Techno-economic and uncertainty analysis of *in situ* and *ex situ* fast pyrolysis for biofuel production

Boyan Li^a, Longwen Ou^a, Qi Dang^{a, b}, Pimphan Meyer^c, Susanne Jones^c,

Robert Brown^{a, b}, Mark Wright^{a, b}

^a Department of Mechanical Engineering, Iowa State University, Ames, IA 50010

^b Bioeconomy Institute, Iowa State University, Ames, IA 50011

^c Pacific Northwest National Laboratory, Richland, WA 99352

*Corresponding Author (markmw@iastate.edu)

Keywords: pyrolysis, *in situ*, *ex situ*, techno-economics analysis, uncertainty analysis

Abstract

This study evaluates the techno-economic uncertainty in cost estimates for two emerging technologies for biofuel production: *in situ* and *ex situ* catalytic pyrolysis. The probability distributions for the minimum fuel-selling price (MFSP) indicate that *in situ* catalytic pyrolysis has an expected MFSP of \$1.11 per liter with a standard deviation of 0.29, while the *ex situ* catalytic pyrolysis has a similar MFSP with a smaller deviation (\$1.13 per liter and 0.21 respectively). These results suggest that a biorefinery based on *ex situ* catalytic pyrolysis could have a lower techno-economic uncertainty than *in situ* pyrolysis compensating for a slightly higher MFSP cost estimate. Analysis of how each parameter affects the NPV indicates that internal rate of return, feedstock price, total project investment, electricity price, biochar yield

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4 and bio-oil yield are parameters which have substantial impact on the MFSP for both *in situ* and
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7 *ex situ* catalytic pyrolysis.
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1. Introduction

Atmospheric CO₂ has increased more than 35% in the last century. It will pass the critical value of 550ppm in this century, unless fossil fuels consumption is significantly **reduced** (Hoffert et al., 2002). As one of the biggest greenhouse gas contributors, transportation fuels have received increasing attention in recent decades. Biomass-based transportation fuels have been considered as a clean and renewable alternative to fossil fuels. Under the authority of the Energy Independence and Security Act (EISA) of 2007, the revised Renewable Fuel Standard (RFS2) mandate requires the blending of biofuels for transportation applications. Commercial-scale biorefinery facilities are required to meet the goals set by EISA. Typically, large biorefinery projects processing 2000 metric tonnes per day of biomass or more, take more than four years to develop a design before startup (Myers et al., 1986). Moreover, biofuel production facilities cannot be easily modified once they have been designed and constructed (Anex et al., 2010). Therefore, a techno-economic analysis (TEA) across different platforms is needed in order to determine the most suitable pathway under given market conditions to avoid investing in enterprises with high commercialization risk. TEA can be used to understand and compare the profitability and breakdown cost for any project, therefore, it has been applied to many biorenewable systems such as corn ethanol production (Ou et al., 2014), gasification (Swanson et al., 2010), pyrolysis (Zhang et al., 2013), and hydrothermal liquefaction (Ou et al., 2015). TEA of catalytic fast pyrolysis has received growing interest in recent years in particular. Previous studies show that the minimum fuel-selling price (MFSP) of biofuel produced by pyrolysis can vary within a fairly large range (\$0.5 to \$2.1 per liter) (Anex et al., 2010; Brown et al., 2013; Thilakaratne, 2014; Wright et al., 2010), which may be attributed to several reasons: (1)

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4 differences in system configurations, (2) variability in assumptions for parameter values, and (3)
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7 inconsistencies in approaches to address technical and market uncertainty (Brown & Wright,
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9 2014).

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12 Biomass fast pyrolysis and bio-oil upgrading technology is a promising way to convert cellulosic
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14 biomass into bio-diesel, bio-gasoline and other renewable fuels. Two related catalytic pyrolysis
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16 configurations (*in situ* and *ex situ*) are receiving growing interest because of their ability to
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18 produce gasoline and diesel range hydrocarbons (Ruddy et al., 2014). The *in situ* catalytic
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20 pyrolysis system combines solid phase pyrolysis reactions and catalytic vapor upgrading within
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22 a single reactor. Whereas in *ex situ*, also known as vapor phase upgrading, fast pyrolysis occurs
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24 in a pyrolysis reactor and then the vapor phase goes into a separate catalytic reactor where
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26 vapors are catalytically upgraded (NREL, 2015).
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34 The different configuration for *in situ* and *ex situ* catalytic pyrolysis leads to the following
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36 outcomes: (1) the total project investment for *ex situ* scenario is higher than the *in situ* case,
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38 due to the configuration complexity associated with the *ex situ* scenario; (2) the *ex situ*
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40 configuration separates the fast pyrolysis with catalytic vapor upgrading process, which
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42 minimizes the contact between biomass pyrolysis solid residue (char and ash) and catalyst, thus
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44 reducing the effects of coking and increasing the catalyst life span. As a result, the catalyst
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46 performance is improved and the maintenance expense for the catalytic reactor is reduced; (3)
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48 the liquid product as well as the organic liquid product obtained by the *in situ* and *ex situ*
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50 catalytic pyrolysis are similar, whereas the *in situ* catalysis pyrolysis has a noticeably better
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52 performance in producing phenols and aromatics, according to study by Yildiz and Ruddy
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54 (Ruddy et al., 2014; Yildiz et al., 2013).
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To our knowledge, the literature does not provide a TEA comparison of *in situ* and *ex situ* pyrolysis that accounts for the process performance variability of these technologies. In order to make a sensible comparison, the data for these systems should be normalized to a common basis. Moreover, sensitivity analysis alone is insufficient to address the uncertainty of the economic analysis since there are inherent uncertainties within each of the parameters. Therefore, model parameters should be represented by appropriate probability distributions instead of static values to improve the representation of potential analysis outcomes. One of the most straightforward ways to apply uncertainty analysis is by using Monte Carlo simulation (Greenland, 2001; Hsu, 2012). Monte Carlo simulations generate parameter samples randomly to quantitatively analyze the output uncertainty level. Although there are numerous comparison studies that evaluate biomass to transportation fuel pathways, few have incorporated the use of stochastic simulations (Anex et al., 2010; Bridgwater et al., 2002; Brown & Wright, 2014; Swanson et al., 2010; Thilakaratne, 2014; Wright et al., 2010; Zhang et al., 2013).

The objective of this paper is to create a side-by-side techno-economic comparison of *in situ* and *ex situ* catalytic pyrolysis scenarios that addresses both sensitivity and uncertainty analysis in the comparison of these technologies. In this study, we (1) collect technical and historical data for key process and economic parameters, (2) conduct stochastic runs of chemical process models for *in situ* and *ex situ* catalytic pyrolysis, (3) investigate the sensitivity range and uncertainty of the MFSP and NPV, and (3) analyze the level of significance of these parameters to the MFSP.

2. Materials and Methods

2.1 Overall process description

This study utilizes the method developed by Brown and Wright (Brown & Wright, 2014) and expands it to include process parameters and analyze parameter significance level. In general, this study involves four steps: (1) collecting probability distributions for key parameters; (2) modifying existing chemical process and economic models to enable stochastic evaluations; (3) developing best-fit distributions of the stochastic MFSP and NPV, and (4) analyzing the significance level of model parameters. Figure 1 in complementary materials illustrates the various steps involved in this analysis. First, historical and experimental data for key parameters are collected and adjusted. Second, best-fit distributions of key parameters were calculated and data sets with 10,000 random values for each key parameter according to their best-fit distributions were generated using MathematicaTM. Third, a Visual Basic for Applications (VBA) interface was developed to import all the generated data sets of parameter values into CHEMCADTM, instruct CHEMCADTM to run through samples from the data sets, and record the corresponding output of key mass and energy results from CHEMCADTM. The MFSP of biofuels were calculated by integrating outputs from CHEMCADTM into a 30 year discounted cash flow rate of return financial spreadsheet. Finally error bars and distributions of the MFSP, and the relative impacts of the key input parameters were determined by analyzing these economical spreadsheets and conducting the uncertainty analysis.

2.2 Data collection

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4 There are hundreds of parameters involved in TEA of biofuel pathways. The scope of this study
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7 is limited to parameters with known significant impact on process profitability as identified by
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10 the Pacific Northwest National Laboratory (PNNL) (PNNL, 2013), and parameters with publically
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12 available data. The list of selected parameters is shown in Table 1.
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15 There were some parameters applied to both *in situ* and *ex situ* cases. Historical wholesale price
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17 for feedstock and various fuels from 2007 to 2012 were gathered based on the following
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19 sources. The Energy Information Administration (EIA) provides U.S. average wholesale prices for
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21 gasoline and diesel, and industrial natural gas and electricity prices (EIA, 2014). **Uncertainty of**
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23 **feedstock price may come from usage of variable types of feedstock and price volatility.**
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28 Feedstock price data are based on pine pulpwood prices from the Texas Forestry Service, and
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30 the mean value of the feedstock price was shifted to \$80/MT (Texas A&M Forest Service). The
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32 remaining data (catalyst to biomass ratio, hydrotreating yield, first stage Hydrodeoxygenation
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34 (HDO) catalyst cost, second stage HDO catalyst cost, second Stage HDO Liquid Hourly Space
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36 Velocity (LHSV), total project investment factor, hydrotreating catalyst life, compression
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38 requirement factor, and hydrogen consumption factor) were gathered from a PNNL report
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41 (PNNL, 2013).
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50 Energy commodity prices exhibit significant volatility due to the complex nature of the energy
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52 market (Regnier, 2007). This volatility can be captured by appropriate probability distributions.
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54 Several candidate distributions were considered: Normal, Lognormal, Exponential, Chi-Square,
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57 Cauchy, Laplace, and Logistic. The best fit distributions were determined from the Anderson-
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4 Darling test (Stephens, 1974). A similar approach was employed to determine the best-fit
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7 distributions for other selected key processing parameters. In some cases, the best-fit
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10 distributions were adjusted to account for differences in the expected mean value, variance, or
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12 distribution type.
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15 Table 1 lists the best-fit distributions, mean, 10% and 90% confidence values for process and
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17 economic parameters. This approach relies on the assumption that historical volatility is an
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19 indicator of future volatility, and variability gathered from literature data is representative of
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21 the uncertainty in a commercial system. Limitations from these assumptions are impossible or
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23 expensive to address because of the nature of commodity markets and the difficulty of
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25 gathering experimental data for all possible process configurations.
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41 Uncertainty of product yields of catalytic fast pyrolysis may result from variability in feedstock
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43 type, properties, compositions, etc. and is another important factor in uncertainty analysis.
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46 Literature data from a number of sources were employed to estimate the distribution for gas,
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48 liquid and solid products from the *in situ* catalytic fast pyrolysis of biomass (Adam et al., 2006;
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50 Agblevor et al., 2010; Aho et al., 2008; Aho et al., 2010; Cheng et al., 2012; Lappas et al., 2002;
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52 Mante et al., 2012; Mihalcik et al., 2011; Mullen et al., 2011; Paasikallio et al., 2013;
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54 Triantafyllidis et al., 2007; Yildiz et al., 2013). Figure 1 shows the *in situ* catalytic pyrolysis
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56 organic oil yield and oxygen content reported in the public literature. The variability in the data
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reflects a diversity of experimental methods and reactor designs. Best-fit distributions of organic oil (bio-oil) yield and biochar were determined based on the data reported in literature. The non-condensable gas yield was adjusted to maintain a closed mass balance across the pyrolysis process.

Mante *et al* (Mante et al., 2012) conducted pyrolysis experiments using crystalline Y-zeolite based catalysts with a fluidized bed reactor and hybrid poplar wood as feedstock. The organic oil yields from his studies ranged between 13.8% and 24.1%. The experiments lead by Agblevor (Agblevor et al., 2010) had an organic oil yield of 21%. A fluidized bed pyrolysis reactor and HZSM-5 acidic catalysts were used in this study, while hybrid poplar wood samples served as feedstock. Paasikallio's group (Paasikallio et al., 2013) employed a fluidized bed pyrolysis reactor with ZSM-5 acidic catalysts and forest thinnings. In their experiments, the organic oil yield varied between 14% and 49%. Mullen *et al.* (Mullen et al., 2011) conducted catalytic fast pyrolysis experiments using a fluidized bed reactor with white oak wood as feedstock. Two catalysts were chosen in this study: Ca^{2+} exchanged Y zeolite and a proprietary β -zeolite type catalyst (catalyst M), which lead to 17% and 11% organic oil yields respectively. A conical spouted-bed reactor with a HZSM-5 catalyst was employed by Olazar's group (Olazar et al., 2000). The organic oil yield from this study is 30.8% with pine sawdust as the feedstock.

Insert Figure 1 here.

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4 There is limited *ex situ* data available in the literature compared to *in situ*. Researchers at the
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6 National Renewable Energy Laboratory (NREL) have obtained comparable pyrolysis oil yields
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8 from *ex situ* catalytic pyrolysis as *in situ* under similar operating conditions. Therefore, this
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10 study adjusts the *in situ* to reflect the similarity in yields from recent *ex situ* catalytic pyrolysis
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12 experiments at NREL. To obtain the *ex situ* distributions, the *in situ* distribution mean was
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14 shifted to the expected *ex situ* yield and the variance was lowered based on engineering
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16 judgment. *Ex situ* experiments have shown more consistent yield results than *in situ* by avoiding
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18 contact between catalysts and biomass, char, and ash. Figure 2 in complementary materials
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20 shows the comparison of biochar and bio-oil yield (wt. %) distributions between *in situ* and *ex*
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22 *situ* cases. Pyrolysis non-condensable gas yields are determined by difference. The mean bio-oil
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24 yields for both *in situ* and *ex situ* cases are around 43 wt. %.

2.3 Modeling and analysis

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27 *In situ* and *ex situ* CHEMCADTM models for 2000 dry metric ton biomass per day biorefineries
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29 were developed by PNNL and Iowa State University (ISU). The catalytic pyrolysis process for
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31 producing gasoline and diesel is described in Figure 2. The *in situ* configuration conducts the
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33 fast pyrolysis and catalytic vapor upgrading processes within the same reactor. The *ex situ*
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35 configuration employs a separate catalytic vapor phase upgrading reactor system, as shown in
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37 figure 2, right after the non-catalytic fast pyrolysis reactor.

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4 Data sets consisting of 10,000 samples of bio-oil and biochar yields for both *in situ* and *ex situ*
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7 were obtained based on their distributions. The generated bio-oil and biochar yield data sets
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9 for *in situ* and *ex situ* were applied to the *in situ* and *ex situ* CHEMCADTM models respectively.
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12 Excel VBA code was developed to import the stochastic samples of parameter values into
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14 CHEMCADTM, and record the corresponding output of key mass and energy results from
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16 CHEMCADTM. These outputs were integrated into financial spreadsheets to calculate production
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18 costs and the biofuel MFSPs. MathematicaTM was employed to analyze the financial
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20 spreadsheets and conduct the uncertainty analysis. Uncertainty analysis results were reported
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22 as error bars and distributions of the MFSP, and the relative impacts of the key input
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24 parameters. P-values were employed to determine the significance of model parameters using
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26 a 0.05 threshold.
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37 **3. Results and Discussion**

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40 The *in situ* and *ex situ* catalytic pyrolysis models for 2000 MTPD of biomass input estimated
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42 average pyrolysis oil yields of 438 and 439 kg/BDMT respectively. The yields are similar because
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44 *ex situ* yields were adjusted to match *in situ* pyrolysis yields after personal communication with
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46 researchers at NREL. Pyrolysis biofuel yields of 152.6 and 143.5 liters per dry MT of feedstock
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48 were obtained. Table 2 describes the key process material yields for the *in situ* and *ex situ*
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50 catalytic pyrolysis processes.
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8 The *in situ* bio-oil yield probability distribution is shown in complementary materials Figure 3 (a),
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10 while the simulated yield of gasoline from the *in situ* process model is presented in
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12 complementary materials Figure 3 (b). These results indicate that there is a strong relationship
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14 between the bio-oil and gasoline yields, but intermediate upgrading steps affect the shape of
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16 the final distribution. At low bio-oil yields, the majority of recovered hydrocarbons are in the
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18 diesel and fuel oil range and the gasoline yield decreases.
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24 Figure 3 shows the mass flow rates for *in situ* and *ex situ* cases. The mass flow rates for the *ex*
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26 *situ* case are shown in parentheses while the mass flow rates for the *in situ* case are shown
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28 without parentheses. Overall, the rate of mass conversion to fuels for the *in situ* and *ex situ* are
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30 12.6 wt. % and 13.5 wt. % respectively, which indicates that the *ex situ* process could have a
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32 higher production rate than *in situ* pyrolysis.
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The MFSP probability density function and cumulative distribution function for the *in situ* and *ex situ* cases are shown in Figure 4. The dark shaded regions indicate 10% to 90% confidence intervals, and the dashed vertical line shows the base case values, which indicates the baseline value for the MFSP determined from previous efforts at ISU. The base case MFSP for the *in situ* scenario is \$0.97/liter, whereas, from the uncertainty analysis of this study, a mean value of

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4 \$1.11/liter is calculated with a standard deviation of 0.29. In the *ex situ* case, a mean value of
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7 \$1.13/liter was calculated from the uncertainty analysis. The base case value of \$1.40 falls
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9 outside the 90% confidence interval of the uncertainty MFSP distribution as figure 4 (b)
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11 indicates. The high MFSP base case value found in *ex situ* scenario is based on literature data
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13 for bio-oil yield; recent developments at the national laboratories indicates higher *ex situ*
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15 pyrolysis yields leading to lower MFSP estimates (NREL, 2015). Furthermore, differences in the
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17 mean and baseline MFSP values are due to the use of probability parameter distributions
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19 instead of standard techno-economic assumptions.
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29 Insert Figure 4 here.
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36 The uncertainty tornado chart in Figure 5 (a) shows the *in situ* catalytic pyrolysis parameter
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38 uncertainty impact on MFSP. Bold legends indicate parameters with high significance at the
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40 0.05 p-value level. The tornado chart features box plots with gates that indicate the minimum
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42 and maximum ranges of the MFSP based on changes to each parameter value. The min/max
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44 ranges are analogous to the values derived from a sensitivity analysis. The colored box areas
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46 are the 0.25 and 0.75 quartile region of MFSP values for the given parameter. The vertical white
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48 lines indicate the mean MFSP value. Figure 5 (a) highlights important differences with
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50 traditional sensitivity analysis plots (traditional tornado charts). Traditional sensitivity analysis
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52 can only indicate the minimum and maximum ranges of MFSP changes by varying each
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54 parameter. However, the historical data and experimental data collected in this study suggest
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4 that the minimum and maximum value for each parameter are less likely to occur than the
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6 values within the 0.25/0.75 quartile, which indicates that parameters with a wide range of
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8 values may have much narrower influence on MFSP than expected. For example, feedstock cost
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10 has a wider range of possible MFSP values than Internal Rate of Return (IRR) and total project
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12 investment, but a narrower range within the 0.25/0.75 quartiles than IRR and total project
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14 investment. This suggests that feedstock cost may have a lesser influence on the MFSP than
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16 other financial assumptions. Furthermore, this new approach is able to determine whether a
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18 parameter tends to have a positive or negative influence on the MFSP. For instance, the
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20 feedstock distribution is skewed towards lower MFSP values and is therefore more likely to
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22 result in a lower MFSP than the average feedstock cost would suggest. This finding contrasts
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24 with traditional sensitivity analysis, which does not provide any likelihood information for the
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26 range of MFSP values.
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36 The uncertainty tornado chart ranks parameters by their influence on MFSP with the largest
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38 direct influence (higher parameter values leading to higher MFSP) shown at the top and largest
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40 inverse influence shown at the bottom. For examples, higher electricity prices reduce the MFSP
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42 because *in situ* catalytic pyrolysis exports electricity to the grid; higher hydrotreating catalyst
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44 life also reduces the MFSP due to the reduction of hydrotreating catalyst replacement costs per
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46 year; higher biochar yield has an inverse impact on MFSP because it correlates with a lower bio-
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48 oil yield, which leads to a lower upgraded fuel production. Feedstock price, internal rate of
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50 return, total project investment and bio-oil yield have the greatest impact on the MFSP,
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52 therefore they are the crucial parameters that may heavily influence the economic
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54 performance of the process. With neither *in-situ* nor *ex-situ* fast pyrolysis achieving commercial
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scale, these parameters shed light on potential ways to improve the economic performance of *in-situ* fast pyrolysis. Among all the parameters, bio-oil yield has a significantly wider range of both possible MFSP values and 0.25/0.75 quartile values than other parameters, which suggests that bio-oil yield has a dominant impact on the MFSP. It is notable that some of the minimum possible MFSP values caused by bio-oil yield changes are below zero. This suggests that in some cases, although statistically unlikely, the biorefinery facility could make sufficient profits from the sale of a co-product such as electricity.

Insert Figure 5 here.

The uncertainty tornado chart for the *ex situ* pyrolysis scenario is shown in Figure 5 (b). It is found that feedstock price, internal rate of return, total project investment, electricity consumption, biochar yield and electricity price are the most impactful parameters on the MFSP. In this case, IRR and total project investment have wider 0.25/0.75 quartile MFSP value ranges than feedstock price. Therefore, IRR and total project investment may have greater impact on the MFSP. Electricity is generated in the *ex situ* case, therefore, electricity consumption, which is a negative value, has positive impact on MFSP and electricity price has an inverse impact on MFSP. Higher biochar yield has an inverse impact on MFSP due to the same reason discussed in *in situ* case.

Figure 6 demonstrates the side-by-side MFSP comparison for the *in situ* and *ex situ* scenarios based on previous studies (a) and this study (b). The dots indicate the mean of the MFSP, while

the lines indicate standard deviation. In the initial analysis, data from previous research in our groups and literature available in 2012 were selected and the same uncertainty analysis methods described in this paper were employed. As figure 6 (a) shows, this initial analysis suggests that *in situ* catalytic pyrolysis might be more economic than *ex situ*, with the expected MFSP of \$1.11 per liter and \$1.40 per liter respectively. Both cases have large error bars (greater than \$0.29 per liter), which indicate large uncertainty. Figure 6 (b) is a revision of the analysis that was informed by recent experimental data as discussed in the method section. These results indicate that *in situ* and *ex situ* catalytic pyrolysis are expected to have a similar MFSP, \$1.11 per liter and \$1.13 per liter respectively. This uncertainty analysis suggests that *ex situ* catalytic pyrolysis is expected to have a smaller standard deviation than *in situ* catalytic pyrolysis, therefore, there could be greater techno-economic risk associated with the *in situ* case.

Insert Figure 6 here.

4. Conclusion:

This techno-economic study calculates and compares two different catalytic fast pyrolysis pathways: *in situ* and *ex situ*. Best-fit distributions and Monte Carlo methods are employed in to investigate the uncertainty of MFSP estimates.

Uncertainty analysis shows that *in situ* catalytic pyrolysis is expected to have a similar MFSP with *ex situ* catalytic pyrolysis, \$1.11 per liter and \$1.13 per liter respectively. However, *in situ* catalytic pyrolysis has a greater standard deviation compared to the *ex situ* catalytic pyrolysis scenario based on recent experimental findings. This suggests that *ex situ* pyrolysis could mitigate some commercialization uncertainty in fast pyrolysis biorefineries.

Acknowledgement:

This project was made possible by support from the US Department of Energy and Pacific Northwest National Laboratory through Contract Number 167288. The authors would like to acknowledge Rajeeva Thilakaratne for developing the baseline process models.

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Table 1. Probability density functions (PDF), mean, and ±10% confidence level values of key parameters that apply to both *in situ* and *ex situ* cases.

Parameter	Distribution		Mean	Confidence (10%)	Confidence (90%)
Industrial Natural Gas Price (\$/m ³)		Lognormal	0.22	0.14	0.31
Industrial Electricity Price (¢/kWh)		Normal	6.05	5.00	7.09
Pine pulpwood (\$/MT)		Lognormal	78.69	67.21	90.18
Gasoline Wholesale (\$/liter)		Lognormal	0.47	0.24	0.76
Diesel Wholesale (\$/liter)		Lognormal	0.46	0.16	0.77
Catalyst to Biomass Ratio		Triangular	3.83	1.23	7.08
Hydrotreating Yield (wt. %)		Triangular	0.44	0.43	0.45
First Stage HDO Catalyst Cost (\$)		Triangular	60.00	43.42	76.58
Second Stage HDO Catalyst Cost (\$)		Triangular	18.50	13.32	24.61
Second Stage HDO LHSV (1/h)		Triangular	0.24	0.16	0.33
Capital Cost (\$)		Triangular	1.10	0.97	1.26
Hydrotreating Catalyst Life (years)		Triangular	1.17	0.77	1.61
Compression Requirement Factor		Triangular	1.00	0.89	1.11
Hydrogen Consumption Factor		Triangular	1.00	0.89	1.11

Table 2. Key process material yields for the *in situ* and *ex situ* catalytic pyrolysis process.

Scenario	In Situ	Ex Situ
Gas Species (kg/BDMT)	321.2	320.3
Pyrolysis Oil (kg/BDMT)	438.0	438.7
Char (kg/BDMT)	240.8	241.0
Natural Gas Utilized (MT/day)	73.9	NA
Gasoline & Diesel Blendstock Yield (wt. % dry biomass)	12.6	13.5
Gasoline & Diesel Blendstock Yield (liter/dry MT)	152.6	143.5

Figure

Figure 1. *In situ* catalytic pyrolysis organic oil yield and oxygen content reported by various sources.

Figure 2. Process diagram for production of transportation biofuel via *in situ* and *ex situ* catalytic pyrolysis.

Figure 3. Material flow rates for *in situ* and *ex situ* (shown in parenthesis) catalytic pyrolysis process.

Figure 4. Probability density function and cumulative distribution function of Minimum Fuel-Selling Price (MFSP) of *In situ* (a) and *ex situ* (b) catalytic pyrolysis. Confidence levels of 10 and 90% are indicated by the dark shaded region.

Figure 5. *In situ* (a) and *ex situ* (b) catalytic pyrolysis parameter uncertainty impact on the MFSP.

Gates indicate min/max MFSP range; boxes indicate 0.25-0.75 quantiles of the MFSP; white

vertical lines show the mean MFSP value. Bold legends indicate significant ($p < 0.05$) parameters.

Figure 6. Uncertainty range comparison of in situ MFSP to ex situ catalytic pyrolysis MFSPs based on previous (a) and recent (b) experimental results.