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Review

A techno-economic review of thermochemical cellulosic biofuel pathways

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HIGHLIGHTS

- Techno-economic analyses of thermochemical cellulosic biofuel pathways are reviewed.
- The results of the techno-economic analyses are compared.
- Differences in assumptions result in a wide range of financial result values.
- The importance of justifying assumptions and analyzing uncertainty is discussed.

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ABSTRACT

Recent advances in the thermochemical processing of biomass have resulted in efforts to commercialize several cellulosic biofuel pathways. Until commercial-scale production is achieved, however, techno-economic analysis is a useful methodology for quantifying the economic competitiveness of these pathways with petroleum, providing one indication of their long-term feasibility under the U.S. revised Renewable Fuel Standard. This review paper covers techno-economic analyses of thermochemical cellulosic biofuel pathways in the open literature, discusses and compares their results, and recommends the adoption of additional analytical methodologies that will increase the value of future pathway analyses.

1. Introduction

In 2007 the U.S. Congress created the revised Renewable Fuel Standard (RFS2) in an effort to replace domestic consumption of petroleum with liquid biofuels. The RFS2 mandates the annual blending of increasing volumes of biofuel with gasoline and diesel fuel for retail. While 1st-generation biofuels such as cane ethanol, grain ethanol, and soya biodiesel have been the largest contributors to the RFS2 to date, the program requires the blended volume of cellulosic biofuels to become the largest biofuel blending category by 2022 at 16 billion gallons (60.6 million liters) on an ethanol-equivalent basis (see Fig. 1) (Schnepf and Yacobucci, 2013). Unlike 1st-generation biofuel feedstocks, which are easily converted to transportation fuels via both biological and catalytic processes, lignocellulose is highly recalcitrant, plants having evolved sophisticated defenses against microorganisms that are able to metabolize polysaccharides. While various lignocellulose pretreatments have been developed to overcome this recalcitrance (Kazi et al., 2010), their technical complexity and expense have slowed efforts to commercialize biological pathways for cellulosic biofuel production, causing it to fall well short of the RFS2's mandated volumes to date (Schnepf and Yacobucci, 2013).

A growing body of research is focused on using heat and/or catalysts to convert lignocellulose to biofuels. Lignocellulosic biomass has long been used as a feedstock for heat and power generation and the technology for the conversion of carbonaceous feedstocks to gaseous products has been employed commercially since the 19th century. Subsequent processes have been developed for the catalytic conversion of biomass-derived synthesis gas ("syngas") to liquid fuels and even for the conversion of biomass directly to liquid fuel intermediates (Huber et al., 2006). In 2012 the thermochemical platform achieved the distinction of becoming the first platform to commence operations at a commercial-scale biorefinery in the U.S. when a catalytic fast pyrolysis and hydroprocessing (CPH) facility yielding 10 million gallons per year (MGY) (37.9 million liters) of biobased gasoline and diesel fuel blendstocks from

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yellow pine feedstock became operational (Lane, 2012). A recent review of U.S. cellulosic biofuel commercialization lists multiple commercial-scale thermochemical biorefineries that are expected to become operational by 2015 (Brown and Brown, 2013).

Overall cellulosic biofuel production has continued to fall well short of the volumes required to achieve the blending mandates established by the RFS2 (see Table 1). Concerns about the lack of cellulosic biofuel competitiveness with petroleum have hampered the large capital investments (company estimates frequently exceed $10/gal or $2.64/l of installed annual capacity) (Brown and Brown, 2013) necessary for widespread capacity construction (Downing and Gismatullin, 2013). This underinvestment has resulted in a chicken-and-egg dilemma: investors are unwilling to finance widespread capacity construction due to production cost uncertainty but the lack of actual cellulosic biofuel production prevents additional knowledge of production costs from being gained. Several universities and the national laboratories of the U.S. Department of Energy have employed a research methodology known as techno-economic analysis (TEA) to quickly and inexpensively calculate this missing information. TEA uses process models to quantify the technical and economic performance of a biorefinery employing one or more specific process pathways and generates a financial return on capital investment. While the uncertainty of an individual TEA's result is high due to the methodology's necessary simplification of complex processes, it enables economic comparisons of pathways to be made that would otherwise not be possible given the current state of commercialization.

This paper reviews the recent TEAs published in the open literature for cellulosic biofuel pathways within the thermochemical platform and compares their results on an adjusted basis. The pathways covered all fall into one of three broad categories based on the primary process step: gasification, pyrolysis, and solvent liquefaction. TEAs of integrated processes that combine two or more pathways from the above categories in a single biorefinery are also covered. This review focuses on pathways that employ thermochemical processes to yield liquid biofuels capable for use in unmodified internal combustion engines as their primary output, although these can take the form of both alcohols (e.g., ethanol, methanol) and hydrocarbons (e.g., diesel fuel, gasoline). A number of co-products taking gaseous, liquid, and solid forms are also considered. This review excludes pathways yielding non-liquid biofuels such as electricity, hydrogen, and synthetic natural gas as their primary outputs; while these products can be broadly categorized as cellulosic biofuels if used in automobiles, the automobile and/or infrastructure upgrades and subsequent costs that must be incurred prior to their use prevent the pathways' straightforward comparison with liquid transportation fuel pathways on a financial basis. (While it can be argued that alcohol fuels also require automobile and infrastructure upgrades prior to use, they are included in this review due to ethanol's widespread blending with gasoline in unmodified vehicles at volumes of up to 15% in the U.S.) Similarly, this review also excludes the acid and enzymatic hydrolysis and fermentation pathways despite their use of combustion to convert lignin co-product into electricity. They are excluded despite their employment of a thermochemical process since they employ a biochemical process to yield a liquid fuel as the primary product. TEAs of these biochemical pathways have been reviewed previously in this journal (Gnansounou and Dauriat, 2010). Finally, all monetary figures are adjusted to 2011 dollars based on inflation and, when the source material employs other currencies, the prevailing dollar exchange rate for the year the analysis was conducted.

Table 1
Originally-mandated, revised, and actual cellulosic biofuel production under RFS2. All figures in million liters ethanol-equivalent.

Year	Original	Revised	Actual
2010	379	25	0
2011	946	23	0
2012	1893	40	0
2013	3785	53	4
2014	6624	64	0 (to June)

2. Pathway overviews

2.1. Gasification

Gasification has been employed on a commercial-scale as a means of converting carbonaceous feedstocks to liquid transportation fuels since the 1940s, when Nazi Germany attempted to make up a wartime shortfall in petroleum by converting coal to diesel and jet fuels via the gasification and Fischer–Tropsch synthesis (FTS) pathway. In the decades since several additional gasification pathways have been developed to convert biomass feedstock to both ethanol- and hydrocarbon-based fuels by reacting the syngas over various metal catalysts or even biocatalysts. These include gasification and acetic acid synthesis (AAS), gasification and methanol-to-ethanol (MTE), gasification and methanol-to-gasoline synthesis (MTG), gasification and mixed alcohols synthesis (MAS), gasification and syngas-to-distillates (S2D), and gasification and syngas fermentation (SF).

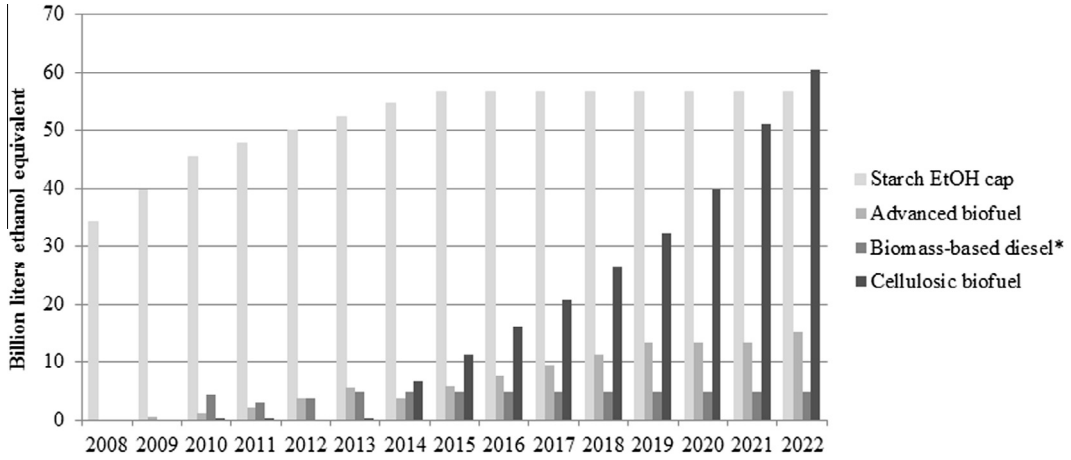

Fig. 1. The RFS2 volumetric mandate by biofuel category. *To be set annually but not to fall below pictured volume.

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