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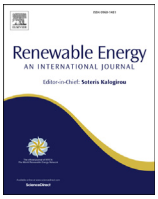

Techno-economic comparison of three energy conversion pathways from empty fruit bunches

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ABSTRACT

Empty fruit bunches (EFB) of oil-palm are one of the most recent renewable energy resources. The objective of this study is to find the most economically-feasible pathway among three energy conversions from 400 t/d wet EFB, which are bioethanol and jet fuel by bioconversion, combined heat and power via gasification, and hydrocarbons through fast pyrolysis and biooil upgrading. A hierarchical four-level economic potential approach (4-level EP) was employed to perform the preliminary techno-economic analysis (TEA) for the three pathways. The 4-level EP includes the input/output structure, the flowsheet structure, the heat integration (HI), and the economic feasibility. The economic potential of the three plants was compared at each level, and the most promising process among them was identified at Level 4, where economic criteria including return on investment (ROI), payback period (PBP), and internal rate of return (IRR) were evaluated. It was found that the biooil hydrocarbon plant is most economical due to the highest economic potential, ROI, and IRR. The heat consumption was reduced considerably by HI in the bioethanol and jet fuel plant. The sensitivity analysis informed that the plant size, the product yield, and the total capital investment highly influenced ROI and PBP in all three processes.

1. Introduction

The depletion of fossil fuels along with environmental concerns necessitates searching renewable and sustainable energy sources. Breakthroughs in the fields of chemistry, biology, and engineering have been reported, showing great potential toward providing energy alternatives [1]. The abundance and relatively low cost of lignocellulosic materials make them attractive as renewable feedstocks [2]. The fundamental challenge of the renewable energy is the competition with the traditional energy resources in economic viability. A large variety of integrated biorefinery processes come from the richness of possible biomass reaction networks [3]. Each of these processes should be technologically and economically judged in order to be commercialized.

Empty fruit bunches (EFB) of oil-palm as a lignocellulosic feedstock are one of the most recent renewable energy resources [4]. About 40 × 10^6 ton/yr of EFB were produced in 2008 in Malaysia and Indonesia. The production rate of palm oil is increasing in the recent decay by about 5% per year [5]. Many researchers have addressed the bioethanol production from EFB using different pretreatment and fermentation methods [6,7]. The fermentable sugar in EFB fiber was increased by sequential acid/alkali-pretreatments resulting in a high ethanol yield [8]. Xylose, being a major component of hemicellulose in EFB, was separated during a dilute acid pretreatment step [9]. In the bioethanol plant, jet fuel-range alkanes (C_8–C_{13}) were produced by integrating a four-step process including acid hydrolysis and xylose dehydration, aldol condensation, low-temperature hydrogenation, and high-temperature hydrodeoxygenation [10,11].

Two main thermo-chemical transforming technologies of biomass are gasification and pyrolysis. Gasification converts biomass into a combustible gas mixture (syngas) by the partial oxidation of biomass at about 800–900 °C [12]. Syngas has many uses from heat or power applications to a variety of synthetic fuels [13]. In the power plant via circulating fluidized-bed gasification from woodchips, the gas engine showed a higher economic profit for capacities smaller than 22 MW_e [14].

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Nomenclature

Abbreviations

4-level EP	Four-level hierarchical economic potential
BEJF	bioethanol and jet fuel
BOE	barrel of oil equivalent
CAPEX	capital expenditure
CEPCI	chemical engineering plant cost index
EFB	empty fruit bunches
EP	economic potential
FFB	fresh fruit bunches
FPBU	fast pyrolysis and biooil upgrading
GCHP	gasification for combined heat and power
HHV	higher heating value
HI	heat integration
IRR	internal rate of return, %
LCOE	levelized cost of electricity, $\$/\mathrm{kWh_e}$
LHV	lower heating value
NPV	net present value, $
NRTL	non-random two-liquid
OPEX	operational expenditure
PBP	payback period, yr
PR	Peng-Robinson
PFD	process flow diagram
PoS	plot of sensitivity
REC	renewable energy certificate
ROI	return on investment, %
SRK	Soave-Redlich-Kwong
TEA	techno-economic analysis

Symbols

A	capacity, kt/yr
a	installed cost factor
b	indirect cost factor
c	project contingency factor
c_r	cost of the raw material, $/kg
C_{AI}	annualized total installed cost, $/yr
C_{cat}	annualized catalyst cost, $/yr
C_{dep}	depreciation cost, $/yr
C_{DI}	total direct and indirect costs, $
C_E	purchased equipment costs, $
C_F	fixed capital investment, $
C_{fix}	fixed costs, $/yr
C_{HE}	extra heat exchanger capital cost, $
C_I	total installed cost, $
C_{ID}	indirect cost, $
C_P	project contingency, $
C_{RM}	raw material cost, $/yr
C_T	total capital investment, $
C_{TP}	total production cost, $/yr
C_{TU}	total utility cost, $/yr
$C_{TU,HI}$	total utility cost after heat integration, $/yr
C_{TUS}	total utility saved by heat integration, $/yr
C_W	working capital, $
d	working capital factor
E	economic potential, $/yr
F_p	mass flow rate of product, kg/yr
f	amount of byproduct or raw material per 1 kg of product, kg/kg
i	interest rate, %
I	cost index
L_{cat}	catalyst life time, yr
L_d	depreciation life, yr
L_p	plant life, yr
N	number of equipment
p_p	market price of product, $/kg
p_{bp}	market price of byproduct, $/kg
P_{ASR}	annual sales revenue, $/yr
P_{cash}	cash flow, $/yr
p_{cat}	market price of catalyst, $/kg
P_G	gross profit, $/yr
P_N	net profit, $/yr
v_{space}	weight hourly space velocity, $\mathrm{h^{-1}}$
β	rate of corporation income tax
γ	capacity exponent
η_{LHV}	energy conversion efficiency based on lower heating value,%
τ	annualizing factor, yr

The pyrolysis reactor is operated around 300–350 °C or 500 °C with or without a catalyst in the absence of oxygen, respectively [15]. In the biomass pyrolysis, a faster heating rate normally gives a higher biooil yield than a slower one. Crude biooil can be upgraded into hydrocarbons by the hydro-processing processes including biooil hydrotreating, aqueous phase reforming, and oil phase cracking [16]. The aqueous phase reforming produces enough hydrogen for the hydrotreating and cracking processes. The economic feasibility was evaluated for the biooil production process from EFB via fast pyrolysis using a fluidized-bed [17].

Techno-economic analysis (TEA) is a type of value engineering that is used to evaluate innovative product design or competitive production [18]. TEA is often performed by designing and modeling a process and then estimating the total capital investment, total production cost, and other economic criteria [14,17,19]. The key factors affecting the economic feasibility of the biomass conversions to a useful form of energy were the plant capacity, feedstock cost, product yield, and process configuration [11,18]. Recently, a four-level economic potential approach (4-level EP) was proposed for the systematic TEA of bioethanol production from EFB [11].

TEA of the energy conversion from EFB was performed in two different pathways such as fermentation and fast pyrolysis [11,17,20]. However, since these biofuel conversion pathways from EFB were not assessed under the same situation, it is difficult to judge which pathway is more economically viable. It will be useful to evaluate the economic feasibility at the same feed flow rate and local situation. Furthermore, the comparison of energy production cost from EFB with traditional fossil fuel is necessary for economic viability.

This study aims to compare the economic profit of the three energy conversion pathways from 400 t/d of wet EFB, which are bioethanol and jet fuel production (BEJF–Case 1), gasification for combined heat and power (GCHP–Case 2), and fast pyrolysis and biooil upgrading (FPBU–Case 3). The 4-level EP approach is applied to this study for the equitable evaluation of economic feasibility. Several solutions to increase the economic profit of the three cases are suggested. The energy production cost from EFB is finally compared with traditional fossil fuels.