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Life cycle optimization for sustainable design and operations of hydrocarbon biorefinery via fast pyrolysis, hydrotreating and hydrocracking

Berhane H. Gebreslassie, Maxim Slivinsky, Belinda Wang, Fengqi You*

Department of Chemical and Biological Engineering, Northwestern University, Evanston, IL 60208, USA

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ABSTRACT

This paper addresses the optimal design and operation of hydrocarbon biorefinery via fast pyrolysis, hydrotreating and hydrocracking of hybrid poplar feedstock under economic and environmental criteria. The hydrocarbon biorefinery encompasses fast pyrolysis for crude bio-oil production, upgrading of the bio-oil through hydrotreating, separation and hydrocracking of long chained hydrocarbons into gasoline and diesel range products, and steam reforming for hydrogen production. We propose a bi-criteria nonlinear programming (NLP) model that seeks to maximize the economic performance measured by the net present value (NPV) and to minimize the environmental impacts. The environmental objective is measured with the global warming potential (GWP) metric according to the life cycle assessment procedures, which covers gate-to-gate environmental impacts of the hydrocarbon biorefinery. The multiobjective NLP model simultaneously determines the production capacity, size of each process units, operational conditions, the flow rates of species and streams at each stage of the process, hydrocarbon biofuel yields, and consumption rate of feedstock, steam, electricity, and natural gas. The bi-criteria NLP model is solved with the ε-constraint method, and the resulting Pareto-optimal curve reveals the trade-off between the economic and environmental dimensions of the sustainable hydrocarbon biorefinery. The optimization results reveal that the unit production cost of the hydrocarbon biofuels is \$2.31 per gallon of gasoline equivalent (GGE) for the maximum NPV solution and \$3.67/GGE for the minimum GWP design. The corresponding greenhouse emission is 8.07 $kgCO_{2\text{-eq}}$/GGE.

1. Introduction

The global economy is heavily reliant on the supply of petroleum based fuels, which are limited resource, environmentally unfriendly, and potentially unstable leading to political vulnerability. In recent years, researchers have put much effort into the development of sustainable and environmentally benign biofuels. Hydrocarbon biorefinery technologies, which convert a wide variety of cellulosic materials to liquid transportation fuels, have been considered as promising approaches to overcome the market barrier resulting from the current vehicle technologies and fuel distribution infrastructure (National Advanced Biofuels Consortium, 2012; The National Academies, 2009). In this respect, the U.S. government proposed the Energy Independence and Security Act of 2007 (Public Law 110-140, 2007) that requires the total amount of biofuel production to increase from 4.7 billion gallons per year in 2007 to 36 billion gallons per year by 2022. Therefore, considering the short time to achieve the goal and the investment on new infrastructures, it is appealing to investigate infrastructure-compatible fuels. Hydrocarbon biofuels provide vehicle performance similar to or better than their conventional counterparts (National Advanced Biofuels Consortium, 2012). Moreover, they can use the current fuel distribution and utilization infrastructure that includes pipelines, pumping stations, and vehicles without significant changes (National Advanced Biofuels Consortium, 2012; You & Wang, 2011). The main advantage of hydrocarbon biofuels is that they are more sustainable than their petroleum counterpart, because they produce less life cycle environmental impact and reduce the consumption of nonrenewable primary energy resources. Furthermore, hydrocarbon biorefinery via fast pyrolysis followed by hydrotreating and hydrocracking can potentially produce hydrocarbon biofuels at lower production cost, and environmental emissions compared to other biomass conversion pathways. Hence, the goal of this work is to design and optimize the hydrocarbon biorefinery via fast pyrolysis, hydrotreating and hydrocracking under economic and environmental criteria to ensure they are economically competitive and environmentally sustainable.

During the past decade, considerable efforts have been made to convert biomass to chemicals and liquid fuels. Experimental studies have been undertaken on biofuel productions (Maschio,

* Corresponding author. Tel.: +1 847 467 2943; fax: +1 847 491 3728.
E-mail address: you@northwestern.edu (F. You).

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Nomenclature

Sets/indices

b	set of emissions in the life cycle emission inventories
el	set of elements in biomass
J	set of chemical species indexed by j
L_{eq}	set of equipment indexed by l
$st(j)$	set of species j in stream st
q	set of biofuels product

Parameters

$CEPCI$	chemical engineering plant cost index
ECC_b^l	base case purchase cost of equipment l in \$MM
fsc	unit price of biomass feedstock in \$/kg
$INCP$	percentage of investment incentive
$INCM$	maximum allowable investment incentive in \$MM
K_{blg}	cost of buildings factor including services
K_{cns}	cost of construction factor
K_{ctg}	project contingency factor
K_{elc}	electrical systems cost factor
K_{eng}	engineering cost factor
K_{pei}	equipment purchase installation factor
K_{pp}	cost of piping factor
K_{icf}	cost instrumentation and controls factor
K_{lg}	legal and contractors fee factor
K_{lnd}	cost factor of land
K_{om}	O&M cost as percentage of the total equipment purchase cost
K_{wcp}	working capital cost factor
$LCIE_b^{cat}$	life cycle emissions inventory of chemical b per functional unit associated with emissions source category *cat*
$Mw_{j/i}$	molar mass of species j or element i
nC	number of carbon atoms
nH	number of hydrogen atoms
nOx	number of oxygen atoms
ngc	natural gas price in \$/kg
pc	unit cost of power in \$/kWh
p_q	the market price of biofuels q in \$/gallon
Q_{stm}	heat per kmol of steam
R_{tax}	income tax
R	reactor product distribution of species
S	split fraction of species and streams
sf	sizing factor
r	conversion rate of species in water gas shift reaction
$stmc$	unit cost of steam in \$/kmol
T_{op}	annual operating hours of the biorefinery h/year
t_{ls}	lifespan of the hydrocarbon biorefinery in years
v_{inc}	the unit value of volumetric incentive in \$/gallon of biofuels produced
x	mole fraction
Π_{cat}	the damage factor that accounts for the GWP associated with chemical species b

Variables

AGP	annual gross profit in \$MM
$APAT$	annual profit after tax in \$MM
$CtCh$	annual catalyst and chemical cost in \$MM
$ECCl$	base case purchase cost of equipment l in \$MM
F	molar flow rate
$FIXC$	fixed O&M cost in \$MM
FSC	feedstock cost in \$MM
$FSCtrans$	feedstock cost transportation cost in \$MM
$\bar{F}$	total molar flow rate
GWP	global warming potential in ktonCO$_{2\text{-eq}}$/year
$GWPcat$	global warming potential contribution of category *cat* in ktonCO$_{2\text{-eq}}$/year
$INCV$	total volumetric incentive in \$MM
$INCC$	total investment incentive in \$MM
LCI_b^{cat}	life cycle emissions inventory entry of chemical b associated with
m	mass flow rate
$\bar{m}$	total mass flow rate
NGC	annual natural gas cost in \$MM
NPV	net present value in \$MM
PC	annual power cost in \$MM
$STMC$	annual steam cost in \$MM
TAC	total annualized operating in \$MM cost
$TPEC$	total equipment purchase cost in \$MM
$TPIC$	total purchase investment cost in \$MM
Vq	annual gallons of biofuels q production

Superscripts

avg	average
con	condenser
cyc	cyclone
cmb	combustor
dem	demister
dis	distillation column/product splitter
dry	dryer
hpf	high pressure flash
hts	high temperature shift
hyc	hydrocracker
hyt	hydrotreater
kdr	knock out drum
lpf	low pressure flash
pyr	pyrolysis
qnc	quench
rfm	steam reformer
tot	total

Subscripts

air	air
bms	biomass
cat	emission source categories
chr	char
dbms	dried biomass
elec	electricity consuming units
exh	exhaust stream
dsl	diesel
fd	feed stream
fg	fuel gas
gasl	gasoline
heatc	heat consuming units
liq	liquid
ng	natural gas
pd	product
stm	steam
vap	vapor

Koufopanos, & Lucchesi, 1992; Meesuk, Cao, Sato, Ogawa, & Takarada, 2011; Salema & Ani, 2011) and techno-economic analysis of hydrocarbon biorefineries based thermochemical conversion pathways was conducted (Jones et al., 2007; Swanson, Platon, Satrio, & Brown, 2010; Wright, Daugaard, Satrio, & Brown, 2010). These technologies are based on biomass gasification followed by Fisher–Tropsch (FT) or fast pyrolysis followed by hydroprocessing.