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Financial viability of biofuel and biochar production from forest biomass in the face of market price volatility and uncertainty

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HIGHLIGHTS

- Uncertainty in market prices drives financial outcomes.
- Monte Carlo simulation allows uncertainty to be quantified.
- Biochar-only production offers a potentially profitable venture.
- Biofuel-biochar coproduction requires RINs to achieve financial success.

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ABSTRACT

A comparative techno-economic analysis of two different thermochemical biomass conversion pathways was conducted to examine the effects of fuel price and other variables on project financial performance. Monte Carlo simulation was used to quantify the effects of uncertainty and volatility of ten critical variables: biofuel, biochar and feedstock prices, discount rate, capital investment, labor cost, loan terms, feedstock drying, and biofuel and biochar conversion rates. Market prices for biofuel and biochar have the largest impact on net present value (NPV) of any variable considered, due in part to the high levels of uncertainty associated with future prices of both. Across the ranges of input values for these variables in simulation analysis, hearth-based pyrolysis biochar production had the highest likelihood of profitability with a mean NPV of $41.5 million and only 20% of outcomes resulting in a net loss, while 68% of outcomes for auger-based biochar-biofuel coproduction represented a financial loss, including a mean NPV of -$24.2 million. However, when additional revenue from Renewable Identification Numbers (RINs) credits generated by biofuel production is considered, financial outcomes of biochar-biofuel coproduction improve to 50% likelihood of experiencing a net loss. Findings of the very strong impact of market prices on financial outcomes, relative to other important technical and economic variables, can inform effective targeting of future renewable energy policy, as well as the design of future techno-economic analyses, which do not currently focus on the effect of market prices on profitability.

1. Introduction

1.1. Background

Today the Earth's climate is widely acknowledged to be changing as a result of anthropogenic greenhouse gas emissions. According to the Intergovernmental Panel on Climate Change (IPCC), one of the essential actions in mitigating the effects of climate change is offsetting a substantial portion of fossil fuel consumption with renewable energy sources [1]. In order to reduce fossil fuel emissions, governments around world have implemented policies that encourage the transition from fossil fuels to renewable fuels through the use of both market-based mechanisms and command-and-control approaches.

In the United States of America (U.S.), the Energy Independence and Security act of 2007 aimed to increase energy security and reduce greenhouse gas emissions. As part of this legislation, the Renewable Fuel Standard established by the Energy Policy Act of 2005 was expanded, setting renewable blending targets for transportation fuels that increase each year to an annual target of 36 billion (36×10^9) gallons (gal) (136.3 billion liters [L]) by 2022 [2]. Compliance with the

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mandate is tracked through the use of Renewable Identification Numbers (RINs), which are generated by the production of renewable biofuel and act as credits that can be bought and sold by obligated parties. According to the U.S. Energy Information Administration (EIA), despite the financial incentive provided to producers by RINs and other mechanisms such as tax credits and loan guarantees, the targets for non-corn cellulosic biofuels have never been met [3,4].

Woody biomass from forests is one source of feedstock that can be used to produce cellulosic biofuel and help meet fuel blending targets. According to a study by the U.S. Department of Energy (DOE), biomass residues from forest management have the potential to provide between 16.2 and 18.9 million (M) dry tonnes (equivalent to 1000 kg and abbreviated *t* unless otherwise noted) of biomass per year for energy [5]. However, there are technical and logistical challenges associated with the production of biofuel from forest biomass that can reduce financial viability. Volatility in market prices for fossil-based transportation fuels can make investments in biofuel production risky and this volatility has likely contributed to the gap between cellulosic biofuel targets and growth in the capacity of the industry, particularly during periods of sustained low prices. Government policy incentives can offer various strategies to improve the financial viability of biofuel production through the use of mechanisms like carbon credits, renewable energy credits, capital subsidies, and reverse auctions to provide price stability. Some previous studies have found production costs of liquid biofuels from forest biomass to be too high to compete with fossil fuels without considering policy incentives [6].

Beyond government policies, the co-production of multiple revenue-generating products is one strategy biofuel producers can employ to improve the likelihood of financial success. Biofuel can be produced simultaneously with other products, such as chemicals and biochar, which is a solid carbon-rich charcoal used in a variety of applications, especially to improve soils for plant growth [7]. The few previous studies that have analyzed the financial viability of biofuel-biochar coproduction have found biofuel production to be most financially viable when biochar is considered as a revenue-generating coproduct. A study of methanol and biochar coproduction with two-stage pyrolysis or gasification processing of forest biomass found that, while gasification could produce methanol at prices competitive with fossil fuels without considering biochar revenue, pyrolysis production required the biochar coproduct to sell for between $220 and $280 per tonne to break-even [8]. Brown et al. [9] analyzed the profitability of two different pyrolysis production pathways using corn stover feedstock: a lower-capital slow pyrolysis system producing biochar and pyrolysis gas, and a higher-capital fast pyrolysis system producing biochar and bio-oil. Profitability for both pathways was found to be sensitive to feedstock prices, fuel selling prices, and the ability to earn carbon offset credits for the biochar [9].

Financial evaluation of emerging energy technologies is often conducted using techno-economic analysis, which is a modeling process that combines one or more measures of project financial performance, typically a benefit-cost analysis, with a detailed technical specification of the technology being evaluated [10,11]. These types of analyses, including the Shabangu et al. [8] and Brown et al. [9] studies of biofuel-biochar coproduction, have commonly relied on static inputs and have produced deterministic outcomes for financial metrics like net present value (NPV). This approach is most appropriate when important variables are known and consistent or accurately predictable over time, but when input variables are subject to uncertainty and volatility, as in the case of market prices for biofuel and biochar, it can produce overly simplistic estimates of project performance without quantification of uncertainty or risk [12].

Some recent techno-economic analyses have employed Monte Carlo simulation to incorporate input variable uncertainty into their estimates of financial outcomes and to quantify the sensitivity of these outcomes to changes in specific variables. Using a simulation approach, Petter and Tyner [12] found that uncertainty in product selling price was a main contributor of risk to investors in biofuel production facilities [12]. This finding may have been overlooked without the use of Monte Carlo methods, as they noted that previous studies of the same facilities that used deterministic sensitivity analysis instead found technical uncertainties associated with product yield and biomass feedstock cost to be the most influential variables in determining financial outcomes. Zhao et al. [10] estimated probability density distributions for both NPV and break-even price for eight different biofuel production pathways and also found that product market prices had the strongest effect on financial outcomes. In a different study, Zhao et al. [13] estimated break-even price distributions for cellulosic biofuel production using both programming and mathematical methods. They found break-even price to be most sensitive to technical uncertainty associated with feedstock cost and fuel yield. Yao et al. [14] accounted for technical uncertainty in alcohol-to-jet biofuel production to produce distributions of break-even price and found significant profitability impacts from technical uncertainty in fuel conversion rates and revenues generated from conversion by-products. No previous studies have used Monte Carlo simulation to analyze biofuel-biochar coproduction and the considerable uncertainty associated with future biochar markets and prices.

This study uses techno-economic analysis to compare two different pyrolysis production technologies using forest biomass feedstock. The purpose is to identify the factors that have the strongest effect on financial success to inform decision making that leads to efficient investment and effective operation of commercial facilities. The goal is to facilitate increased renewable biofuel and bioproduct production. The study improves on previous research in several important ways. It uses Monte Carlo simulation to account for uncertainty and volatility in key technical and financial variables associated with biofuel and biochar coproduction via pyrolysis. To our knowledge, no previous published study has accomplished this. Furthermore, rather than using a simple normal distribution based on a percentage range applied to a base case value, the distributions of these variables are established based on market transaction evidence and data collected from the operation of pilot scale facilities, with special emphasis on documentation of biofuel and biochar pricing.

Two biomass conversion pathways are evaluated. The first technology requires higher capital investment and can be used to produce both cellulosic biofuel and biochar, or biochar only, depending on market conditions. The second technology is a less costly investment, but only produces biochar with no liquid fuel option. Because of the substantial uncertainty associated with future biofuel and biochar prices, we hypothesize that the market prices for the goods produced will be the most impactful variables in the financial success of biofuel-biochar coproduction. Based on findings by previous studies and the experience of the authors with pilot scale systems, we also hypothesize that biofuel production will not be financially viable without considering biochar as a revenue-generating coproduct.

This section proceeds with a summary of the conversion pathways and their products, followed by a thorough review of available information about potential markets and prices for biochar to contextualize the potentially lucrative, but highly uncertain future status of biochar production. In the Methods section, technical descriptions of the two pyrolysis technologies considered in this study are provided and the methods used for financial evaluation are presented. Then, results of the analysis are presented and their implications for investment in and operation of biofuels facilities are discussed. Finally, the main conclusions are summarized with an emphasis on technology investment and management of coproduction operations.

1.2. Biomass conversion using pyrolysis

Biomass can be transformed into energy and products using biological conversion, including fermentation and digestion [15], or thermochemical conversion, including combustion, gasification [16],

Table 1
Review of biochar prices.

Cited biochar price	Mean price (2015 USD t^{-1})	Type of study	Description	Source
$2.47 kg^{-1}	$2512.40	Survey of biochar sellers	Unblended, wholesale or retail, U.S.	International Biochar Initiative, [32]
$2.06 kg^{-1}	$2062.61	Survey of biochar sellers	Unblended, wholesale, Global	International Biochar Initiative, [51]
$600 t^{-1}	$651.99	Economic analysis of biochar and bio-oil production	Assumed selling price	Yoder et al. [29]
$500 t^{-1}	$508.58	Economic analysis of biochar as soil amendment	Assumed selling price	Filliberto and Gaunt [52]
$87 t^{-1}	$96.13	Economic analysis of biochar as soil amendment	Assumed selling price based on production costs Improved profit for farmers at this price	Granstein et al. [53], Galinato et al. [37]
$114.05 t^{-1}[a]	$126.01	Economic analysis of biochar as soil amendment	Assumed selling price based on energy content and price of coal Reduced profit for farmers at this price	Granstein et al. [53], Galinato et al. [37]
$350.74 t^{-1}	$387.53	Economic analysis of biochar as soil amendment	Assumed selling priced based on production costs Includes $1 t^{-1} CO_2 price Reduced winter wheat profit at this price	Granstein et al. [53], Galinato et al. [37]
$0–$500 t^{-1} (mean $250)	$258.06	Techno-economic analysis of biochar and methanol production	Assumed selling price based on "upper limit of biochar for soil amendment in the US."	Shabangu et al. [8]
$258 t^{-1}	$285.06	Economic analysis of biochar production and use as soil amendment	Cost of applied biochar to cropland	McCarl et al. [54]
$207 t^{-1}	$213.67	Cost-benefit analysis of biochar as soil amendment	Cost of applied biochar to cropland. At this price, NPV is negative. Breakeven could be achieved at price between $9 and $51 t^{-1}	Dickinson et al. [38]
−$222 to $584 t^{-1} (mean $181)	$196.69	Cost-benefit analysis of biochar as soil amendment	Net cost to produce, deliver, and spread biochar on fields. Includes electricity sales and renewable energy credits	Shackley et al. [55]
490–600 EUR t^{-1} (mean 545 EUR t^{-1})	$725.77	Personal Communication	European Biochar Market	Cited in Dickinson et al. [38]
$899–$2778 t^{-1} (mean $1834)	$1834	Techno-economic analysis of biochar and other pellets	Wholesale price from personal communication with industry	Campbell et al. [11]

[a] Wood-based biochar energy content is assumed to be the same as the energy content of central Appalachian coal at 12,500 BTU/lb, with the price of coal at $116.38 per tonne, and combustion value of biochar at 98% of value of coal [37].

hydrothermal processing [17], and pyrolysis [18]. Biochemical and thermochemical pathways can also be combined, as in the thermal pretreatment of lignocellulosic feedstocks to improve biochemical ethanol and biogas production [19]. Among thermochemical conversion pathways, combustion is most common, and is widely used to produce heat and electricity and to dispose of waste biomass [20]. Gasification is commonly used for heat and power [21], but also used in the production of fuels and chemicals, including alcoholic fuels such as methanol [22]. Hydrothermal processing is thermal decomposition in water under pressure and, unlike other thermochemical pathways, it can use very high moisture feedstocks such as manure [17].

Both of the technologies evaluated in this study employ pyrolysis, in which biomass is heated in a low oxygen environment to produce some combination of liquid, gaseous and solid outputs. The liquid and solid outputs are commonly referred to as bio-oil (also called pyrolysis oil) and char, which is called biochar if it is used as a soil amendment [23]. The gas output from pyrolysis can include both volatile gases and non-condensable light gases such as CO_2, CO, CH_4 and H_2 [24]. Bio-oil is typically separated from light gases through condensation, but liquid fuels can also be produced from mixed gases using catalysis [11]. Recovered light gasses can also be combusted to produce process heat and power. A technical comparison of thermochemical conversion pathways is beyond the scope of this paper and is adequately addressed elsewhere (see previous references in this section), but some details of pyrolysis and its products are useful to review here.

Although variables such as heating rate, oxidation rate, residence time, catalyst effectiveness, and other factors create a complex environment for the thermal decomposition of biomass, pyrolysis is often divided into three categories: slow, fast and flash pyrolysis. With some variation, many authors have defined these categories based on temperature, heating rate and residence time. Tripathi et al. [25] define these thresholds as 400–500 °C at 0.1–1.0 °C/s for 5–30 min for slow pyrolysis, 850–1250 °C at 10–200 °C/s for 1–10 s for fast pyrolysis, and 900–1200 °C at 1000 °C/s or more for 0.1–1.0 s for flash pyrolysis. Regardless of the exact thresholds of each category, the conditions of pyrolysis and characteristics of the feedstock determine the physical and chemical properties of the bio-oil, gas and char outputs.

In theory, pyrolysis conditions can be varied to alter the ratio and production rates of these outputs given a specified feedstock throughput. Slow pyrolysis at low temperatures and long residence times generally produces higher yields of char, while fast pyrolysis at higher temperatures and shorter residence times favors higher yields of liquid products [26]. Char conversion rates for wood feedstocks range from 20% to 40% by mass or more depending on technology, temperature and residence time, with higher char yields generally associated with chars of lower total carbon content [27]. At the higher end of the temperature range (e.g. > 1000 °C), biochar yield can be as low as 5% [12,14], which is similar to yields associated with some gasification systems. Bio-oil conversion rates also vary widely, and generally range from 5% to 75% across technologies producing many different bio-oil and liquid fuel outputs [28]. This study uses conversion rates from 22% to 32% by mass for biochar and 7–11% by mass for liquid fuel, which are grounded in data collected from pilot scale operations.

Under flexible operating conditions, the biofuel-to-biochar ratio can potentially be optimized based on selling prices of the two products [29]. In practice, however, altering the conditions of pyrolysis on-the-fly results in changes in the characteristics or quality of the products. For practical purposes and technical reasons, most industrial pyrolysis systems have been designed to operate under certain conditions to yield products of known quality, and altering those conditions can have adverse effects on the products and equipment. Therefore, the yields of different products from a specific type of feedstock are generally considered fixed [29].

Even with these types of constraints on operations, several characteristics of pyrolysis systems are broadly associated with better profit potential. In general, pyrolysis conversion of biomass is more likely to be financially viable when it: (1) uses waste biomass feedstock rather than more costly purpose-grown biomass, (2) captures value from multiple char and energy products, including heat and power, and (3) captures market value from carbon sequestration, through carbon credits for example [7]. The benefits of using waste feedstock extends not only to cellulosic biomass (i.e. herbaceous and woody plants), such as logging and agricultural residues, but also to food waste, manure, and animal tissue [30], although non-woody feedstocks may be associated with lower quality biochars [31]. Compared to combustion and gasification systems that produce only heat and power, pyrolysis has the advantage of producing liquid fuel and char products that can be shipped to distant markets [24].

1.3. Biochar pricing

When char is co-produced with liquid fuel and can be sold as a carbon-sequestering biochar soil amendment, it has the potential to generate additional revenue when biofuel prices are low. Despite this potential advantage, markets for biochar are currently not well established and there is considerable uncertainty about future prices. Table 1 illustrates the wide variation in biochar pricing used in previous studies and provided by biochar trade organizations. In 2013, based on a survey of biochar sellers conducted by the biochar non-profit group *International Biochar Initiative* (IBI), prices for biochar worldwide were found to vary between 80 U.S dollars ($) t^{-1} and \$13,480 t^{-1} [32]. However, these prices do not distinguish between wholesale and retail prices, which are likely to diverge substantially, and it is unclear what types of post-conversion processing enhancements may have been applied to higher-price biochars. Results from the IBI study found the mean price in the U.S. in 2014 to be \$2512 t^{-1}, based on 23 observations of biochar sellers.

One of the reasons why the price of biochar is so variable, is the wide variation in product physical and chemical characteristics [18], as well as the diversity of potential uses and associated markets, ranging across agriculture, forestry, mining, horticulture, nursery, and industrial adsorbent sectors [7]. Indeed, as interest in biochar grew in the early part of the 21st century, especially for its potential climate benefits [23], several organizations championed the need to establish biochar standards. Both the International Biochar Initiative (IBI, first publication May 2012) and European Biochar Certificate (EBC, first publication March 2012) worked to set such standards (Table 2, [33]).

Table 2
Example of thresholds for specific properties set by two widely used biochar standards (Adapted from European Biochar Certificate (EBC) Version 4. 8 and International Biochar Initiative (IBI) Biochar Standards Version 2.0).

Criteria	EBC Standard	IBI Standard
Carbon content (% of total mass, dry basis)	≥50%	10% minimum, with 3 classes: Class 1: ≥60% Class 2: ≥30% and < 60% Class 3: ≥10% and < 30%
Molar $H/C_{organic}$ Ratio	0.7 maximum	0.7 maximum
Surface area	No minimum, preferably higher than 150 $m^2 g^{-1}$	No minimum
Heavy metals	Specific maximum levels set for most metals in two different grades: basic and premium	Specific maximum levels set for most metals
PAHs[a] (sum of 16 US EPA PAHs)	Basic grade: < 12 mg kg^{-1} Premium grade < 4 mg kg^{-1}	6–300 mg kg^{-1}
PCBs[b]	< 0.2 mg kg^{-1}	0.2–0.5 mg kg^{-1}
Dioxins and furans	< 20 ng kg^{-1}	< 17 ng kg^{-1}

[a] Polycyclic aromatic hydrocarbons.
[b] Polychlorinated biphenyls.

In part, this was driven by the potential for low-carbon fly ash and fossil-based carbon products to be falsely characterized as biochar soil amendments, and also the potential impacts of contaminants like polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCB), dioxins and furans, which can form during pyrolysis.

Even under such standards, there is wide latitude with regards to ash content, molar O/C ratio, macronutrient concentrations, electrical conductivity, pH, bulk density, particle size, water content, surface area, water holding capacity, volatile matter and other properties. Perhaps it is not surprising then, that reported prices range from $80 to over $13,000 per ton. High value biochars are typically characterized by high carbon content, low H/C and O/C ratios, low ash content, high surface area, high conductivity and high ion exchange capacity, with low levels of contaminants. Value can also be enhanced by post-conversion treatments such as inoculation with desirable microbes, treatments to change pH or other chemical characteristics, granularization or pelletization to improve material handling and performance, and composting or blending with chemical fertilizers and organics, which can result in high levels of available macronutrients. Given the diversity of feedstocks, conversion processes, post-conversion treatment options and possible markets, biochar is likely to remain a differentiated product subject to targeted marketing, rather than a widely traded commodity.

Despite the diversity of potential biochars and markets, in general biochar has attractive qualities as an agricultural soil amendment, and this is both a defining characteristic [34] and the largest potential market. The addition of biochar to soils has been found to increase crop yields and reduce the need for irrigation and fertilizer inputs. Although effects are dependent on case-specific variables, including soil type, climate and geography, a meta-analysis across many studies has found the average effect on yield to be around 10% [35].

However, biochar use as a commodity input in agriculture is not widespread, and the net benefits to farmers are generally considered uncertain [36]. Currently, biochar markets in this sector are characterized by diffuse spot market transactions and negotiated prices. If biochar becomes accepted and widespread as an agricultural input, the market demand could be substantial and prices would be determined by the value that it can provide to users. Rational consumers of biochar will only be willing to pay a price up to the marginal net benefits associated with biochar application from higher yields and lower water and fertilizer application. From a derived demand perspective, this break-even point will be closely tied to the value of and demand for specific agricultural outputs such as cereals, fruits and vegetables.

Studies of the economic value of biochar as a soil amendment for cereal crops have generally found the net benefits to be small. A study of winter wheat production in Washington, U.S., found reduced profits at biochar prices ranging from $87.00 t^{-1} to $350.74 t^{-1} [37]. Dickinson et al. [38] found that limited agronomic benefits together with relatively high biochar cost estimates made biochar a poor investment option for cereal farmers in northwest Europe and Sub-Saharan Africa, even when assuming benefits accrued 30 years into the future. Collison et al. [39], on the other hand, found that biochar application could improve crop yields and quality, while reducing fertilizer and cultivation costs, but did not attempt to estimate the expenditures associated with biochar use. However, cereals are one of the least valuable agricultural commodities, and biochar use in the production of more valuable row crops and horticultural products could potentially support higher market prices. Dickinson et al. [38] simulated the scenario of higher value crops by doubling cereals prices and found positive NPV after 25 years in northwest Europe and 5 years in Sub-Saharan Africa.

The use of biochar as a soil amendment also has the potential to sequester carbon because of high carbon stability, which varies depending on biochar physical and chemical properties [34]. In addition to biochar recalcitrance in the soil, net carbon benefits can be highly dependent on case-specific parameters such as feedstock sources, production emissions, fossil energy displacement, fertilizer use avoidance, soil emissions, and transportation costs [7]. Although there is currently no obligatory market for carbon in the U.S., if one were implemented in the future, the monetary value of carbon sequestration would almost certainly increase the value of biochar.

Galinato et al. [37], found that the application of biochar in winter wheat production in the state of Washington, U.S., only resulted in positive net benefits under their lowest-cost biochar scenario plus the addition of a $31 t^{-1} carbon offset value, which effectively lowers the cost to farmers to $56 t^{-1}. Char from pyrolysis can be used as a solid fuel in combustion systems. Some studies have found [26] or suggested [38] that consuming biochar for energy production may have a higher economic value than as an agricultural input. In the Midwestern U.S., Field et al. [26] found that when carbon prices are not taken into account, the economic value of agronomic use is lower than the value of biochar as solid fuel, but that agronomic use reaches parity with energy content value at carbon prices as low as $50 per tonne of CO_2.

More generally, biochar has a wide range of chemical and physical properties and is less likely to be treated as a commodity and more likely to be sold as a differentiated product. Unlike fossil fuels, market transaction evidence for biochar pricing is sparse. This introduces uncertainty in predicting the financial outcomes of projects that derive revenue from biochar, and adds risk to investments in such projects. There is also uncertainty associated with future biofuel prices and RINs values, but more evidence of past pricing and price volatility exists to guide decision making. This study accounts for uncertainty and volatility in the prices of both products.

2. Methods

2.1. Process descriptions

Two different thermochemical conversion technologies were considered in this study: (1) an auger-based pyrolysis system that is capable of both biochar-biofuel coproduction and biochar-only operation, and (2) a hearth-based pyrolysis system that produces biochar with no liquid fuel output. Technical information for both systems is based on empirical data collected at 1 tonne per hour capacity pilot-scale facilities operated by industry partners in California using feedstock from North American pine species (*Pinus spp*). Process data were collected at these facilities between 2014 and 2017.

Both production pathways begin with standard size wood chips delivered to the facility gate, which are purchased on a dry weight basis. Delivered wood chip size specifications are assumed to be those of a standard pulp chip, i.e. less than 7.62 cm (3.00 in.) in the longest dimension, which can be produced in the field at harvest sites from forest biomass using conventional chipping equipment. Moisture in chips from standing dead trees in semi-arid regions can be as low as 15%, and it can range up to 50% or more in chips from live trees. Both pathways include pre-conversion processing and drying equipment to achieve narrower feedstock specifications in terms of size, shape, particle homogeneity and moisture content (Fig. 1).

The auger-fed pyrolysis technology depicted in panels A and B of Fig. 1 can operate in two different configurations. Fig. 1A represents a scenario where the system is configured to coproduce both liquid biofuel and biochar, while Fig. 1B depicts the same technology configured to produce only biochar. In both auger-based production scenarios, the technology pyrolyzes dried wood in an oxygen free environment, achieving temperatures near 500 °C at pressures ranging from 1 to 4 atmospheres. Solid residence times are about 15 min and gas residence times are a few seconds.

Because this process requires relatively narrow specifications for feedstock size and moisture content, it begins with on-site chipping, screening and drying of delivered wood chips. Fossil natural gas or light combustible gases from the pyrolysis process provide fuel for drying to the target moisture content of 10%. When the proper size and moisture content are achieved, the wood chips are fed through a lockhopper feed

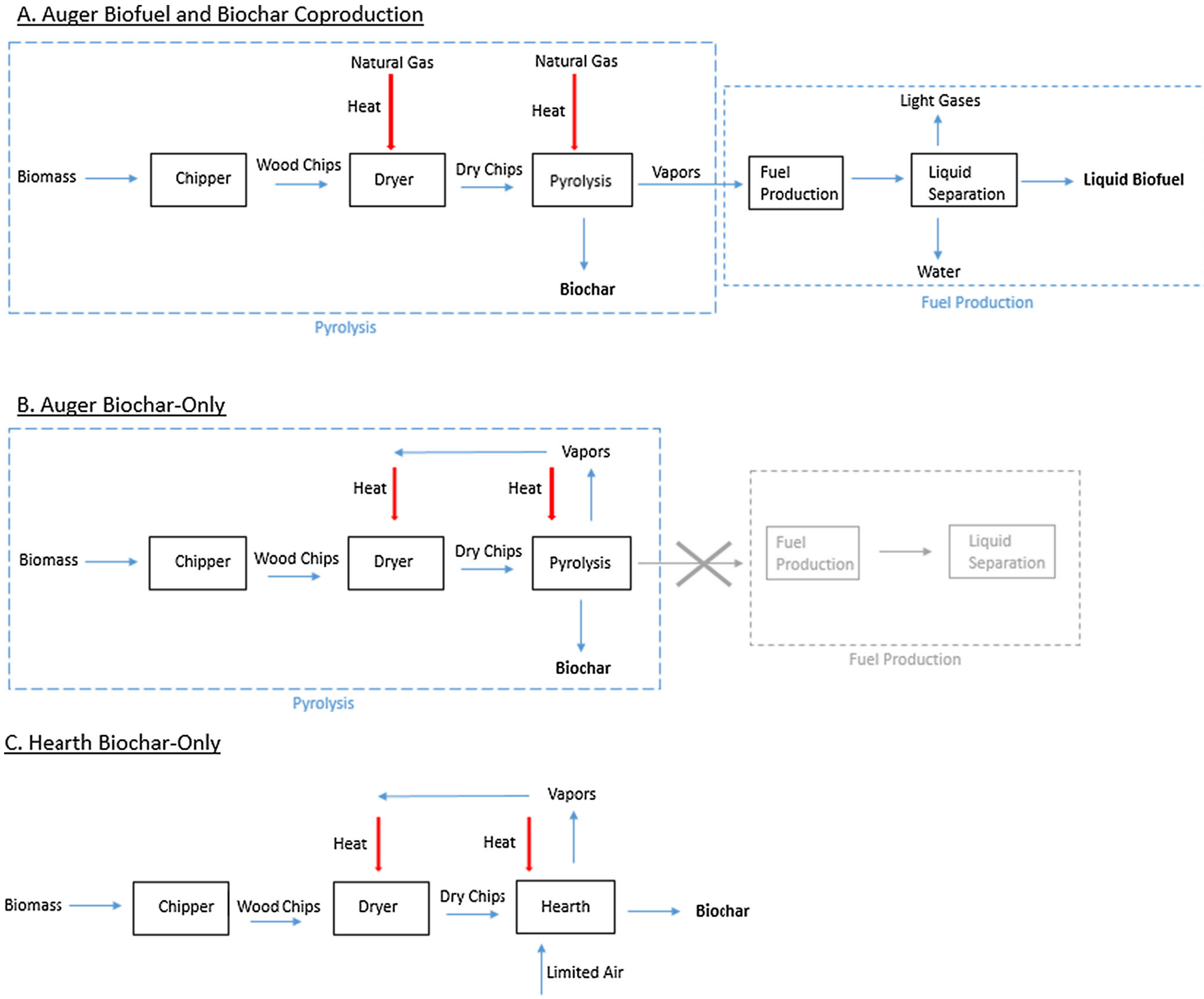

Fig. 1. Schematic diagrams of the production pathways. Auger-based pyrolysis production technology, which is capable of either biochar-biofuel coproduction (A) or biochar-only production (B). Hearth-based technology, biochar-only production (C).

system into the pyrolyzer. In the pyrolyzer, wood chips are heated in a zero oxygen environment until energy-rich vapors and light gases are produced, leaving the remaining mass fraction as char. In the coproduction scenario, energy-rich vapors are interacted with a catalyst to produce a mixture of water, light gases, and biofuel, which are uncoupled in a separation step. In both the pyrolysis and the liquid separation phases of the process, light gases with relatively low energy content are either separated and flared or captured in a recycle system and used to fuel the feedstock dryer. After the liquid separation phase, the mixture undergoes distillation into gasoline, diesel, and other fuel grades. This process has a lower liquid yield by mass than pyrolysis used to produce bio-oil via condensation, but generates a higher quality, near "drop-in" liquid cellulosic biofuel with characteristics of near zero oxygen and low benzene content. This fuel can be blended directly with conventional petroleum-based gasoline, and is hereafter referred to as "biofuel".

When the auger system is used for coproduction of biochar and biofuel, both the dryer and the pyrolyzer require natural gas for heating (Fig. 1A). Alternatively, in a biochar-only configuration (Fig. 1B), the pyrolysis vapors are recycled and used as an offset for natural gas to supply the heat necessary to dry feedstock and run the pyrolyzer instead of being interacted with a catalyst to produce liquid fuel. Operating in a biochar-only configuration reduces revenues by eliminating fuel sales, but also reduces operating costs by eliminating the consumption of catalysts and natural gas and reduces utilities and labor costs associated with fuel production.

In this analysis, pyrolysis conditions and yields from the conversion process are not considered flexible in response to market conditions. In other words, the ratio of biofuel to biochar cannot be optimized based on market price. However, it is possible to choose pathway A or B based on market conditions. These are treated as discrete operating options, and do not allow for a continuous inverse tradeoff between the yields of biofuel and biochar.

The second conversion technology considered in this study utilizes an autothermal pyrolysis process in a multi-chambered hearth vessel, as shown in panel C of Fig. 1. There is a minor influx of air entering some of the zones of the reactor for heating purposes. The 10 tonne per hour production system modeled in this study is assumed to consist of ten 1-tonne per hour units operating in parallel. This configuration was determined to be the most cost effective option of upscaling the pilot plant. Appropriately sized and dried wood chips are fed into the top chamber of the hearth using a conveyor. The biomass is then transported continuously downward through a series of increasingly oxygen-limited chambers at temperatures ranging from 450 °C to 650 °C at near atmospheric pressure. The residence time of the solids averages 25–45 min, with significant variation depending on particle size. The

Table 3
Financial accounting assumptions.

Parameter	Input Value	Source
Nominal discount rate	7.5%	Petter and Tyner [12]
Inflation rate	2.5%	Petter and Tyner [12]
Loan interest rate	8% APR	Zhao et al. [10]
Loan term	10 years	Zhao et al. [10]
Federal income tax rate	21%	United States Congress [56]
Plant life	20 years	Wright et al. [57]
Depreciation	Variable declining balance (MACRS) 7 year period	Peters et al. [40]
Construction spending		Zhao et al. [10]
Year 1	8% of FCI and land	
Year 2	60% of FCI	
Year 3	32% of FCI and working capital	

volatile gases released are recycled within the system to provide fuel for the heat required to run the process, which makes the system self-sustaining after initial start-up heating using diesel fuel. A fraction of the volatile gases can be used for other purposes, such as producing process electricity, but in this pathway gases are used for heat only. After completing passage through the hearth chambers, the remaining mass fraction of biomass has been converted into char, which is sent to a water quench for cooling.

2.2. Economic analysis

Financial evaluation metrics of net present value (NPV) and minimum product selling price were calculated based on capital costs, operating costs, and revenues for a 20 year project period. Minimum product selling price is the lowest selling price at which NPV = 0. Revenues are a function of production rates of biofuel and biochar and the selling price of those products.

The total capital investment (TCI) of each scenario is the sum of fixed capital investment (FCI) and working capital. FCI reflects the cost of building and equipping a plant, including the cost of engineering, construction, equipment purchase and installation, buildings, and land. FCI is estimated by pricing the individual pieces of production equipment that are inside battery limits (i.e. processing equipment that is directly involved in the manufacturing of the product), and then using factors representing a proportion of the total purchased equipment cost to estimate direct capital costs (e.g. equipment installation, service facilities, buildings, land) and indirect capital costs (e.g. engineering, construction, contingency) that are outside of battery limits [40]. Prices of individual pieces of equipment were found using previous studies of similar facilities, information provided by industry partners, and the Standardized Cost Estimation for New Technologies tool (SCENT) [41]. Because the cost of a piece of equipment is partially dependent on size, costs were scaled when necessary, using the following equation:

$$Cost_x = Cost_{base} * \left(\frac{Size_x}{Size_{base}}\right)^R \quad (1)$$

where R is a scaling factor. Scaling factors can vary from less than 0.3 to greater than 1.0, depending on the type of equipment, and can have a large impact on equipment cost estimation. The most commonly assumed value is 0.6, and is the value used in this study [40]. All equipment costs were normalized to 2015 U.S. dollars using the Chemical Engineering Plant Cost Index (CEPCI). Equipment and infrastructure related to harvest and transportation of feedstock and transportation or shipping and delivery of energy products is not included in capital costs, but are assumed to be included in the cost of feedstock (i.e. feedstock is the gate price of delivered feedstock) and final products, with transportation cost borne by the customer in both cases. Working capital represents cash kept on hand for day-to-day plant operations like accounts receivable, cash on hand, and raw material and product inventory. In this study, working capital is assumed to equal a fixed percent of FCI [40], and is recouped in the last year of the analysis.

Annual operating costs are classified as either fixed, variable, or labor. Fixed operating costs, including maintenance, insurance, and local taxes, are estimated as a percentage of FCI [40]. Variable operating costs are composed of feedstock costs, utilities, and consumable inputs (e.g. catalysts and chemical inputs) and are based on information and data provided by industry partners. Labor requirements were provided by industry partners, and combined with national wage rate data from the U.S. Bureau of Labor Statistics for chemical manufacturing, wood product manufacturing, and biomass electricity plants, depending on the job description and labor requirements of the pathway. Overhead equal to 50% of wages is applied to account for associated costs including health insurance, office supplies, and travel expenses [40,42].

Key economic and financial accounting assumptions are summarized in Table 3. The project timeline is 20 years. Projects are assumed to be 50% loan financed on average, with a 10 year payback period and an 8% annual interest rate. Depreciation is calculated using the variable declining balance method. In this study, an inflation rate of 2.5% is applied to all future costs and revenues in cash flow calculations. The real discount rate is 10%, which is composed of the nominal discount rate of 7.5% and the 2.5% inflation rate.

All scenarios are treated as *n*th plant analyses, meaning that technologies are treated as mature and additional costs associated with a first-of-a-kind plant, such as special financing, equipment redundancies, research and development costs for new technologies, and extended startup periods are not included in accounting [43]. Construction is assumed to take place over a 3 year period with construction spending of 8%, 60%, and 32% in years 1, 2 and 3. There is a one year start-up period to account for the time it takes to attain long-run production rates, with 50% of full revenue generation and 50% of variable costs incurred, after which the full rate of production begins.

Economic analysis was conducted in Excel version 2013 (Microsoft Corporation, Redmond, WA, USA) using @Risk version 7.5 (Palisade Corporation, Ithaca, NY, USA), which is a commercial risk analysis software add-in for Excel.

2.3. Monte Carlo method

Monte Carlo simulation was conducted in Excel using the @Risk 7.5 add-in software. NPV outcomes for each pathway were estimated using simulations of one hundred thousand iterations each. In each iteration, values for key variables are drawn randomly from clearly defined probability distributions (e.g. single or multiple discrete values, normal distribution, triangular distribution, etc.) and aggregated simulation results are used to produce a probability distribution of NPV outcomes. Sensitivity analysis was also conducted using Monte Carlo simulation. This approach allows all random inputs to vary simultaneously across distributions that are based on the best available data, which provides more insightful results than sensitivity analysis conducted across a fixed percent change for each variable with all others held constant.

Key variables that were hypothesized to have the most uncertainty associated with them, whether because of observed volatility, technical uncertainty, lack of data, or subjectivity in selection, were defined as random variables with known probability distributions. Random variables in this analysis include: capital costs, biochar and biofuel conversion rates, product selling prices, feedstock price, natural gas costs, labor costs, proportion of project loan financing, and the discount rate. Base-case values, ranges, and data sources for these random variables are shown in Table 4, with triangular distributions used in simulations for all variables except biochar price. Triangular distributions are continuous probability distributions defined by a minimum value,

Table 4
Summary of inputs with uncertainty distributions.

Variable	Minimum	Base-case	Maximum	Distribution	Source
Discount rate	4%	10%	16%	Triangular	Petter and Tyner [12]
Biofuel price	$1.54 gal^{-1}	$2.48 gal^{-1}	$3.22 gal^{-1}	Triangular	Table 5
Biochar price	$ 71 t^{-1}	$1292 t^{-1}	$2,512 t^{-1}	Pert	Table 1
Feedstock price	$0 t^{-1}	$40 t^{-1}	$80 t^{-1}	Triangular	U.S. DOE [5]
Capital investment	−30%	Scenario-specific	+30%	Triangular	Peters et al. [40]
Biochar conversion rate	22%	27.4%	32%	Triangular	Industry Partners
Biofuel conversion rate	7%	9.3%	11%	Triangular	Industry Partners
Natural gas costs	−54%	Scenario-specific	+54%	Triangular	Described in text
Labor costs	−17.5%	Scenario-specific	+17.5%	Triangular	Described in text
Loan financing	0%	50%	100%	Triangular	Described in text

maximum value and mode, and are commonly used in business and finance when limited information is available to describe the true distributions of variables [44]. They are more likely than normal distributions to draw values from the tails of the distribution. Biochar price is defined with a Pert distribution, which is defined with a minimum, maximum, and mode like the triangular distribution, but with thinner tails [12]. This gives less weight to the extreme values of a wide distribution, such as the price range described in Table 1, where extreme values are reported but not well documented. All other input variables are assumed to be known without error and are treated as fixed values in the calculations (Table 3).

In addition to inflation, the discount rate includes a risk premium, which can vary with the riskiness of the investment, or the expectations of the investor for return on investment. To assess the impact of discount rate on results, it is defined across a triangular distribution ranging from 4% to 16% with a mean value of 10%. Because of the risk inherent with novel technologies, securing financing in the form of loans can vary from project to project and may depend on the existence of public policies that provide loan guarantees. Assumptions about project financing vary substantially in the literature (or are not even described in some papers). To account for the potential effect of the ability to secure loan financing on profitability, the proportion of total capital expenditure financed with loans ranges from 0% to 100%, with a mode of 50%. Capital costs are difficult to estimate and expected accuracy for the factorial method applied here ranges from ± 20% to ± 30% [40]. To quantify and assess the impact of this uncertainty, TCI is input has an uncertain distribution ranging from −30% to +30% of the estimated TCI for each scenario. The selling prices of biofuel and biochar are both defined across distributions of values to represent a wide range of potential future market conditions. As discussed in the Introduction, there is considerable uncertainty associated with the future of biochar markets and associated prices. Although liquid transportation fuels do not suffer from this same level of uncertainty, historical prices have been somewhat volatile, suggesting a similar range of prices is possible in the future. The price range for biofuel of $1.54 gal^{-1} to $3.22 gal^{-1} ($0.41 L^{-1} to $0.85 L^{-1}) was defined using a weighted average of premium gasoline, diesel, and heating oil prices from 2005 to 2017, which was weighted based on the biofuel production fractions most closely represented by these fuel grades (Table 5). In addition, the analysis includes a separate "RINs scenario" to evaluate the effect of RINs on project performance. In the RINs scenario simulation, biofuel price is a random variable as described, but a fixed RINs value of $2.49 gal^{-1} ($0.66 L^{-1}) is added to the price. This value is based on the spot market price for cellulosic RINs for March 2018, which was $2.49 gal^{-1} ($0.66 L^{-1}, [45]).

The price range for biochar has a minimum of $71 t^{-1} and a maximum of $2512 t^{-1}. The base-case price of $1292 t^{-1} is equal to the mid-point of these values. The minimum biochar price of $71 t^{-1} is based on the value of energy content of biochar relative to coal energy content and price, which was determined to be a logical minimum based on previous studies and the comparison of solid fuel uses to soil amendment for low value agricultural crops [26]. The average energy content of Central Appalachian coal is 27.57 MMBtu t^{-1} (12,500 Btu lb^{-1}), and its most recent commodity spot price is $67.35 t^{-1}, which is equal to $2.44 MMBtu^{-1} [46]. Based on laboratory testing of three biochar samples from similar pyrolysis systems, the average energy content of biochar produced using coniferous feedstock was estimated to be is 29.15 MMBtu t^{-1} (13,222 Btu lb^{-1}). Assuming the same value per MMBtu as coal, the price of biochar based on energy content is $71.13 t^{-1}. The maximum value is equal to the highest value found in biochar trade organization reports. This wide range is congruent with price reporting in the literature (Table 1).

The cost of feedstock can vary widely depending on geographic and environmental factors, upstream logistics costs associated with harvesting and transportation, and market value for other uses [47]. The U.S. Department of Energy Billion-Ton Report [48] considers a range of feedstock prices from $36 to $73 per tonne. The base-case delivered cost of wood chips in this paper was assumed to be $40 per dry tonne, with a range from $0 to $80 per dry tonne. In our accounting, the minimum feedstock price of $0 represents a scenario in which the feedstock is procured from a waste biomass stream, but still incurs on-site processing costs associated with chipping, screening and drying feedstocks to appropriate specifications. This low gate price is included for two reasons: (1) biomass waste management is one of the main benefits of biochar production [7,23], and (2) the on-site use of biomass residues from wood products manufacturing is commonly cited as a reason to co-locate biochar production with such operations [49]. With feedstock assumed to be delivered with between 15% and 50% moisture content, 54% less energy is required to dry the lowest moisture feedstock than feedstock of the mean moisture content of 32.5%, and 54% more energy is required to dry the highest moisture feedstock. Therefore, a range of natural gas cost ranging from 46% to

Table 5
Price information used in determining biofuel selling price.

Corresponding fuel product grade	Minimum Price gal^{-1}	Mean Price gal^{-1}	Maximum Price gal^{-1}	Biofuel production fraction	Corresponding fossil fuel price source
Premium Gasoline	$1.74	$2.56	$3.27	48.3%	Premium gasoline. U.S. wholesale price by refiners [58]
Diesel	$1.35	$2.42	$3.28	32.2%	No. 2 diesel. U.S. wholesale price by refiners [59]
Heating Oil	$1.35	$2.35	$3.14	19.5%	Heating oil. NY Harbor future contract 1 [60]
Weighted Average	$1.54	$2.48	$3.22	100%	Weighted average based on production fractions

All prices are based on data for years 2005–2017 and are presented in 2015 USD.

154% of mean costs was constructed as a direct measure of costs avoided or incurred due to feedstock delivered with lower or higher moisture content, respectively.

To account for uncertainty in production related to the relative novelty of these technologies, biochar and biofuel conversion rates are considered random variables, with distribution parameters shown in Table 4. The upper limits of 11% conversion rate for biofuel and 32% for biochar are slightly lower than the maximum conversion rates observed during pilot scale operations optimized for coniferous feedstocks. The distribution of labor cost was defined based on the regional variation in total hourly employer compensation cost across the four major regions of the U.S to account for the one of the potential effects of choice of location in facility siting. According to the U.S. Bureau of Labor Statistics, total compensation in the most expensive region (Northeast) is 35% higher than in the least expensive region (South), so the range of labor cost is distributed around the estimated amount for each scenario, with the maximum being 35% larger than the minimum [50].

3. Results

3.1. Project costs

A summary of financial and production characteristics of the technologies is presented in Table 6. Annual operating costs are also shown in Fig. 2. Although the capital costs are the same whether the auger system is used for biochar-biofuel coproduction or biochar-only production, the operating costs are reduced substantially when biofuel production ceases, lowering utilities and labor costs and eliminating natural gas and catalyst use. The price received for each gallon of biofuel must therefore exceed the increased cost associated with producing each gallon in order for biofuel production to be preferable to a biochar-only configuration of the auger system. By virtue of having lower capital costs and lower operating costs compared to the auger system, the hearth system can produce biochar at lower cost than the auger system operated in the biochar-only configuration. However, the hearth system does not have the capacity to produce biofuel when market conditions are favorable to do so.

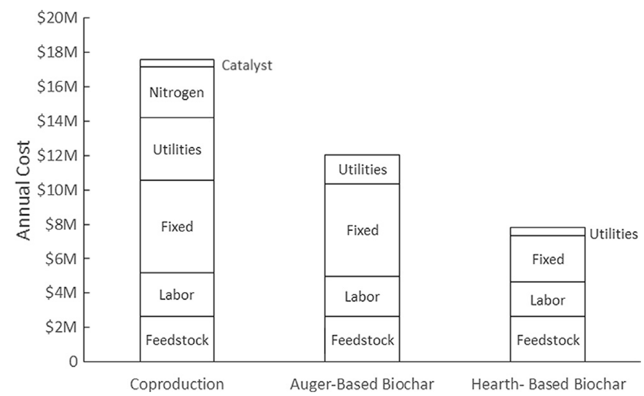

Fig. 2. Operating costs by scenario.

Table 6
Cost and production characteristics summary.

	Auger-based coproduction	Auger-based biochar-only	Hearth-based biochar
Total Capital Investment	**$76.7 million (M)**	**$76.7 M**	**$38.7 M**
Fixed Capital Investment	$69.0 M	$69.0 M	$34.7 M
Working Capital[a]	$6.9 M	$6.9 M	$3.5 M
Land[b]	$836 thousand (k)	$836 k	$504 k
Annual Fixed Operating Expenses	**$5.4 M**	**$5.4 M**	**$2.7 M**
Maintenance[c]	$3.8 M	$3.8 M	$1.8 M
Insurance and Taxes[d]	$1.5 M	$1.5 M	$774 k
Annual Labor Expense	**$2.6 M**	**$2.4 M**	**$2.0 M**
Annual Variable Expenses	**$6.4 M**	**$1.7 M**	**$474 M**
Natural Gas	$1.98 M	$0	$356 k
Electricity	$1.63 M	$1.63 M	$111 k
Diesel	$39 k	$39 k	$5.9 k
Catalyst	$459 k	$0	$0
Nitrogen	$2.93 M	$0	$0
Water	$9.7 k	$9.7 k	$9.7 k
Production Characteristics[e]			
Annual Feedstock Consumption	65.7 k t	65.7 k t	65.7 k t
Annual Biofuel Production	1.8 M gal [6.8 M L]	0 gal	0 gal
Annual Biochar Production [f]	17.7 k t	17.7 k t	17.7 k t
Biofuel Conversion Rate	9%	0%	0%
Biochar Conversion Rate	27%	27%	27%
Annual Operating Time	6570 h	6570 h	6570 h

[a] Working capital is equal to 15% of TCI [40].
[b] Land is 6% of purchased equipment cost [40].
[c] Maintenance is accounted for as 5% of TCI [40].
[d] Insurance and local taxes are estimated as 2% of TCI [40].
[e] Some production characteristics vary across a range of values in Monte Carlo Simulation. Values in this table represent base-case levels.
[f] Biochar production amounts take into account 15% loss in production.

3.2. NPV distributions

Distributions of NPV outcomes from the Monte Carlo simulations are presented in Fig. 3 and summarized in Table 7. Across the assumed ranges of input values for random variables, hearth-based biochar production has the highest mean NPV at $45.1 million, with 90% of outcomes between −$34 million and $139 million. Under base-case price conditions, the mean NPV of auger-based biochar-biofuel coproduction is −$24.2 million, with 90% of outcomes falling between −$114 million and $65 million. In order for biochar-biofuel coproduction to break-even (NPV = 0), the biofuel price would need to be at least $4.31 gal^{-1} ($1.14 L^{-1}). Under the distributions in Table 4, if fuel production is idled for the entire 20 year project period, the NPV of this pathway improves to −$15.7 million, with 90% of outcomes between −$102 million and $73 million. Results suggest that hearth-based biochar production has the highest likelihood of financial success given the information and pricing used in simulations. Hearth-based biochar production has the smallest probability of loss, with 19.6% of outcomes resulting in NPV less than zero. Over the 20 year project period, an auger-based biochar-only operation has a 62.0% probability of a financial net loss. Coproduction has a 67.5% chance of a net loss. The introduction of a RINs credit equal to the current market value of $2.49 gal^{-1} ($0.66 L^{-1}) significantly improves the financial performance of co-production, generating a mean NPV of $7.8 million, with 90% of values between −$76 million and $100 million and a 50% probability of profitability.

3.3. Biochar and biofuel prices

Fig. 4 panel A shows the relationship between biochar price and NPV. The point where the upward sloping lines cross the x-axis represents the minimum biochar price at which each scenario breaks even. The break-even biochar price is lowest for the hearth system at $838 t^{-1}. Biochar price must be at least $1425 t^{-1} for the auger system biochar-only operation to break-even. When the biofuel price distribution is centered on $2.48 gal^{-1} ($0.66 L^{-1}), the break-even biochar selling price is $1504 t^{-1} for auger-based biochar-biofuel

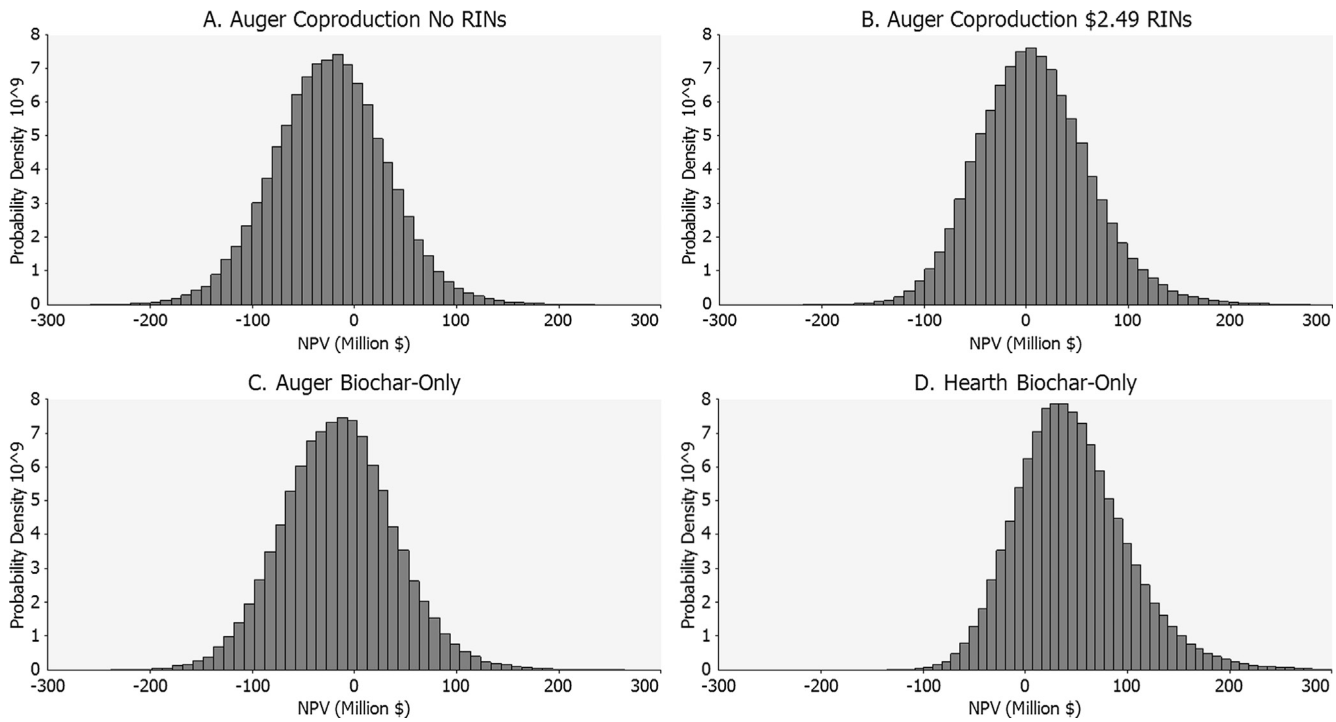

Fig. 3. NPV distributions.

Table 7
Summary of results.

	Coproduction (No RINs)	Auger biochar-only	Coproduction ($2.49 RINS)	Hearth Biochar
Mean NPV	−$24.21 M	−$15.71 M	$7.76 M	$45.13 M
Min Biochar Price	$1504 t^{-1}	$1425 t^{-1}	$1204 t^{-1}	$838 t^{-1}

coproduction. At this biofuel price, the NPV of a biochar-only operation is higher than the NPV of coproduction, regardless of biochar price. At a biofuel price greater than $3.08 gal^{-1} ($0.81 L^{-1}) additional revenues from producing biofuel are greater than the additional costs associated with producing it. When the price of biofuel is below $3.08 gal^{-1} ($0.81 L^{-1}), the system is more profitable producing biochar only. At biofuel prices above $3.08 gal^{-1} ($0.81 L^{-1}), the NPV of coproduction becomes larger than biochar-only suggesting the plant should resume coproduction.

Fig. 4 panel B shows the combinations of biofuel and biochar prices that result in NPV = 0. The break-even price of $838 t^{-1} for hearth-based biochar is not affected by biofuel price and is represented by a horizontal line. For the auger system engaged in coproduction, the biochar price required to break-even is dependent on the biofuel price, becoming lower as the biofuel price increases. The minimum break-even biofuel price is $4.31 gal^{-1} ($1.14 L^{-1}) under the base-case biochar price of $1292 t^{-1}. Below $3.08 gal^{-1} ($0.81 L^{-1}) biofuel production is idled and the downward sloping line becomes horizontal, indicating no relationship between biofuel and biochar prices below that point. The ability to generate revenue with biochar is clearly essential to the profitability of this technology, with break-even NPV not achieved at a biochar price of zero until biofuel prices reach $14.92 gal^{-1} ($3.94 L^{-1}). The downward sloping break-even line for coproduction crosses the horizontal line for hearth-based biochar break-even at a biofuel price of $7.92 gal^{-1} ($2.09 L^{-1}). This is the minimum biofuel price for coproduction to be more profitable than hearth-based biochar production.

Based on the difference between the observed average price for transportation fuels from 2005 to 2017 ($2.48 gal^{-1}, or $0.66 L^{-1}), and the prices at which the NPV of coproduction surpasses the NPV of the biochar-only operations ($3.08 gal^{-1} [$0.81 L^{-1}] for auger biochar-only and $7.92 gal^{-1} [$2.09 L^{-1}] for hearth-based biochar), minimum RINs prices of $0.59 gal^{-1} ($0.16 L^{-1}) and $5.43 gal^{-1} ($1.43 L^{-1}) would be required for coproduction to financially outperform auger biochar-only and hearth-based biochar, respectively. As of March 2018, spot market prices for cellulosic RINs were $2.49 gal^{-1} ($0.66 L^{-1}, [45]). Therefore, based on recent market prices, the RINs price needed to bridge the gap with auger biochar production seems realistic and within the realm of possibility. The much larger price needed to bridge the gap with hearth biochar production is approaching twice the market price of liquid fuels, and is substantially higher than the current RINs market price. With an assumed $2.49 gal^{-1} ($0.66 L^{-1}) RINs credit, the plant would always choose to undertake coproduction, and mean NPV becomes positive at $7.7 million (Table 7, Fig. 3).

Operators of facilities with coproduction capability are faced with the decision of when to produce biofuel and when to reduce operating costs by idling that capacity in favor of biochar-only operation. To maximize profits, with the base-case distribution of biofuel prices ranging from $1.54 gal^{-1} to $3.22 gal^{-1} ($0.41 L^{-1} to $0.85 L^{-1}), the plant would rarely produce biofuel. However, to illustrate the value of maintaining flexibility in the decision of whether or not to produce fuel, if the price range was equally distributed above and below the $3.08 gal^{-1} ($0.81 L^{-1}) cutoff price and the decision of which production strategy to pursue was made on an annual basis (rather than choosing one strategy for the entire 20 year project period), NPV could be improved by $3.1 million, from −$15.9 million to −$12.8 million.

3.4. Sensitivity analysis

Simulation-based sensitivity analysis was used to compare the relative magnitudes of the effects of key variables on NPV. This approach allows effects to be considered across a range of potential future market and operating conditions. The six most-influential variables for each production scenario are presented in Fig. 5. While there is some variety

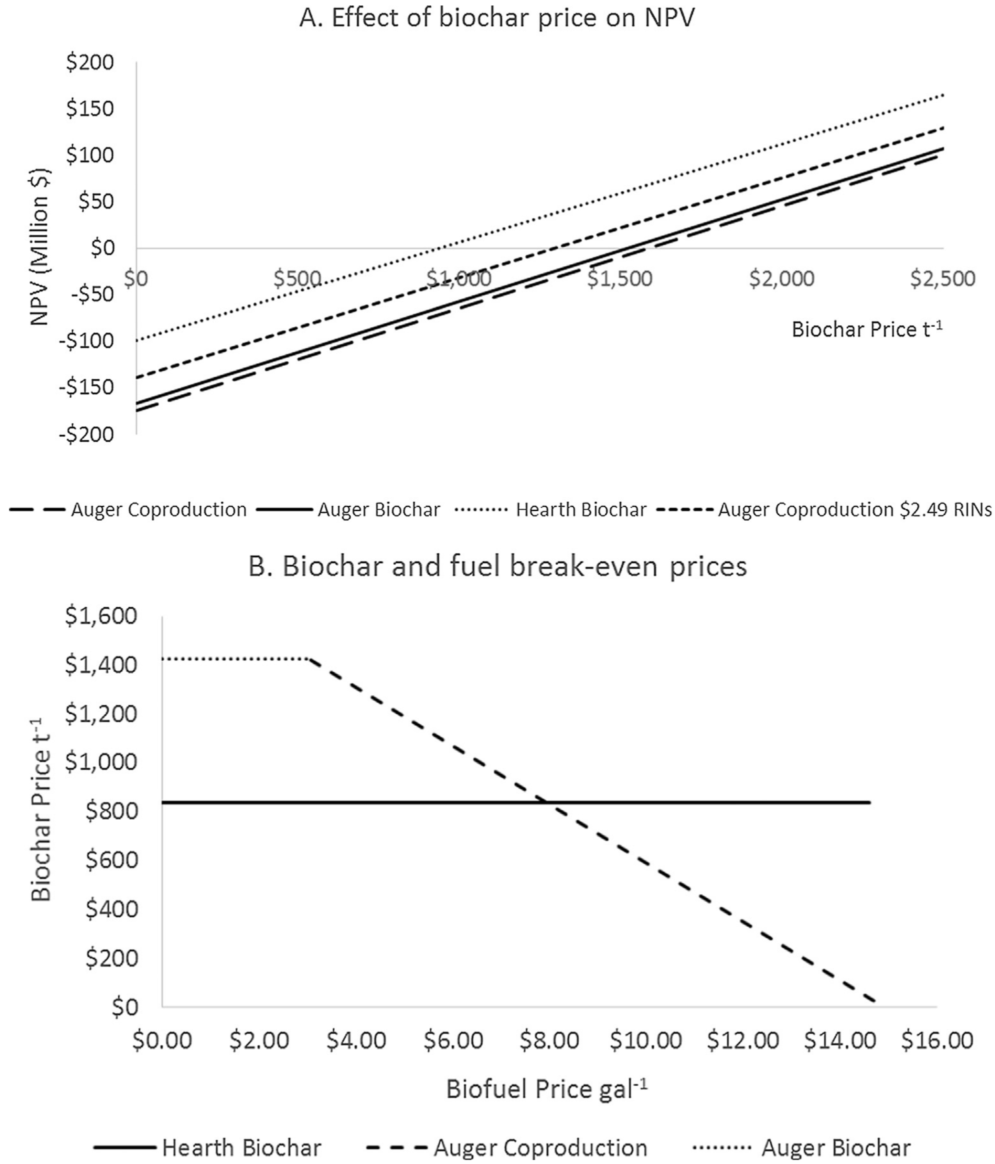

Fig. 4. Panel A. The effect of biochar price on NPV. Panel B. Biochar and Fuel Minimum Selling Price for NPV = 0. *Note*: With RINs, the Auger Coproduction line in Panel (B) would shift left by the amount of RINs.

in the collection of most-influential variables across scenarios, selling price of biochar has the largest effect on mean NPV by a wide margin for all cases. Even for biochar-biofuel coproduction, the price of biochar has an outsized effect on NPV because of a combination of the high conversion rate of biochar relative to biofuel (27.4 versus 9.3% of feedstock mass, respectively, in the base case), and the large range of the biochar price distribution. This result illustrates the large impact that uncertainty and volatility in current and future biochar prices is likely to have on new biochar enterprises and, by extension, associated risk, cost of capital, and growth of this industry. For the coproduction scenario, biofuel price has the second largest effect on NPV over the entire range of prices from the lowest price with no RINs to the highest price plus a $2.49 gal^{-1} ($0.66 L^{-1}) RINs credit ($1.54 gal^{-1} to $5.71 gal^{-1}, or $0.41 L^{-1} to $1.51 L^{-1}), assuming the RINs credit increases net revenues as described.

Biochar conversion rate is one of the more impactful variables in all cases, suggesting that future technological advances can have a meaningful impact on reducing minimum fuel selling prices, but the effect of conversion rate on NPV is small compared to the effect of product market prices. Furthermore, recall that high biochar conversion rates are often associated with lower total carbon content of biochar, which has an impact on product characteristics and price. Variation in capital costs appears to be less influential on financial outcomes than might be expected, with a 30% change in capital costs ranking sixth, fourth, and fifth for auger coproduction, auger biochar-only, and hearth biochar, respectively. Discount rate had a strong effect on the NPV of the hearth system, but not on the auger system, likely as a result of the higher value of future revenues being discounted for the hearth system.

The cost of feedstock was the third most influential variable for auger biochar-only, and fourth most influential for auger coproduction and hearth biochar. The cost of natural gas for drying feedstock was not one of the six most-influential variables for any of the scenarios. Labor costs were amongst the six most influential variables for hearth biochar production, but not for either of the auger-based scenarios. The percent of capital costs financed through loans was in the top six only for the auger biochar-only scenario, with increased amounts of loan financing associated with increased NPV. However, the effects of both labor cost and proportion loan financed were small relative to other variables.

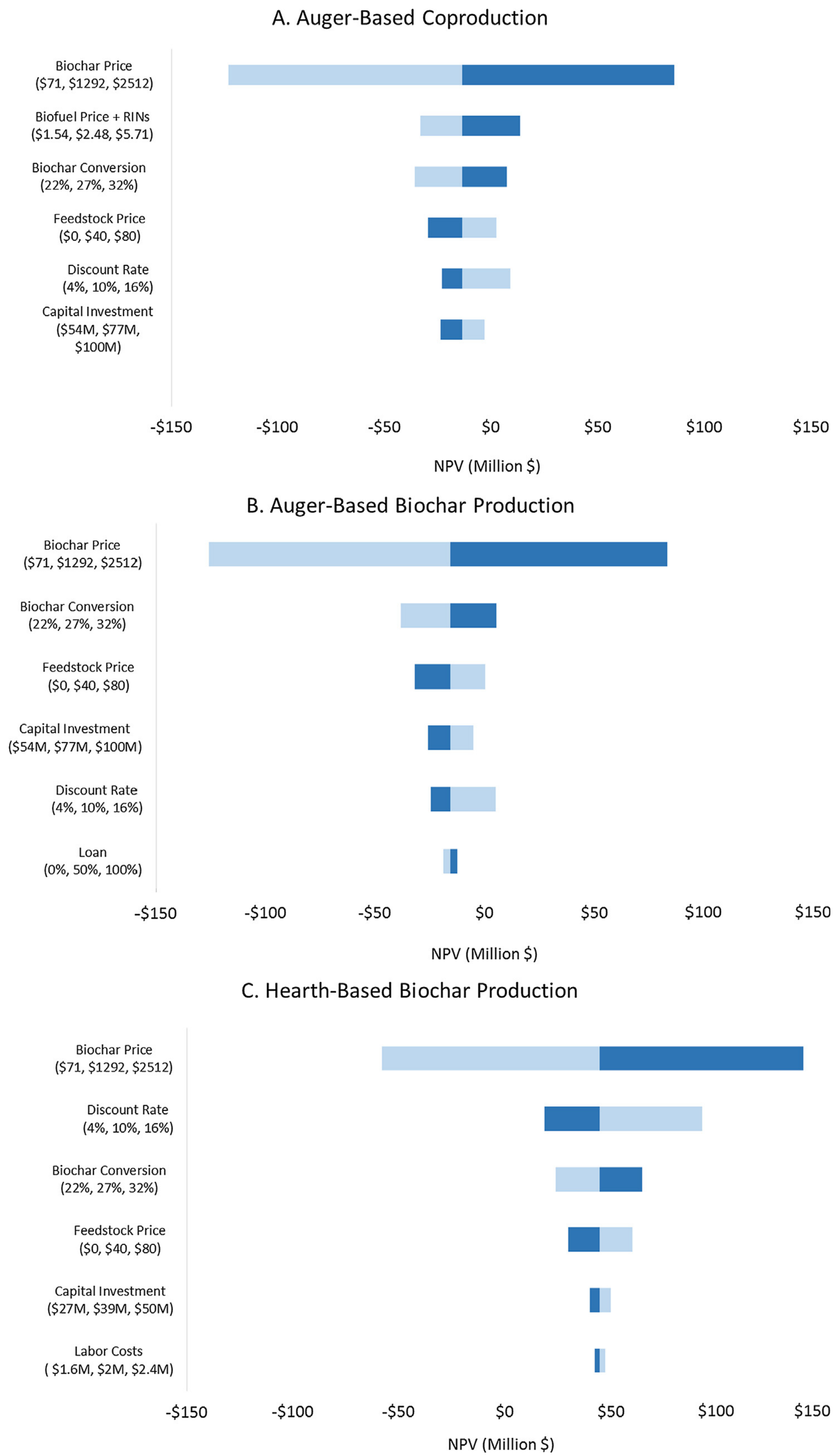

Fig. 5. Sensitivity tornados that illustrate the sensitivity of NPV to the random variables in the analysis. Dark shaded bars indicate an increase in value of the input variable and light shaded bars indicate a decrease in input variable value over the base case value.

4. Discussion

Though the important effect of feedstock price is often stressed in analyses oriented toward biomass supply logistics, our results suggest that the effect of product market conditions is much stronger. For example, assuming the feedstock was delivered to the facility for \$0 t^{-1}, which represents a waste management scenario, the coproduction scenario still returns a negative NPV of −\$5.5 million at the average historic market biofuel price, compared to the base case NPV of −\$24.2 million. On the other end of the feedstock cost range, the profitability of hearth-based biochar is reduced from \$45.1 million to \$27.3 million NPV at the high end of the assumed feedstock price range (\$80 t^{-1}).

These results shed light on the barriers that are likely to limit the ability of firms to profitably produce cellulosic biofuels, contributing to the inability to meet blending targets set by public policy. Although numerous factors impact the financial outcomes of these operations, by far the largest predictors of financial success are market prices for outputs. This fact is sometimes overlooked in analyses primarily concerned with raw material supply and cost of production or the technical aspects of production pathways, such as catalyst efficiency. Coproduction has significant appeal in the face of high price volatility and uncertainty in biochar markets because profitability is not dependent solely on the market for a single product. However, as these results suggest, biochar-only operations with lower capital costs may prove more profitable except under high fuel prices and favorable RINs conditions.

The minimum break-even coproduction biofuel price is \$4.12 gal^{-1} (\$1.09 L^{-1}) and although this is above the maximum fuel prices reached at the beginning of the decade, it is well within the range of what could be garnered with additional revenue associated with RINs credits. However, in a coproduction environment biofuel production is highly dependent on selling the biochar coproduct, and considerable uncertainty still exists with regards to biochar markets and prices. With no market for biochar (\$0 t^{-1}), minimum fuel selling price jumps to over \$14.00 gal^{-1} (\$3.70 L^{-1}), which is unrealistic even at historically high fuel prices and maximum RINs values. This analysis shows that financial outcomes of biofuel and biochar coproduction can be improved somewhat though flexible decision making in response to changes in market conditions.

Although the financial risks associated with investment in a biofuel production facility can be offset through public grants, loans, and loan guarantees, the small impact of capital costs relative to product prices suggests that policies providing price support or long-term price stability, such as off-take agreements, are likely to have the largest positive impact on the growth of the cellulosic biofuel industry. This is consistent with previous findings by the small number of techno-economic analyses that quantify the effect of product price volatility and uncertainty on financial outcomes [12–13]. Production targets and RINs fill this need to some degree. However, if low fossil fuel prices persist and push down prices for biofuels in the long run, shifting away from biofuel production to single-product biochar production is likely. In this case, investment in less capital-intensive technologies would be more profitable because they offer a pathway to biochar production with less financial risk and a lower cost of production. This is an important consideration for biochar, which will have uncertain markets until agricultural benefits are established or additional sources of financial value, like the carbon credit markets that exist in the European Union, emerge in the U.S. in the future.

5. Conclusion

Results of this techno-economic analysis have provided support for our hypothesis that the market prices of products have the largest effect on the financial performance of both biofuel-biochar coproduction and stand-alone biochar production. In a coproduction scenario, biochar has the potential to support biofuel production under certain market conditions, and also offers the operational flexibility to reduce costs by allowing the idling of biofuel production when fuel prices are unfavorable. However, heavy reliance on biochar sales as a necessary ingredient for the financial success of biofuels operations is likely to remain risky until more robust markets and more stable prices for biochar emerge. These findings have timely and insightful implications for informed decision making by both industry and policy makers.

In addition, our findings that the price producers receive for biofuel and biochar dominates the effect of other key input variables on the financial outcomes of such enterprises is a relevant finding for future techno-economic studies. Past techno-economic studies have more commonly focused on factors such as conversion rates, feedstock cost, and capital costs, often overlooking the important role that price has in determining the financial viability of these technologies. As public policy evolves in countries interested in promoting renewable fuels, pricing may increasingly include economic incentives like RINs and carbon credits. We believe that the markets for biofuel and biochar are deserving of more attention in future studies, and that simulation methods like those used in this study should be the expectation rather than the exception for such studies.

We have identified that there is substantial uncertainty and volatility in biochar and biofuel prices that make future prices difficult to predict, and that these aspects of pricing can have significant impacts on project performance. This reality can make planning for and financing bioenergy facilities difficult. The results of this paper can help facilitate growth in the cellulosic biofuel and biochar industries by shedding light on strategies that maximize financial success and minimize risk in the face of volatile biofuel markets and uncertain biochar prices.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.apenergy.2018.08.085.

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