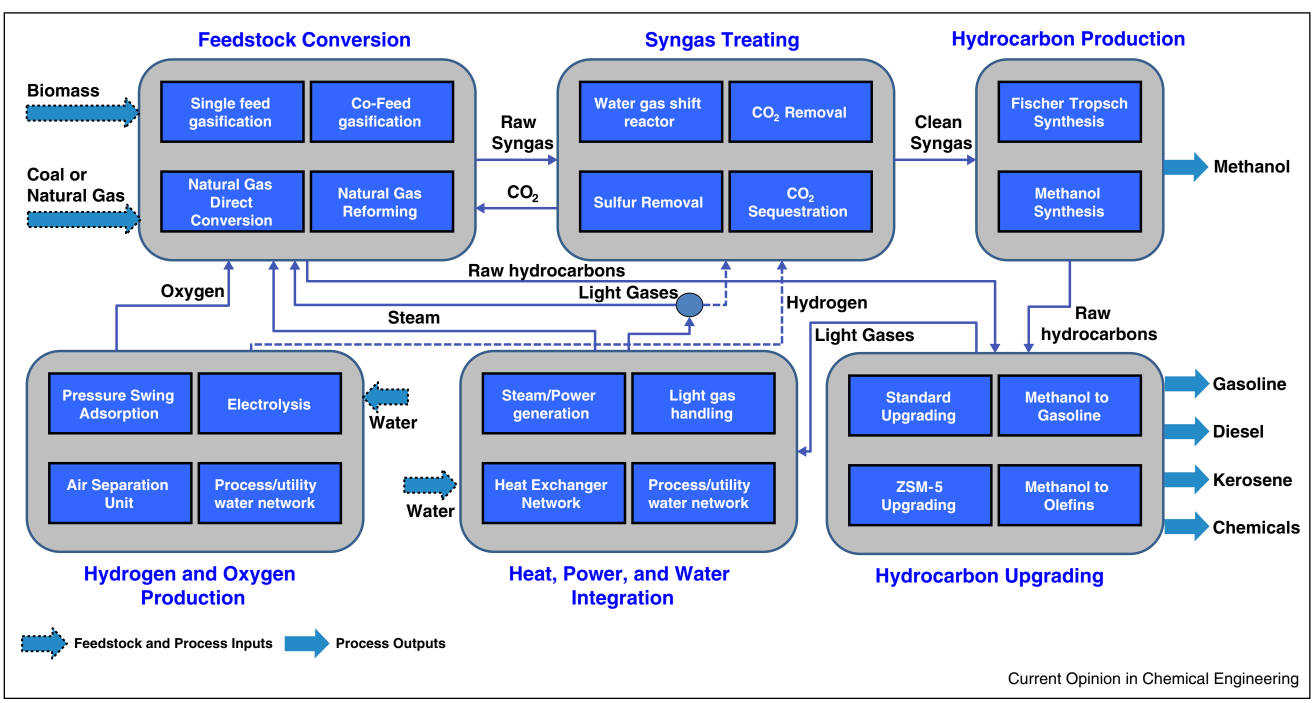
Spot price of crude oil in recent years [3].

content [13]. The economic and the environmental analysis suggested that this process can be economically competitive and can reduce CO_2 emissions [13].

In 2009, Agrawal and Singh [14] proposed conversion of biomass through fast-hydropyrolysis and hydrodeoxygenation and integrated this process with a steam methane reformer. The resulting process increased the combined fuel yield 60% compared to the equivalent single feedstock counterparts [14]. In 2010, Li *et al.* suggested that mixing the reformed gases from natural gas and biomass gasification can provide the optimal H/C ratio while avoiding extra water–gas-shift units [15]. Liu *et al.* proposed co-producing liquid fuels and electricity through gasification and autothermal reforming [16] to reduce GHG emissions significantly. Chakravarti and coworkers presented results on a natural gas enhanced biomass to liquids process [17•]. The process is simulated and optimized for a fixed topology, and some topological alternatives were considered for which the selection was made qualitatively [17•]. These process simulations provided valuable information regarding the economics and environmental benefits of the process alternatives investigated, however they cannot simultaneously compare competing technologies. As other process alternatives or technologies are developed, the number of possible process designs grow exponentially, and simulating each design alternative individually becomes impossible.

In this regard, superstructure based optimization approaches are becoming more popular because they simultaneously compare technologies and weigh the strengths and weaknesses of each process alternative. Gencer *et al.* [18•] synthesized and optimized a superstructure with two different alternatives for biomass conversion (gasification and fast-hydropyrolysis). A more comprehensive superstructure was presented by Baliban

Figure 2



Block flow diagram of integrated biomass and fossil fuel systems: although the major sections of all the considered refinery designs are consistent, there are numerous process alternatives that need to be evaluated simultaneously.