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6 **Flex fuel polygeneration: Integrating renewable natural gas into Fischer-Tropsch synthesis**

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Abstract

Flex Fuel Polygeneration (FFPG) is the use of multiple primary energy sources for the production of multiple energy carriers to achieve increased market opportunities. FFPG allows energy supply adjustments to meet market fluctuations and increase resilience to contingencies such as weather disruptions, technological changes, and variations in supply of energy resources. As an example of FFPG, we explored natural gas and municipal solid waste as the primary energy sources converted into electricity and transportation fuels as the energy carriers through the processes of anaerobic digestion, Fischer-Tropsch synthesis (FTS), and combined cycle power. We combined previous techno-economic analyses of conventional energy production plants to obtain equipment and operating costs, and then evaluated the economic performance of the FFPG plant designs. We investigated the effect of changing operating parameters on economic performance of the baseline FTS and FFPG systems.

Keywords

Biogas, anaerobic digestion, municipal waste, Fischer Tropsch Synthesis, Flex Fuel Polygeneration

LIST OF ACRONYMS

AD: anaerobic digestion
BTL: biomass-to-liquids
Btu: British thermal unit
CTL: coal-to-liquids
DCFROR: discounted cash flow rate of return
EIA: Energy Information Administration
EPA: Environmental Protection Agency
FCI: fixed capital investment
FFPG: flex fuel polygeneration
FTS: Fischer-Tropsch synthesis
GTL: gas-to-liquids
IRR: internal rate of return
kPa: kilopascal
kWh: kilowatt hour
LFG: landfill gas
LO: livestock operations
MJ: megajoule
MM: million
MSW: municipal solid waste
MW: megawatt
NETL: National Energy Technology Laboratory
NG: natural gas
O&M: operating and maintenance
RIN: renewable identification number
RNG: renewable natural gas
WGS: water gas shift

1 Introduction

Flex Fuel Polygeneration (FFPG) is the use of multiple primary energy sources for the production of multiple energy carriers to achieve greater market opportunities. Processing plants of all types are susceptible to fluctuations in the costs of energy sources and the prices of energy carriers. Reducing the risks associated with energy production technologies via input and output diversification can increase the net present value (NPV) of processing plants. Single feedstock production pathways are especially susceptible to price volatility due to the erratic nature of many energy commodity prices. Facilities that utilize multiple feedstocks and/or create multiple products can potentially decrease the risk of unfavorable prices and thereby increase their NPVs [1].

Factors that determine the success or failure of commercial energy production include capital and operating costs, government policies, available technology and resources, sustainability, industrial and consumer acceptance, weather, and location [2-4]. Resilience is defined as the ability of an entity or system to withstand, adjust to, and reduce the consequences of contingencies while still retaining function [5-7]. Severe weather events can temporarily disrupt petroleum, natural gas, and biomass supply chains as well as product markets, potentially resulting in increased feedstock or product prices [8-10]. Weather can also affect crop production and harvesting, supply chain infrastructure, processing, refining, and distribution [11]. While energy security, climate change, and fossil fuel depletion are likely to provide new investment opportunities for alternative energy routes, venturing into new energy sectors also increases financial risk [12]. If energy production plants are designed so that they are able to adapt to market supply and demand fluctuations, the risk involved with investing in these plants decreases. If an energy plant is flexible enough to shift towards lower consumption of expensive feedstock while adjusting its products portfolio to maximize profits, it is more likely to obtain greater financial returns.

Since the 19th century, stationary combustion systems have been at the heart of producing energy that can be introduced and utilized by the electrical grid [13]. Along with electricity, other product avenues from processing primary energy sources are fuels and chemicals. In 2012, fuel from petroleum made up around 99% of the energy used in the U.S. transportation sector [14]. However, this has changed in recent years. Along with petroleum, natural gas and coal are mined and used as gaseous or liquid fuel sources for transportation, electricity, or heating/cooling applications. Technologies such as coal-to-liquid and gas-to-liquid convert feedstocks into longer-chain hydrocarbons and alcohols depending on the catalysts and operating conditions. However, these primary energy processing technologies often transform one feedstock into one main product and can be susceptible to market volatility. As an example, in 2012 a drought occurred in the U.S. that negatively impacted corn growers and associated industries. The price per bushel of corn rose to over \$8, causing corn ethanol production margins to fall sharply since producers were unable to utilize a different, less expensive feedstock [9].

Polygeneration, the conversion of an energy source into multiple energy carriers, has been previously explored as a way to respond to such swings in market demand for various energy products [15, 16]. Polygeneration represents a means of effectively utilizing available resources in a manner that is both more cost effective than traditional pathways and less sensitive to supply shortages and product price volatility. The most familiar example is co-generation, where steam can be diverted to either electric power generation or production of process heat. Flex fuel, the use of multiple primary energy sources for production of an energy carrier, is most prominently practiced by electric utilities that fire combinations of coal, fuel oil, natural gas, and wood pellets in steam boilers or meet peak power demand by firing fuel oil or natural gas in gas turbines that can rapidly come online [17]. FFPG can employ both multiple energy primary sources (including fossil and renewable energy) and technologies to produce multiple energy products (fuel, electricity, chemicals, and heat). As Floudas et al. [18] state in their study on hybrid and single feedstock energy processes, hybrid (or FFPG) systems have the opportunity to increase their energy resource portfolio and the flexibility to generate additional products from multiple sources.

Along with this, hybrid systems can substitute renewable resources for fossil fuels, thereby reducing GHGs. Cai et al. [3] have shown that combining multiple energy plants into a single system has the ability to decrease overall equipment, installation, and labor costs. Liu et al. [19] state that the important economic parameters in analyses comparing polygeneration with stand-alone production are the price of products. The value of the products relative to each other and the reliance of the product portfolio on each are key variables when determining project NPV and plant flexibility of product production. There are many technologies to be considered when creating FFPG plants, the choice of which depends on plant location, feedstock availability, product demand, and other factors that influence the functionality of the plant. The technologies and feedstocks utilized can be tailored to specific locations when designing FFPG plants.

Polygeneration plants come in a variety of forms, integrating multiple products or feedstocks, renewable and fossil energy sources, and alternative processing technologies. A study done by Jana [20] delivers multiple outputs from a single input of agricultural waste. Performance estimates from the investigation show that turning agricultural residues into a range of products such as electricity, refrigeration, utility heat, and ethanol can improve sustainability and efficiencies. Polygeneration for a rural community provides an economically feasible, decentralized energy production scenario by maximizing feedstock utilization and conversion efficiency [20]. Another study done by Swanson et al. [21] integrated biomass gasification into two FTS plants and analyzed the fuel product value. The analysis simulated processing 389 MW of biomass in a low temperature, fluidized gasifier and a high temperature, entrained flow gasifier. These systems required between \$500 and \$650 million in investment and resulted in a product value of \$4-5 per gallon of gasoline equivalent. Of the factors considered in the study, those that had the largest impact on the product value were feedstock cost and return on capital investment. Another biomass processing plant analyzed by Zhang et al. [22] focused on pyrolysis as the core technology. The study simulated the polygeneration of monosaccharides, hydrogen, and transportation fuels from turns 2,000 tons/day of lignocellulosic material. The pathway of biomass to products included pretreatment and processing of the feedstock via pyrolysis, following by liquid/solid separation and recovery. The components of the system that influenced the internal rate of return (IRR) were feedstock costs, product yields, and product credits.

Previous related studies [23-26] explored biomass and natural gas as flex fuels in the production of transportation fuels with a focus on environmental performance. In a study done by Liu et al. [23], it was found that supplementing natural gas conversion to transportation fuels with biomass gasification can reduce GHG emission prices needed to cost effectively employ carbon capture and sequestration. By including biomass, emissions from the production process are significantly reduced, which therefore creates an attractive system for low-carbon natural gas power. Another study by Borgwardt [24] considers integrating biomass gasification with natural gas into methanol production. From the study, it was found that the use of natural gas and biomass, as opposed to coal, reduces net carbon dioxide emissions and can also eliminate one of the production steps. Borgwardt mentions the potential use of gas and sludge derived from waste water treatment facilities as potential future feedstock to convert to transportation fuels. Another methanol production scenario from biomass and natural gas was studied by Dong and Steinberg [26]. By analyzing the hydro-gasification of biomass via the Hynol process they were able to show benefits of emission reduction and higher yields. Emissions were reduced because of operation under reducing conditions. The study states that under the conditions studied, CO₂ is reduced and SO₂ and NO_x are not found. Additionally, increased process yields are achieved by recycling H₂ rich and other unconverted process gases, therefore eliminating the need for an oxygen plant and improving overall conversion efficiency.

Differing from previous works, the present study explores the economic performance of an FFPG that converts natural gas and organic wastes as the primary energy sources into electricity and transportation fuels as the energy carriers through the processes of anaerobic digestion, Fischer-Tropsch synthesis

(FTS), and combined cycle power. Three biogas production and upgrading scenarios and their economics are considered, including municipal solid waste (MSW), livestock operation waste, and landfill waste anaerobic digestion. Twenty year NPVs were calculated based on each scenario to analyze the long term plant profitability relative to standalone FTS processing plants. Historical prices and Monte Carlo simulations are employed to generate forecasts and simulate a broad range of outcomes to give a complete portfolio of plant economic performance under varying circumstances.

Methodology

The FFPG selected for this study is illustrated in Fig. 1. Natural gas and MSW were selected as the primary energy sources due to their ability to be processed into syngas and their relative availability at low cost. Natural gas production in the United States from 2005-2013 increased from 18.1 Tcf to 24.4 Tcf, a growth of 35% [27]. Future U.S. natural gas production is estimated to increase 45% from 2013 to 2040 [27]. Along with utilizing natural gas, three different technologies were considered to produce biogas that can accompany natural gas in the FFPG system. In these technologies, MSW and animal waste are processed via anaerobic digestion (AD) to provide an alternative renewable feedstock and address a growing waste disposal challenge [28]. Fischer-Tropsch synthesis (FTS) converts the resulting synthesis gas to liquid fuels [29] while combined cycle power generates electricity [30].

Anaerobic digestion is attractive as it can produce an alternative source of methane from a wide variety of biomass feedstocks. Breaking down the biomass with microorganisms, AD can convert 79 to 85% of biodegradable feedstocks to biogas while the residual stable organic matter can be composted and used as an environmentally safe and nutrient rich soil amendment agent [31]. In this study, three different scenarios of biogas production are considered, including AD of MSW in digestion tanks, animal waste from livestock production facilities, and MSW from landfills. When feeding MSW to AD tanks, a pre-treatment step consisting of mechanical and manual sorting is employed to remove oversized and non-digestible materials. Following removal of inorganic materials, the remaining waste is sent to non-sterile reaction vessels where gas production occurs in a relatively simple process [29]. Biogas production that takes place at livestock production facilities is typically carried out in covered lagoons and plug flow digesters [32]. The biogas produced in these systems is often utilized on-site for energy and heat production; however, the gas can also be cleaned and compressed, resulting in a product that is analogous to traditional natural gas. Similar to animal waste biogas, biogas from landfills, termed landfill gas (LFG), can be collected with relatively low capital costs, upgraded, and used for electricity and heat or as a substitute for natural gas. Once the biogas is produced through AD, it is combined with purchased natural gas. The gas stream is then cleaned in a water scrubber to remove any traces of sulfur that can poison FT catalysts [33].

The cleaned biogas and natural gas are reacted with steam and oxygen in an autothermal reactor (ATR) to produce hydrogen, carbon monoxide, and carbon dioxide. The carbon dioxide and water are removed while the hydrogen and carbon monoxide are sent to a Fischer-Tropsch reactor where reactions over a cobalt catalyst produces a range of straight-chain alkanes [34]. The FT liquids are distilled to separate olefins and alkanes, the latter of which are refined to naphtha and diesel range hydrocarbons [34]. While one FFPG was developed, five scenarios are studied to compare the financial advantages and disadvantages. The first scenario, termed FTS No Co-gen, is a FTS plant that utilizes NG and converts it to FT liquids but is required to purchase electricity, as it is not produced on site. The second scenario analyzed is termed FTS with Co-gen, and is similar to the first plant but includes a steam generator that produces electricity for the plant and sells the excess amount to the grid. The third, fourth, and fifth scenarios substitute natural gas in the FTS process with RNG from the digestion of MSW in digestion tanks, animal waste, and MSW from landfills, respectively. More information regarding each scenario is outlined in Table 1 and Figure 1.

FFPG System

The FFPG system analyzed in this study is the integration of NG and RNG into a FTS process to produce liquid fuels and electricity. Three different RNG production scenarios are analyzed to determine their impact on the 20-year NPV of the overall system. The MSW AD system employed in this study processes 250,000 tons/year of mixed solid waste in digestion tanks. Although companies in the U.S. have struggled to receive investment to produce facilities of this size due to a lack of subsidies, there are several plants of this scale in operation globally and others that are being constructed to come online in the near future [35]. AD of MSW has been implemented at scales ranging from 1,000 to 300,000 tons/year [35]. Improved technologies, advantages associated with larger scale, and the rising need to manage waste resources will continue to drive forward increased capacities of plants to anaerobically digest municipal wastes to gaseous products. The second method, AD of animal waste, is a technology that has been successfully employed at large livestock operations to generate on-farm electricity and heat. Challenges in the past of manure AD systems include poor design and improper installation, however the technology has improved and can be a profitable operation for most livestock operations [32]. The animal waste AD system assumed in this study digests waste from the equivalent of approximately 40,000 heads of dairy cattle, or 282,000 heads of swine. The AD of livestock waste provides a waste management solution and can generate a valuable product. The third method to produce RNG for the FFPG system is from landfills. Landfills inherently produce large amounts of biogas during the decomposition process that is often flared in order to combust the harmful release of methane gas to the environment. However, over 600 landfill to gas energy projects are now in place in the U.S. to capture the energy source and use it onsite for electricity generation, or upgrade it to vehicle grade compressed natural gas (CNG) and pipeline quality RNG [36]. The biogas, containing approximately 55% methane, is cleaned, upgraded to high-Btu gas via pressure swing adsorption (PSA) and combined with pipeline natural gas which is then fed to an autothermal reformer to produce CO and H₂ [37]. The biogas produced by AD replaces 10% of the NG used in the baseline FTS system.

Table 1. Details of the production scenarios considered

Scenario	1	2	3	4	5
Name	FTS No Co-gen	FTS with Co-gen	FFPG MSW AD	FFPG LO AD	FFPG LFG
Feedstock	NG	NG	NG and RNG	NG and RNG	NG and RNG
Biogas Production	-	-	MSW AD in Tanks	Livestock Waste AD	Landfill Waste AD
Fuel Synthesis	FTS	FTS	FTS	FTS	FTS
Co-generation of Electricity	No	Yes	Yes	Yes	Yes

Acronyms: FTS: Fischer-Tropsch synthesis, Co-gen: co-generation of electricity with steam turbines, FFPG: flex fuel polygeneration, AD: anaerobic digestion, MSW: municipal solid waste, LO: livestock operation, LFG: landfill gas, NG: natural gas, RNG: renewable natural gas.

Figure 1. Energy production process diagram (asterisked number lists in subsections denote the scenarios in which the subsection is included)

Along with having the flexibility of multiple feedstocks, FTS plants have flexibility in their liquid product distributions as well as the amount of electricity that is generated through a steam turbine. The FTS products in this study are upgraded to diesel and naphtha range hydrocarbons, however other products such as fuel gases, LPG, bulk chemicals and waxes are possible depending on operating parameters and upgrading processes [38]. The selectivity of products is influenced by a number of factors, including the type of catalyst (iron or cobalt), reactor type, reaction temperature, pre conditioning, $H_2:CO$ ratios, and operating pressure [39]. When the reaction temperature in the FT reactor is increased, the conversion of CO and H_2 to CH_4 increases while the probability of chain growth decreases. This is due to the rate of hydrogenation of the produced CH_4 units [40].

Capital and Operating Expenses

The FTS employed in this study utilizes equipment and process information by the National Energy Technology Laboratory (NETL) [41]. The equipment, direct, and indirect costs determined by NETL were developed and scaled from previous NETL reports, with code blocks in AspenPlus® that were used to provide details on the process simulation. NETL states that the accuracy of the cost estimations fall within the range of -15% to +30% of actual costs due to the complexity and uniqueness of each individual project analyzed. Traditional FTS plants are often in production capacity to take advantage of economies of scale. Fischer-Tropsch plants are traditionally built very large to take advantage of economies of scale [42]. However, such large-scale plants require enormous capital investment and provide few opportunities for incorporating new GTL technologies as they are developed [43]. Only 5% of the world's gas fields can be monetized through large scale GTL technologies due to costs of storing and transporting the liquid products [44]. Small scale GTL avoids the need for multiple wells to sustain the gas flow and reduces the need to develop distant markets for products. Larger GTL projects also have higher technical risks in

sequestering the large volumes of carbon dioxide that result. Small scale GTL plants are being proposed that are 10 to 1,000 times smaller than traditional steam methane reforming and FT synthesis plants [45]. The FTS plant in this study was scaled appropriately to the biomass resource that can be anaerobically digested to methane.

The equipment costs were adjusted using a power law rule to account for differences in capacity. The equipment costs for the MSW anaerobic digestion system, which processes mixed waste to produce syngas, were scaled to a case study done by Allen Kani Associates et al. [46]. Utilizing mixed waste, which contains both organics and inorganics, requires separating equipment to remove the majority of the metal contaminants from the waste stream, as well as equipment to minimize the particle size of the material fed into the reactors [46]. The costs of upgrading the gas produced by the MSW AD system to pipeline quality were taken from a range of studies [47-49]. The capital costs for the livestock operation AD were modified from those provided by a range of studies done by the USDA [32] and the Iowa Biogas Assessment Model (IBAM) developed by EcoEngineers [50]. The IBAM is an economic analysis tool that provides general biogas facility cost evaluations based on data gathered in literature. Costs were scaled from the base model in the IBAM to match the biogas output of the MSW AD facility. Capital costs for the landfill gas method were based off of a costing model generated by the EPA [51]. The costing model provides initial economic feasibility analysis to determine the profitability of landfill gas projects. The processing equipment was scaled to produce an equal amount of energy as the MSW-AD facility and includes the required equipment for compressing, separating, and drying the biogas to pipeline quality. The distance from each biogas production scenario to a pipeline is considered negligible, assuming that the plant is constructed or the landfill is located near a pipeline. In literature, natural gas pipeline is often estimated at \$330,000/mi [51], which can impact the feasibility depending on the distance required to be traveled. However, in the present study pipeline costs are not included. The capital costs for each FFPG system are generated by combining costs from both FTS and the biogas AD and associated upgrading equipment. There is a likely reduction in costs from shared equipment when estimating capital costs for joint systems[52]; however, this reduction is not taken into consideration in this study. The basic costs for each AD method and FTS are outlined in Table 2. The costs are in 2013 dollars.

Table 2. Capital and Operating Costs for Single Plants

Parameter	FTS No Co-gen	FTS with Co-gen	MSW AD to RNG	LO AD to RNG	LFG AD to RNG
FCI (\$MM)	\$246.0	\$260.2	\$66.4	\$13.0	\$8.7
Operating Costs (\$MM/yr)	\$22.6	\$22.6	\$32.5	\$24.6	\$22.8

Acronyms: FCI: fixed capital investment, FTS: Fischer-Tropsch synthesis, Co-gen: co-generation of electricity with steam turbines, FFPG: flex fuel polygeneration, AD: anaerobic digestion, MSW: municipal solid waste, LO: livestock operation, LFG: landfill gas, RNG: renewable natural gas.

When scaling equipment size, the costs were calculated using the power law relationship with suggested exponents between 0.6 and 0.73 [30, 53]:

$$C_{p,s} = C_{p,b}(S_s/S_b)^n \quad (\text{Eq. 1})$$

where:

$C_{p,s}$ = predicted cost of specified equipment

$C_{p,b}$ = known cost of the base case equipment

S_s = size of specified equipment

S_b = original capacity

n = economy of scale sizing exponent (less than unity)

Inflation was normalized among the various analyses employed using the relation:

$$C_{p,c} = C_{p,p}(I_c/I_p) \quad (\text{Eq. 2})$$

where:

$C_{p,c}$ = inflation-adjusted costs of equipment in current year

$C_{p,p}$ = known cost of equipment in a previous year

I_c = inflation index factor for current year

I_p = inflation index factor for the previous year in which equipment cost is known

Twenty year net present value (NPV) was used to evaluate the economic performance of the FTS and FFPG systems. Sensitivity analyses were performed by adjusting the prices of feedstock, products, and capital costs to determine the influence on the resulting NPVs. An uncertainty analysis was performed via Monte Carlo simulation to assess the influence of price fluctuation on NPV over time. Further details on this analysis are subsequently described. The O&M costs for the GTL and anaerobic digestion systems are comprised of fixed and variable costs. The main O&M costs for the systems are calculated, as differences in minor costs play a small role in this study and vary with each specific project. O&M costs for the FTS system were scaled from the NETL model and include labor, overhead and maintenance, insurance and taxes, feedstock, water and chemical costs [41]. The O&M costs for the AD facilities include labor, pretreatment, collection and disposal costs, as well as compost curing [46]. Costing assumptions are detailed in Table 3.

Table 3. Assumptions and Operating Parameters

Assumptions	Value
Financing	100% Equity
Type of depreciation	DDB
Depreciation period (yr)	7
Construction period (yr)	2.5
Start-up time (yr)	0.5
Income tax rate (%)	39%
Annual operation (hrs)	7,900
Cost year for analysis	2013
Diesel production rate (MMgal/yr)	15.9
Gasoline production rate (MMgal/yr)	7.1
Avg. diesel selling price (\$/gal)	\$3.79

Avg. gasoline selling price (\$/gal)	\$3.25
Avg. electricity selling price (\$/kWh)	\$0.065
Avg. cost of natural gas (\$/MMBtu)	\$5.12

Acronyms: DDB: Double declining balance.

Feedstock and Product Prices

Monte Carlo simulations using Crystal Ball® were performed to evaluate the effect of fluctuations in the market prices of feedstock and products on NPV. As described by Smith [54], often times a statistical method to estimate uncertainty involves formulating the data around a common distribution, thus simplifying the analysis. Monte Carlo simulation methods, on the other hand, generate data from a known or historical distribution and therefore are better suited to estimate uncertain parameters than single distribution estimation methods. To generate distributions of data by the Monte Carlo method for integration into estimation models, previous data can be used to generate possible values for each parameter. Once the distributions for each parameter are determined, data is generated from the distributions and used as inputs into a model [54]. In this study, historical price trends are used to provide a framework for feedstock and product price determination. Following a method utilized by Brown [55], uncertainty prices for commodity prices were represented by fitting distributions to each input parameter. The distributions were developed from historical price data of each commodity and applied to annual averages for gasoline, diesel, electricity, and natural gas prices forecasted by the EIA 2013 Annual Energy Outlook [56]. For MSW and renewable identification number (RIN) prices, the distributions were applied to the most recent annual averages [57, 58] and adjusted for inflation. The best-fit commodity distributions were developed in Oracle Crystal Ball and chosen using the Anderson Darling goodness-of-fit test [55, 59]. For each Monte Carlo analysis 2,000 trials were run using the probability distributions where feedstock and product values were randomly varied according to the defined distribution for each value. The resulting Monte Carlo distributions and values are displayed in Table 4.

The historical price distribution of NG was calculated using 1992-2011 market Henry Hub Natural Gas Spot Prices supplied by the 2011 EIA Annual Energy Outlook [60]. The MSW tipping fee, a price paid by waste generators to dispose of their waste, counts as a revenue source for waste-to-energy producers [61-63]. The price of tipping fees varies greatly across the U.S. due to population density, amount of waste, and available space to dispose of the waste. Currently, tipping fees in the U.S. range from \$35-\$240 per ton with the average falling around \$50-\$60 per ton [35]. However if a carbon tax was imposed the fee could range even higher, similar to the approximate average \$100/ton implemented in the EU [64]. U.S. average tipping fees from a report by the National Solid Waste Management Association (NSWMA) were used [57]. Regarding energy carriers, Naphtha products are often represented by light and heavy naphtha streams including hydrocarbons up to boiling points of 75°C and 165°C, respectively [65]. For the purpose of this study the naphtha stream is assumed to contribute to gasoline range products. The selling price distribution of naphtha and diesel were determined using historical 20 year prices supplied by the 2012 EIA Annual Energy Outlook [66]. Historically, there was a correlation of 0.77 between diesel and naphtha prices. The selling price distribution of industrial electricity was determined using reported national industrial retail prices for the past 20 years supplied by the EIA Electric Power Annual 2011 [67]. Lastly, D5 RIN values were developed from information published by EcoEngineers for 2013-2014 [58]. While the presence of RIN values cannot be counted on as certain when analyzing the future economic feasibility of a system due to regulatory uncertainty, the RFS2 calls for 21 billion gallons of Advanced Biofuel and 16 billion gallons of Cellulosic Biofuel by 2022. The required volumes of biofuel blends are likely to be encouraged through incentives such as RINs. As determined by the EPA [68],

biogas from landfills, agricultural digesters, and MSW digesters are eligible to generate cellulosic RINs (D-3 and D-7). However, due to the low volume of D-3 RINs currently generated there are no broker price spreads available yet. The basis of D-3 RINs is the value of D-5 RINs plus cellulosic waiver credits. With the uncertainty in the length of availability of the cellulosic waiver credit, D-5 RINs are considered in this study.

Table 4. Feedstock and Product Values and Distributions

Statistic	Diesel (\$/gallon)	Gasoline (\$/gallon)	Electricity (\$/kWh)	MSW (\$/ton)	NG (\$/MMBtu)	Biogas RIN (\$/MMBtu)
Distribution	Lognormal	Lognormal	Logistic	Logistic	Logistic	Logistic
Mean	\$3.79	\$3.27	\$0.065	\$65.44	\$5.06	\$0.71
Median	\$3.78	\$3.26	\$0.065	\$65.38	\$5.06	\$0.71
Standard Deviation	\$0.10	\$0.09	\$0.001	\$4.32	\$0.17	\$0.03
Minimum	\$3.44	\$2.96	\$0.063	\$51.18	\$4.25	\$0.59
Maximum	\$4.09	\$3.57	\$0.068	\$81.89	\$5.63	\$0.84

Profitability Analysis

A discounted cash flow rate of return (DCFRROR) spreadsheet was used to calculate a 20-year NPV for each scenario developed by the National Renewable Energy Laboratory (NREL) and modified by Wright et al. [69]. Different methods have been used in the literature to analyze the performance of energy production plants. Often sensitivity analyses are performed on the plants to determine which parameters play the largest roles in plant profitability. These sensitivity analyses, along with Monte Carlo simulations, can provide a comprehensive understanding of economic performance. For the sensitivity analyses, the discount rate is held constant while adjusting single feedstock and product prices by one standard deviation of historical annual data to determine the influences on the NPVs. This method was used to calculate the mean NPV, standard deviations, and cumulative distribution functions for the baseline FTS and FFPG scenarios. In the following analysis, the baseline FTS system is compared to the FFPG system to determine FFPG's ability to alleviate disruptions caused by fluctuations in feedstock and product prices and improve the NPV. It should be noted that NPV alone can be biased with different size project investments. Due to this fact, it is important to understand the associated initial investments and include sensitivity profiles with varying parameters to understand the relative effect on the resulting NPVs.

Results and Discussion

The FFPG systems integrate each AD method with the FTS Co-gen facility to produce liquid fuels and electricity. The capital costs and NPV for each scenario, given the base case operating values for each parameter (fuel price, electricity price, etc.), are shown in Table 5. The FTS No Co-gen has the lowest overall capital cost of \$246MM because it does not include a steam generator to produce electricity or additional equipment to produce RNG. By including an electricity generation station, the capital cost increases to \$260MM for the FTS with Co-gen scenario. The FFPG scenarios have larger capital costs

than the FTS with Co-gen scenario as a result of the additional equipment needed to produce biogas and upgrade it to RNG. The capital cost of the MSW AD to RNG system accounts for 20% of the FFPG MSW AD scenario capital costs, while the LO AD and LFG AD to RNG account for 5% and 3% of their respective FFPG systems. As research and development focuses on improving and increasing the scale of these technologies the costs will continue to decrease as efficiencies increase.

The negative NPVs signal the challenge associated with two different topics. First, scaling down a FTS plant to a scale where biogas utilization has the opportunity to displace a fraction of the traditional natural gas used. Second, the high costs associated with upgrading biogas to RNG due to the current state of technology. Traditional FTS plants operate in the range of 40-500 MGY of liquid fuel produced, but in this study it was scaled down to 23 MGY of liquid products. Instead of capitalizing on economy of scale benefits that are traditionally associated with increasing the capacity of a plant, the inverse occurred and resulted in high costs. With a fixed discount rate of 10%, the NPV for the FTS No Co-gen amounted to -\$49.4MM while the FTS with Co-gen amounted to an NPV of -\$35.3MM. The FFPG scenarios resulted in similar or improved NPVs, with MSW AD resulting in an NPV of -\$34.5MM, and LO AD and LFG AD resulting in NPVs of -\$27.3MM and -\$15.8MM, respectively. These are the base NPVs that each scenario is compared to when a single parameter is altered in the sensitivity analysis.

Table 5. Capital costs and NPV for each scenario

Parameter	FTS No Co-gen	FTS with Co-gen	FFPG MSW AD	FFPG LO AD	FFPG LFG
Capital Costs (\$MM)	\$246.0	\$260.2	\$326.6	\$273.7	\$268.9
Operating Costs (\$MM)	\$22.6	\$22.6	\$32.5	\$24.6	\$22.8
Mean NPV (\$MM)	\$(49.4)	\$(35.3)	\$(34.5)	\$(27.3)	\$(15.8)

Acronyms: NPV: net present value, FTS: Fischer-Tropsch synthesis, Co-gen: co-generation of electricity with steam turbines, FFPG: flex fuel polygeneration, AD: anaerobic digestion, MSW: municipal solid waste, LO: livestock operation, LFG: landfill gas, RNG: renewable natural gas.

The initial scale of the FTS plant was scaled to the size where 10% of the NG was substituted by a single RNG facility. However there are opportunities to increase the NPV by increasing the amount of RNG that is used in combination with NG. To stay in line with the scale of current projects, additional plants are added (as opposed to increasing scale) to provide the additional capacity to produce and upgrade biogas. For each AD plant that supplies the FTS scenario with biogas, an additional 10% of RNG is substituted for purchased NG from the pipeline. Shown in Figure 1, by increasing the amount of RNG that substitutes NG (requiring an additional plant for each 10%), the resulting NPV significantly increases for the AD scenarios. Additional RNG from subsequent MSW AD facilities results in a lower increase in NPV. The high capital costs associated with MSW AD facilities results in the production of RNG at a price similar to what NG can be purchased for. One approach to improve the NPV for the MSW AD scenario is to increase the scale of the individual MSW AD facility rather than increase the number of facilities to capitalize on economy of scale. However, to ensure the benefit of economy of scale, further analysis of scaling factors for anaerobic digesters should be carried out. Along with scaling factors, feedstock availability as well as the impact of increased transportation and logistics costs should be considered.

Increased costs associated with larger scale feedstock collection and storage could negate the benefits associated with economy of scale.

For the MSW AD system, the NPV increased by approximately \$7.4MM for every additional 10% of RNG that substituted NG. The cost to produce RNG from the MSW AD scenario is \$35/MMBtu, however when tipping fees and RINs are accounted for, the cost can be reduced to between \$7 and -\$9/MMBtu depending on the tipping fee. For the LO AD and LFG scenarios, every additional 10% of RNG increased the NPV by \$19MM and \$21MM. The resulting cost to produce RNG from these scenarios amounts to \$7/MMBtu and \$2/MMBtu, respectively. When RINs are included, these scenarios generate revenue for the production of RNG, approximately -\$3/MMBtu and -\$8/MMBtu, and contribute to an increasing NPV.

Figure 1. NPVs with increased RNG plants

Acronyms: NPV: net present value, FTS: Fischer-Tropsch synthesis, Co-gen: co-generation of electricity, FFPG: flex fuel polygeneration, AD: anaerobic digestion, MSW: municipal solid waste, LO: livestock operation, LFG: landfill gas, NG: natural gas, RNG: renewable natural gas.

The addition of multiple AD plants to provide the FTS scenarios with more RNG can improve the NPV. To further explore the benefit of integrating more RNG into the FFPG scenarios, the effect of an increasing NG price was evaluated to compare the FTS systems vs the FFPG systems that utilize 50% RNG. While the increased NG price had an impact on the FTS and FFPG scenarios when 10% of the NG was substituted by RNG, a greater difference in plant profitability was observed with systems that integrated even larger amounts of RNG. The FTS scenarios resulted in the largest negative slopes in

Figure 3, denoting the largest decreases in NPV of \$26MM per \$1 increase in NG prices. On average the FFPG scenarios NPVs decreased \$12MM per 1\$ increase in NG prices. At a NG price of \$3/MMBtu, the difference between FFPG LFG and FTS No Co-gen was \$86MM, while at \$11/MMBtu the difference was \$218MM.

Out of the three FFPG scenarios that integrate RNG as a substitute for traditional NG, LFG scenario produces the most profitable 20-year NPV with the given conditions. The scenarios that integrated more RNG as a substitute for NG yielded the highest NPVs, especially when the price of NG increased. Additional costs and challenges may be encountered when scaling up the size and number of AD plants, however improved profitability can be realized.

Figure 3. NPVs with increased NG prices and 50% RNG substitution

Acronyms: NPV: net present value, FTS: Fischer-Tropsch synthesis, Co-gen: co-generation of electricity, FFPG: flex fuel polygeneration, AD: anaerobic digestion, MSW: municipal solid waste, LO: livestock operation, LFG: landfill gas, NG: natural gas, RNG: renewable natural gas.

Following the preliminary results of the costs and NPVs, sensitivity analyses were performed to determine the impact of modifying multiple variables, one at a time. Table 6 shows the deviation away from mean NPV while changing the range of each variable +/- 30% of its 20 year average price. All of the systems produce negative NPVs when the base values for each system are used. The factors that have the largest potential negative impact on the 20 year NPV are variations in the selling price of fuel products, capital costs, and the cost of natural gas.

The NPV of every scenario was altered the most when changing the price of diesel. Diesel accounts for nearly 70% of the annual income, thus making the impact of a price change prominent. Changing the diesel price impacted the resulting NPV by over \$115MM for the FTS No Co-gen scenario. However, altering the price of diesel had less impact on the FFPG scenarios, causing a NPV change of \$109MM for

the LFG system. Following the price of diesel, the parameter with the second highest impact by adjusting the values by 30% was the capital cost. As opposed to an alteration in the price of diesel, a changing capital cost had a larger impact on the FFPG scenarios than the FTS scenarios. With higher capital investment requirements, a deviation away from the expected capital costs leads to potentially larger losses or gains compared to the FTS, which has lower capital requirements.

The next two parameters with the largest impact on NPV were the price of gasoline and the price of NG. Both of these values impacted the NPV of the scenarios that did not use RNG greater than those that did utilize RNG. Decreasing the price of natural gas by 30% changed the NPV of the FTS No Co-gen scenario by -\$39.7MM, while changing the FFPG LFG scenario by -\$34.1MM. If higher amounts of RNG were integrated into the system, the FFPG would be affected less (Figure 1). The value of the electricity compared to the value of naphtha and diesel range fuels was low and did not play a significant role in the NPV when the price fluctuates. Changing the price of electricity affected the FTS No Co-gen scenario by \$7.2MM because of the need to purchase lower-priced electricity. However for the scenarios that sell excess electricity, it altered the NPV by approximately \$1M. In order to increase the profitability by shifting towards higher electricity generation the selling price of electricity must increase greatly and the selling price of liquid fuels drop substantially compared to their historical price range. Unless substantial subsidies distort the market, this seems an unlikely scenario.

Table 6. Average difference from the mean NPV as a result of changing specific parameters by +/- 30% with 50% RNG substitution (\$MM)

	FTS No Co-gen	FTS with Co-gen	FFPG MSW AD	FFPG LO AD	FFPG LFG
Diesel price (\$/gal) 2.65, 3.79, 4.93	\$115.7	\$112.4	\$109.2	\$110.4	\$109.0
Capital costs (%) 130, 100, 70	\$69.7	\$72.8	\$90.8	\$76.0	\$74.1
Gasoline price (\$/gal) 2.28, 3.25, 4.23	\$42.2	\$41.1	\$40.5	\$40.6	\$40.2
NG price (\$/MMBtu) 3.58, 5.12, 6.66	\$39.7	\$38.7	\$34.4	\$34.4	\$34.1
IRR (%) 7, 10, 13	\$43.7	\$48.5	\$63.2	\$52.4	\$53.1
Electricity price (\$/kWh) 0.05, 0.06, 0.07	\$7.2	\$1.1	\$0.9	\$1.1	\$0.1
MSW tip fee (\$/ton) 46.75, 66.80, 86.80	\$ -	\$ -	\$29.6	\$ -	\$ -
RIN value (\$/RIN) 0.48, 0.69, 0.90	\$ -	\$ -	\$6.2	\$6.2	\$6.1

Acronyms: FTS: Fischer-Tropsch synthesis, Co-gen: co-generation of electricity, FFPG: flex fuel polygeneration, AD: anaerobic digestion, MSW: municipal solid waste, LO: livestock operation, LFG: landfill gas, NG: natural gas, RNG: renewable natural gas, RINS: Renewable Identification Number, O&M: operating and maintenance, IRR: internal rate of return.

Sensitivity analyses give a snapshot of plant economic performance based on a limited set of information. To support the sensitivity analyses, probability distribution functions (PDF) from Monte Carlo analyses run in Crystal Ball® were generated for each scenario (see Fig. 4). The PDFs provide the percentage that the NPV is above 0 over the course of the Monte Carlo simulations, as well as averaged mean NPVs and standard deviations. Similar to the results seen in the sensitivity analyses, the FFPG systems that integrate RNG produced overall higher mean NPVs. The FTS No Co-gen and with Co-gen systems produced mean

NPVs of -\$44.1 and -\$30.1M respectively. The FFPG MSW AD, LO AD, and LFG scenarios generated mean NPVs of -\$22.0M, -\$21.4M, and -\$10.2M, all of which are higher than the FTS systems. Not only were the mean NPV values higher, the FFPG systems also generated on average a higher percentage of positive results over the 2,000 Monte Carlo simulations that were run.

Figure 4. NPV cumulative distribution functions with base feedstock and product prices

Acronyms: NPV: net present value, FTS: Fischer-Tropsch synthesis, Co-gen: co-generation of electricity, FFPG: flex fuel polygeneration, AD: anaerobic digestion, MSW: municipal solid waste, LO: livestock operation, LFG: landfill gas

Over the course of the Monte Carlo simulations, 1.8% of the FTS No Co-gen system NPVs were positive, while the FTS with Co-gen system generated 7.5% positive NPVs. When RNG systems are included, the NPVs are positive more than 15% of the trials. The FFPG MSW AD system generates positive NPVs 20.9% of the time, compared to 15.1% for the FFPG LO AD system and 30.4% for the FFPG LFG system. These results accentuate the ability to generate higher value by diversifying feedstocks and products with FFPG. The FTS scenarios depend on natural gas as the single feedstock. The exposure to multiple inputs and outputs decreases the sensitivity of NPV to sharp changes in prices. There are additional factors that may impact the effectiveness and feasibility of adding additional plants including facility location, the distance from pipelines, available wastes, the ability to obtain capital to invest, and working with private and public entities. However, evaluating these potential impacts are outside the scope of this study.

Overall, the FFPG LFG and LO AD scenarios produced the highest 20-year NPVs out of all the scenarios analyzed. The largest difference in NPVs between the two FFPG plants and the other scenarios considered occurred when the price of traditional NG was increased. The lower capital costs associated with the FFPG LF and LO AD plants, the value generated by RINS, and the displacement of traditional NG use also led to higher NPVs. Considering the number of RNG plants, the benefits of the FFPG increased as the number of RNG plants increase for the LFG and LO AD scenarios. For the MSW AD scenario, as the number of plants increased, the NPV increased at a lower rate than the alternative AD scenarios. The NPV of the FFPG MSW AD was comparable to the FTS with Co-gen scenario. While the FFPG AD system received a tipping fee for the waste collected as well as RINs for the RNG generated, the high capital costs balanced the generated income. Gas to liquid plants in the future should consider integrating renewable sources of feedstock into their production scenarios, whether that involves investing in AD processing infrastructure or partnering with existing entities working in anaerobic digestion. The addition of a renewable feedstock allows the companies to generate RINs, alleviate dependence on fossil fuels, decrease their susceptibility to fluctuations in a single feedstock, and reduce environmental emissions.

Conclusion

This study investigated how Flex Fuel Polygeneration (FFPG) can provide feedstock flexibility and better utilize market opportunities. Models were developed using public domain literature to design hypothetical FFPG energy plants. The FFPG energy plants considered in this analysis combined a traditional Fischer Tropsch synthesis (FTS) facility with a co-generation power plant to produce transportation fuels and electricity from three different sources of renewable natural gas (RNG). Sensitivity analyses were performed and showed the impact of individual parameters on plant 20-year NPV. From the sensitivity analyses it was determined that to increase the resiliency of a plant, more than one highly valued product should be produced to allow adjustment of production towards the most profitable scenario. Following the sensitivity analyses, Monte Carlo simulations were performed to give a more comprehensive understanding of plant performance when more than one variable was changed simultaneously. These simulations represent a more realistic view of plant performance by integrating historical trends of parameter values used to produce estimated NPVs. When adding additional technologies to a FFPG plant the overall capital and O&M costs increase, however this can also increase the profitability and longevity of a plant, allowing it to adapt to market and commodity price changes.

1 Additional feedstocks and a diverse product portfolio can alleviate unprofitable periods due to price
2 fluctuations. If a facility becomes negatively impacted by the shift in feedstock or product prices, a
3 flexible system allows for a longer time span to re-evaluate and adjust its energy production approach to
4 operate more profitably due to the lower impact on the NPV of the system. The FFPG facilities are
5 affected less, therefore allowing alternative decisions to be made at a potentially lower loss than the single
6 feedstock FTS systems. With low feedstock costs and high product prices, the FTS with Co-gen system
7 has potential to achieve similar NPVs as the FFPG MSW AD system. However, introducing flexibility
8 can lead to a greater potential to mitigate risk and increase revenue in the future. RNG derived from waste
9 products can be utilized in many different applications to offset costs and risks associated with the
10 utilization of a single feedstock, specifically natural gas. By integrating biogas into FFPG, more
11 opportunities can be explored to improve utilization of waste materials, offset the use of energy derived
12 from fossil fuel, and the mitigation of risk by diversifying feedstock and product portfolios.

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