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# Techno-economical analysis of a thermo-chemical biofuel plant with feedstock and product flexibility under external disturbances

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ABSTRACT

Biofuel is one candidate that can address the global warming and energy security challenges faced by the transportation sector. However, biofuel production is subject to unpredictable external disturbances caused by demand variation, regional instability and extreme weather. It is highly desired to design a biofuel plant such that it has operational flexibility to survive through these disturbances. Gasification based thermo-chemical conversion is one of the promising approaches: the plant can produce a variety of products including electricity, liquefied petroleum gas, gasoline, and diesel while taking almost any kind of biomass as feedstock. In this paper, technical and economic performance of thermo-chemical biofuel plants is evaluated under external disturbances, including extreme weather, market fluctuation, and policy uncertainties. Four plant configurations with varying electricity generation capacity and different in-plant hydrogen production methods (methane autothermal reforming or water-gas shifting) are considered. It has been found that by providing additional electricity production capacity and producing hydrogen via methane reforming, the biofuel plant could have the best chance to maximize profit under external disturbances. Results from this research are expected to help relevant biofuel stakeholders, i.e. investors, plant managers, and government agencies, to make key decisions with regards to investment, plant operation, as well as policy.



## 1. Introduction

Globally the transportation sector relies heavily on petroleum. For example, in 2009 93.7% of the total energy consumed in US came from petroleum [1]. Furthermore, 62.7% of the petroleum was imported, and 40.8% of that imported petroleum came from a single organization – the Organization of the Petroleum Exporting Countries (OPEC) [1]. As a result, any issue concerning oil supply could deeply influence transportation system, and further impact the economy. In order to secure oil shipment at the Persian Gulf, the US government has spent 6.8 trillion US dollars from 1967 to 2007 [2]. On the other hand, combustion of petroleum derived transportation fuel releases carbon dioxide and transportation represents a leading contributor to greenhouse gas emissions. In 2009, the US transportation system contributed 31.0% of the total US greenhouse gas (GHG) emissions [1]. The two major issues i.e. energy security and global warming present serious threats to the long term sustainability of the current transportation system. The governments and the transportation industry, collectively, have been developing alternative transportation fuels along with corresponding vehicle technologies. Biomass derived liquid hydrocarbon fuel (biofuel) represents a promising solution due to its high energy density and compatibility with the current vehicle technology and existing infrastructure for distribution as well as delivery [3].

The current U.S. biofuel market is dominated by ethanol derived from corn grain, a domestic feedstock [4]. Production of corn ethanol does not rely on the supply of foreign oil, which suggests it may enhance energy security. However, the recent bankruptcy of one of the world's largest corn ethanol producers, VeraSun, indicates that biofuel production has its own issues that can negatively affect energy security. The massive investment boom in corn ethanol production in the aftermath of Hurricane Kartrina was largely due to adjustments in international oil markets, U.S. agricultural (i.e., corn and soybean) prices and policy incentives. Since then the crude oil and corn grain prices have been evolving in a way that goes against corn ethanol production. In addition, concerns with regard to food prices, indirect greenhouse gas (GHG) emissions, soil erosion, and water use have led to appeals to cancel the 600 billion annual subsidies given to corn

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ethanol [5–8]. Second generation biofuels avoid many drawbacks associated with corn ethanol (such as the limited ability for petroleum substitution and climate change mitigation) without causing significant ecosystem damages, by utilizing non-food lignocellulosic biomass as feedstock [9–12]. Unfortunately, there are risks remaining which may endanger the long term viability of lignocellulosic biofuel production. In nature, viability of any biofuel production is related to the ecological system on the input side and the economic system (i.e. energy market) of the output side, both of which are complex, dynamic, and even unpredictable. It has been recently argued that facing a combination of disturbances from feedstock supply, energy market, and subsidy policies, future biofuel plants should be designed to be resilient against these disturbances [13]. It is also argued that flexibility is one of the key features to achieve resilience [13].

Gasification followed by Fischer-Tropsch (FT) type synthesis represents a promising route to convert different kinds of feedstocks into a wide range of fuel products, such as ethanol, gasoline, diesel and electricity [14,15]. Two main features of gasification technology are: (1) it could tolerate a large variation in feedstock characteristics, allowing a gasification based biofuel plant to use alternative feedstocks in order to maintain production when the supply of the major feedstock is disrupted [16]; (2) it could flexibly choose the final product portfolios among hydrocarbon fuels and electricity according to market conditions and subsidy policies. Although this technology has the potential to be flexible in terms of its input/output selection, additional investment is required to achieve this flexibility. It is unclear whether the additional investment can be justified. That is, whether or not a gasification-FT based “flexible” biofuel plant could economically survive better in the long term, (1) when the feedstock supply is affected by extreme weather conditions, (2) when the energy market becomes volatile, and (3) when the biofuel subsidy policy is subject to change. A number of previous studies have carried out techno-economical evaluations of gasification based biofuels production [17–19]. However, neither did they examine the effect of feedstock supply variation due to extreme weather conditions, nor did they consider the collective effects of the market fluctuations and policy variations. This paper will answer these questions by simulating a gasification-FT based flexible biofuel plant located in the Midwest region of the U.S. Results from this research are expected to help relevant biofuel stakeholders, i.e. investors, plant managers, and government agencies, to make decisions with regards to investment, plant operation, and policy.

## 2. Methodology

### 2.1. Plant configuration

Since there is currently no commercial gasification based FT biofuel plant in operation yet, the analysis in this paper will be based on plant level process simulation using Aspen Plus®, a commercial simulation software that has been widely adopted in related research [20,21]. According to the U.S. Department of Energy National Renewable Energy Laboratory (DOE NREL), a biomass daily feeding rate of 2000 MT is an appropriate capacity to balance the plant economy-of-scale against biomass transportation cost [14]. The biofuel plant under consideration includes the following sub-systems: feedstock drying and handling, gasification, syngas conditioning, FT synthesis, FT syncrude separation, steam and electricity generation (i.e. power island). The biomass is dried in the first section by using the hot flue gas from the subsequent section. The prepared feedstock is then gasified in an oxygen-blown pressurized circulating fluidized bed reactor, where oxygen is separated from the air via an air separation unit (ASU). A fluidized bed gasifier is selected here due to its wide feedstock compatibility [22]. The syngas from the gasifier then enters into the third section for a series of cleaning steps in order to remove impurities, i.e. acid gas and tar. Before the syngas is to be synthesized into fuels, its $CO/H_2$ ratio needs to be adjusted to 0.5 [19].

Finally, the cleaned and conditioned syngas is converted into Liquefied Petroleum Gas (LPG), gasoline, diesel and wax using iron-based catalyst in a slurry bed reactor. Distribution of FT fuel products is simulated according to the Anderson-Schulz-Flory distribution [23]. The wax in the FT products is further upgraded into LPG, gasoline and diesel via hydrocracking, with distribution of 5% LPG, 15% gasoline and 80% diesel by weight [24]. The refined FT fuels are distilled, separated and cooled as the final products. The once through (OT) syngas conversion efficiency, in terms of carbon monoxide consumption ratio, could be as high as 80%. Thus, it is usually not necessary to recycle the syngas back to the FT reactor [17]. Instead, the unconverted syngas is burned to generate electricity at the power island, which provides electricity for internal use with the remaining energy sent to the power grid for revenue. The power island consists of a gas turbine, a heat recovery steam generation system (HRSG) and a steam turbine. The HRSG collects heat from FT reactor and gas turbine exhaust gas to produce steam in order to drive steam turbines. The steam turbine system has three sets of steam turbines, which use the high pressure steam (HP), intermediate pressure steam (IP) and the low pressure steam (LP).

Four plant configurations are simulated in this paper, as illustrated in Fig. 1. Configuration #1 is designed to have FT fuels as the only production target, which means the capacity of the power island is only enough to consume the unconverted syngas after the FT reactor process. In order to increase the flexibility of the fuel plants production, Configuration #2 adopts a power island that has the capacity to convert all the syngas into electricity. Such a plant could choose whether to maximize FT fuels or electricity production according to the market conditions and available subsidies. A plant configured to solely produce electricity is not considered here since the target is to produce liquid hydrocarbon fuels for transportation.

It should be noted that syngas generated from the oxygen blowing gasifier considered here has a higher $CO/H_2$ ratio than needed by FT synthesis [19,25]. Also, hydrocracking of heavy wax requires the supply of hydrogen. One way to supply the needed hydrogen is via a water-gas shift (WGS) reaction, which makes a portion of the carbon monoxide in the syngas react with steam to produce hydrogen. Its capital cost is low at the expense of a lower FT fuel yield. An alternative approach is to produce hydrogen by decomposing methane (separated from syngas or purchased as natural gas) in an autothermal reactor (ATR). ATR leads to a high initial investment; however, it does not consume the CO in the syngas, thus yielding additional FT fuel. In this paper, WGS is used for hydrogen production in Configurations #1 and #2 while ATR is used in Configurations #3 and #4. Table 1 summarizes the four different fuel plant configurations. The capital investments are calculated according to [17,19,26–28].

### 2.2. Energy market fluctuation

In order to evaluate the economic performance of the biofuel plant over its life span, it is required to forecast the prices of products and co-products. The projection in the EIA’s Annual Energy Outlook 2010 (AEO2010) has been adopted in this paper. However, it should be noted that this projection only reflects a general trend. The energy market is volatile due to the uncertainty of unanticipated events, like accidents, strikes, local intense