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Techno-economic comparison of biomass-to-transportation fuels via pyrolysis, gasification, and biochemical pathways

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ABSTRACT

This analysis compares capital and operating cost for six near-term biomass-to-liquid fuels technology scenarios representing three conversion platforms: pyrolysis, gasification, and biochemical. These analyses employed similar assumptions to allow comparisons among the results. Most prominently, the feedstock is assumed to be corn stover and plant capacity was 2000 tonne/day for each plant. There are large differences in the total capital investments required among the three platforms. The stand-alone biomass-to-liquid fuel plants are expected to produce fuels with a product value in the range of \$2.00–5.50 per gallon (\$0.53–1.45 per liter) gasoline equivalent, with pyrolysis the lowest and biochemical the highest. These relatively high product values are driven primarily by an assumed feedstock cost of \$75 per dry ton and the cost of capital for the plants. Pioneer plant analysis, which takes into account increased capital costs and decreased plant performance associated with first-of-a-kind plants, increases estimated product values to \$2.00–12.00 per gallon (\$0.53–3.17 per liter) gasoline equivalent.

1. Introduction

Biomass-derived transportation fuels have been promoted as a way to diversify our energy supply, utilize indigenous and renewable resources, reduce US reliance on imported oil, and mitigate the impacts of energy on climate and the environment. In the United States, the revised annual renewable fuel standard (RFS2) authorized under the Energy Independence and Security Act (EISA) of 2007 mandates increased use of alternative fuels, with a substantial portion to come from cellulosic biomass. The annual volume of cellulosic biofuel required under RFS2 begins at 100 million gal (0.4 million m^3) in 2010 and increases each year, eventually reaching 16 billion gal (60.6 million m^3) by 2022 [1] (see Fig. 1).

Meeting the ambitious goals of the EISA will require large investments of capital in new biofuel production facilities. Once constructed, these facilities will not be easily converted to other conversion pathways, so it is important that we make these largely irreversible investments carefully so we do not lock ourselves into undesirable configurations. Given that large process plant projects typically take more than four years for complete development from project definition through startup [2], the majority of the RFS2 biofuel mandates will be met with current and near-term technologies.

In this study, we report on a side-by-side techno-economic comparison of near-term advanced biofuel conversion technologies projects. This study compares the conversion of corn stover biomass-to-liquid transportation fuels via three leading conversion platforms: fast pyrolysis followed by hydroprocessing, gasification followed by Fischer–Tropsch synthesis and hydroprocessing, and biochemical conversion using dilute acid pretreatment with simultaneous saccharification and cofermentation. The capital and production costs are estimated for each platform based on detailed process models of n^{th} plant facilities,

Abbreviations: GGE, gallon of gasoline equivalent; HHV, higher heating value; LGE, liter of gasoline equivalent; NPV, net present value; PV, product value with NPV = 0 in 20 years and 10% IRR; MACRS, modified accelerated cost recovery system; TPI, total project investment; TCI, total capital investment; IRR, internal rate of return.

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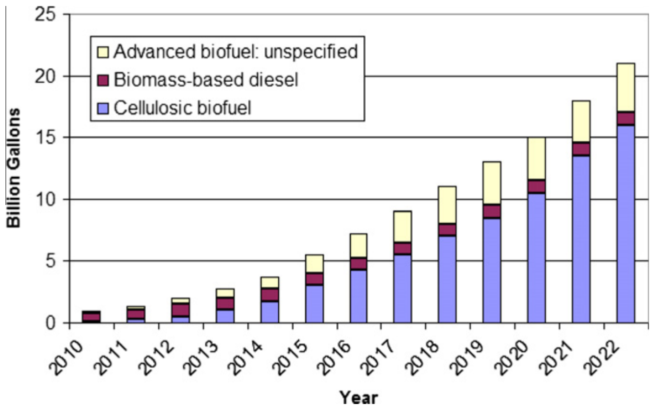

Fig. 1. EISA advanced biofuel volume mandates over time.

and the impact of technology maturity on the performance of a pioneer plant is evaluated.

2. Material and methods

2.1. Scenario selection

An enormous number of possible conversion pathways, technologies, and process configurations exist for biofuels production from biomass [3]. In addition, many different sources of biomass are being considered as feedstocks for biorefineries, and several types of fuels can ultimately be produced. It is clear that not all combinations of feedstock, conversion process, and fuel product can be evaluated with the finite resources available to any one study. So, a manageable and meaningful set of comparisons is chosen for this study based on several key criteria.

The scenarios are chosen from many options according to the following three criteria. One, the technology under consideration must be commercially feasible in the next 5–8 years and preferably currently has a high level of technology development. Two, the size of the facility must be feasible with current agricultural output. Based on this, corn stover was chosen as a single representative feedstock for all processes because it was viewed as one of the most plentiful sources of biomass available in that timeframe [4,5]. Three the final product should be compatible with the present gasoline and/or diesel infrastructure either through blending or as a direct replacement. A consistent design basis for all processes is chosen, including feedrate (i.e., 2000 dry metric tonne per day). Prior analysis [6] has shown that this size realizes significant economies of scale benefits for reasonable harvest costs and transport distances.

Based on these scenario selection criteria, a matrix of technological options was created. Process data were gathered from journal articles and other public literature to fill a scenario selection matrix. Of particular interest was literature providing experimentally verified data at either bench or pilot scale. Despite efforts to collect comparable data, the data sources varied from well-developed pilot scale experiments to laboratory-scale feasibility experiments. Data were gathered for a number of specific economic, sustainability, and technology factors including: estimated capital costs, yields, efficiencies, water use, and scale of development. Data gaps in certain categories were apparent, especially for some of the sustainability indicators. Once the matrix was populated with data, technology options were evaluated and screened qualitatively to eliminate those scenarios with lower perceived probability of successful near-term implementation.

Two gasification scenarios were chosen. The first is an oxygen-fed, low temperature (870 °C), non-slagging, fluidized bed gasifier, and the second is an oxygen-fed, high temperature (1300 °C), slagging, entrained flow gasifier. Both gasifiers are followed by catalytic Fischer–Tropsch synthesis and hydroprocessing to naphtha and distillate liquid fractions. The two gasifier technologies effectively allow for comparison between significantly different gasification pathways. Cold gas cleaning is chosen for both scenarios. Fischer–Tropsch catalytic synthesis is chosen for the fuel production because of long commercial experience by Sasol and other companies. This fuel synthesis option also supports the third selection criterion because gasoline/diesel range hydrocarbons are the primary product.

Two pyrolysis scenarios were chosen. In the first, a fraction of the bio-oil product is reformed to produce hydrogen for bio-oil upgrading, and in the second hydrogen is purchased from an external source. Both scenarios employ a fluid bed fast pyrolysis reactor followed by hydroprocessing. Bio-oil upgrading via hydroprocessing requires hydrogen input of 3–5% of the weight of the bio-oil feed. Both scenarios produce naphtha- and diesel-range stock fuel suitable for transportation fuel applications.

Seven scenarios involving biochemical conversion of lignocellulosic biomass to ethanol were selected, with four involving pretreatment variations (i.e., dilute acid, two-stage dilute acid, hot water, and Ammonia Fiber Explosion [AFEX]) and three involving downstream process variations (i.e., pervaporation, separate fermentation of C-5 and C-6 sugars, and onsite enzyme production from hydrolysate). Detailed analysis of each of these scenarios is reported in an associated paper [7]. This study reports and compares the performance of the biochemical scenario that yielded the lowest product value among the seven: the dilute acid pretreatment scenario. ("Product value" is defined for the purposes of this study as the value of fuel product per gallon of gasoline equivalent that yields a net present value of zero for the project given a 10% rate of return on investment).

2.2. Process design

Two or more scenarios representing each conversion platform (i.e., biochemical, gasification, pyrolysis) were selected for further analysis following the screening process. Benchmark techno-economic models were developed for each scenario. These are described and discussed in detail in associated articles in this journal issue. Conceptual processes are modeled using Aspen Plus [8] process simulation software to generate detailed material and energy balance data for each process configuration. Process simulation tools bring thermodynamic rigor to conceptual process analyses and also provide an integrated system depiction. When all process unit operations are integrated, including recycle streams, researchers can more fully explore how key process variables impact downstream operations or the biorefinery as a whole. In several instances, existing Aspen Plus models were adapted for this particular project [6,9]. Other processes were less developed, or there were not relevant existing Aspen Plus models available, which required additional process modeling time and resources. Process flow sheets and a preliminary process design were developed for each of the selected conversion platform process scenarios.

2.3. Peer process design review

The process flow sheets and preliminary process designs for each of the platform scenarios were reviewed by teams of technical reviewers through independent platform reviews. In addition, a technical review of the overall project was held in an effort to assure that the platform scenarios, technical and economic assumptions, and figures of merit are comparable and appropriate. A total of 32 technical reviewers representing industry, government agen-