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Financial sustainability for a lignocellulosic biorefinery under carbon constraints and price downside risk

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HIGHLIGHTS

- Stochastic program determines production, risk management strategy for biorefinery.
- Scheduled production commitment decreases as tiered carbon tax rate increases.
- Risk averse producers prefer the forward contract as a mode of product sales.
- Time varying forward prices and inventory enable producers to increase profits.
- Inventory is beneficial to producers, below the threshold for inventory costs.

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ABSTRACT

The development of an environmentally sustainable and financially viable replacement for fossil fuels continues to elude industry investors even though the benefits of replacing them is undisputed. Biofuels are among the promising replacements for fossil fuels. However, the development and production process for bio-based fuels creates uncertainty for industry investors. In order to increase process profitability, financial tools can be implemented with current technology. This paper proposes the use of forward contracts to mitigate risk, and it also considers the impact of carbon tax constraints and price uncertainty. Specifically, a stochastic optimization approach is implemented to develop strategies, which increases the net present value (NPV) of a production facility through determination of an optimal production schedule, as well as the creation of a portfolio of forward contracts to reduce product price risk. Results of numerical case studies show that if the policymaker is risk averse, production is higher in the early planning period rather than the later period. This paper also investigates the ability to maintain inventory in order to create additional financial benefit.

1. Introduction

Production of fuel from biomass feedstock faces uncertainty in technology, logistics and market development, thus creating challenges for the industry investor [1]. Non-food feedstocks such as corn stover and perennial grasses have the most potential to be adopted in the future generation of biofuel facilities. In order to develop a viable biofuels industry, it is necessary to overcome challenges in process technology, and to determine optimal platform design. In addition, the financial viability of the process are sufficiently unstable that investment in the industry will require succinct understanding of market dynamics, and careful management of financial risks. Financial derivatives, such as forward and swap contracts are widely used in the energy industry to hedge against the price downside risk [2]. Moreover, the price of biofuel based energy products does not take into account the cost of greenhouse gas emissions resulting from their production [3]. National governments can play a role in accomplishing a deduction of greenhouse gas emission by imposing carbon emission tax [4], thereby increasing the production cost of a biorefinery. According to [5], although a biorefinery is generally recognized as a tax credit earning facility thanks to its greenhouse gas emission reduction, this is not universally true due to the choice of calculation criteria. As a result, it is necessary to consider the production schedule under stringent carbon tax policy.

The main purpose of this study is to determine an optimal production schedule and ethanol forward contract strategy for a

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Nomenclature

Sets
- i chemical components
- j operating unit
- r unit carbon tax price regions
- l ethanol spot price scenario index
- q month index

Parameters
- M_i molecular weight of chemical component i
- Φ_i composition of chemical component i in feedstock
- T_j required temperature in operating unit j
- Cp_i heat capacity of chemical component i
- $Price_i$ price of chemical component i
- H_i enthalpy of chemical component i
- $Purindex_j$ purchasing cost index for operating unit j
- a_j installing cost multiplier for operating unit j
- b_j base price for operating unit j
- $ratio_r$ upper bound ratio of greenhouse gas emission for Region r
- $unit_r$ unit carbon tax price for Region r
- FOC_r process fixed operating cost corresponding to Region r
- $\underline{fs}$ lower bound of the feedstock's hourly availability
- $\overline{cap}$ production capacity of the process
- $Boil$ boiler efficiency
- $Turbo$ turbo generator efficiency
- η electricity surplus ratio
- tax tax rate
- IRR internal return rate
- $time$ process lifetime
- K user defined lower bound for NPV
- F_q forward contract price for month q
- $P_{l,q}$ ethanol spot price for month q and scenario l
- $P_{ethanol}$ ethanol historical mean spot price
- $cost$ unit inventory cost
- $\overline{S}$ lower bound for ethanol spot price of the future month
- $\underline{S}$ upper bound for ethanol spot price of the future month

Variables

First stage variables

Binary variables
- y_r indicator variable, carbon emissions in Region r

Continuous variables

Mass balance variables:
- $f_{i,j}$ flow of chemical component i to operating unit j
- $totalC$ total amount of organic compound discharged to water
- $biogas$ total amount of biogas generated for electricity generation
- $genCH_4$ total amount of CH_4 generated
- $genCO_2$ total amount of CO_2 generated
- $genNO_x$ total amount of NO_x generated
- fs feedstock used
- $prod$ the amount of ethanol produced
- GHG total amount of Greenhouse gas produced

Energy balance variables:
- Q_{h_j} energy needed to heat the operating unit j
- Q_{c_j} energy produced from operating unit j
- Q_{fc} energy produced from cooling the final product

Utility variables:
- HP high pressure steam required for heating
- LP low pressure steam required for heating
- CW cold water required for cooling
- $electricity$ total amount of electricity generated
- $steam$ total steam generated

Cost variables:
- $sales$ revenue earned from ethanol and surplus electricity
- VOC variable operating cost
- FCC fixed capital cost
- WC working capital
- IC equipment installing cost
- PC equipment purchasing cost
- TDC total direct capital
- TIC total indirect capital
- NI annual net income for the plant
- NPV net present value

Second stage variables

Continuous variables
- x_q production level for month q
- w_q the amount of ethanol sold in forward market for month q
- c_q the amount of ethanol sold in spot market for month q
- I_q inventory levels for month q
- $carbon\_tax_{l,q}$ carbon tax collected for month q and scenario l
- $revenue_l$ quarterly revenue for scenario l
- NI_l quarterly net income for scenario l
- NPV_l net present value for each scenario
- α value at risk
- z_l an auxiliary variable defined in cVaR constraint

biochemical lignocellulosic biorefinery, in order to maximize its net present value under an acceptable level of risk. Throughout this study, the process model developed in [6] is used. In addition, the forward contracts are assumed to be readily available between the biorefinery and its counter-party. The forward contracts' strike prices are determined empirically through historical spot price average. The contract pricing problem is not addressed in this paper, but is discussed in the future work.

The paper is organized as follows. Section 2 provides a literature review of lignocellulosic biorefinery process optimization, the study on environmental and financial analysis of a lignocellulosic biorefinery, and the work on risk management in energy industry. Section 3 includes the description of the process parameters and assumptions, the formulation of the optimization model, and the solution procedure. The results are discussed in Section 4. Finally, in Section 5 the conclusions are drawn.

2. Literature review

2.1. Integrated lignocellulosic biorefinery process optimization

A typical lignocellulosic biorefinery includes feedstock storage and handling, pretreatment, saccarification and fermentation, product, water, and solid recovery, as well as waste water treatment [7]. For each step, several alternative technologies are available. A complete design of a biorefinery process model is achieved by choosing one technology for each of these steps while understanding the implications of each selection for the overall system performance. To date, researchers have proposed various methodologies to optimize the production process under specific objectives.

For example, Zondervan et al. [8] have established a biorefinery optimization model for a multi-product system. They consider a production network of 72 processing steps that can be used to pro-