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A mixed biomass-based energy supply chain for enhancing economic and environmental sustainability benefits: A multi-criteria decision making framework

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HIGHLIGHTS

- A mixed supply chain is developed to enhance sustainability benefits of bioenergy.
- A decision-making framework is constructed to balance sustainability dimensions.
- A stochastic optimization model is developed to explore the effects of uncertainty.
- This study provides insights on bio-oil production processes and system structure.

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ABSTRACT

Bioenergy sources have been introduced as a means to address challenges of conventional energy sources. The uncertainties of supply-side (upstream) externalities (e.g., collection and logistics) represent the key challenges in bioenergy supply chains and lead to reduce cross-cutting sustainability benefits. We propose a mixed biomass-based energy supply chain (consisting of mixed-mode bio-refineries and mixed-pathway transportation) and a multi-criteria decision making framework to address the upstream challenges. Our developed framework supports decisions influencing the economic and environmental dimensions of sustainability. Economic analysis employs a support vector machine technique, to predict the pattern of uncertainty parameters, and a stochastic optimization model, to incorporate uncertainties into the model. The stochastic model minimizes the total annual cost of the proposed mixed supply chain network by using a genetic algorithm. Environmental impact analysis employs life cycle assessment to evaluate the global warming potential of the cost-effective supply chain network. Our presented approach is capable of enhancing sustainability benefits of bioenergy industry infrastructure. A case study for the Pacific Northwest is used to demonstrate the application of the methodology and to verify the models. The results indicate that mixed supply chains can improve sustainability performance over traditional supply infrastructures by reducing costs (up to 24%) and environmental impacts (up to 5%).

1. Introduction

1.1. Motivation

Bioenergy has been suggested as a sustainable source of energy that has high potential to displace fossil-based energy [1]. Sustainable bioenergy sources can promote economic opportunities, energy security, and environmental benefits [2]. Biomass, as a key bioenergy resource, can be produced from natural materials, such as forest harvest residues (FHR), energy crops, algae, and agricultural wastes [3,4]. Biomass represents a promising renewable resource due to its domestic abundance and low price. Biomass-based energy from a combination of sources (forest, agricultural, and algal) comprises the largest portion (50%) of renewable energy resources in the U.S. [5]. The enormous domestic biomass potential (one-billion-ton annual supply) can meet commercialization and sustainability goals, which is critical to long-term viability for renewable energy. The replacement of fossil energy imports with bioenergy can address environmental pressures and offer

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Nomenclature

Indices

c	collection
dt	double-trailer truck
f	fixed bio-refinery
i	set of collection sites
j	set of staging sites
k	set of mobile (portable) bio-refinery sites
l	set of fixed (nonportable) bio-refinery sites
m	mobile bio-refinery
M	large positive constant
p	pre-processing
s	staging
st	single-trailer truck
t	set of time periods
tt	tanker truck

Parameters

A	biomass accessibility rate
Cap_i	annual capacity of a collection site (metric tons)
Cap_m	annual capacity of a mobile bio-refinery (metric tons)
Cap_f	annual capacity of a fixed bio-refinery (metric tons)
D	distance of collection site to a portable bio-refinery or fixed bio-refinery location (miles)
EF_{mass}	total GHG emissions factor of biomass transportation (kg CO_2 eq. per ton-mile) – the ton is equal to 1000 Kg in this study
$EF_{mass}CO_2$	CO_2 emissions factor of biomass transportation (kg CO_2 per ton-mile)
$EF_{mass}CH_4$	CH_4 emissions factor of biomass transportation (kg CH_4 per ton-mile)
$EF_{mass}N_2O$	N_2O emissions factor of biomass transportation (kg N_2O per ton-mile)
EF_{oil}	total GHG emissions factor of bio-oil transportation (kg CO_2 eq. per ton-mile)
$EF_{oil}CO_2$	CO_2 emissions factor of bio-oil transportation (kg CO_2 per ton-mile)
$EF_{oil}CH_4$	CH_4 emissions factor of bio-oil transportation (kg CH_4 per ton-mile)
$EF_{oil}N_2O$	N_2O emissions factor of bio-oil transportation (kg N_2O per ton-mile)
EF_{pro}	total GHG emissions factor of production process (kg CO_2 eq. per ton)
$EF_{pro}CO_2$	CO_2 emissions factor of production process (kg CO_2 per ton)
$EF_{pro}CH_4$	CH_4 emissions factor of production process (kg CH_4 per ton)
$EF_{pro}N_2O$	N_2O emissions factor of production process (kg N_2O per ton)
EF_{up}	total GHG emissions factor of upstream activities (kg CO_2 eq. per ton)
$EF_{up}CO_2$	CO_2 emissions factor of upstream activities (kg CO_2 per ton)
$EF_{up}CH_4$	CH_4 emissions factor of upstream activities (kg CH_4 per ton)
$EF_{up}N_2O$	N_2O emissions factor of upstream activities (kg N_2O per ton)
F_{site}	annual fixed cost for a defined site, e.g., collection, staging, refinery, or storage ($)
F_{truck}	annual fixed cost of a defined truck, e.g., single-trailer, double-trailer, or tanker trucks ($)
G_{mass}	GWP of biomass transportation (kg CO_2 eq.)
G_{oil}	GWP of bio-oil transportation (kg CO_2 eq.)
G_{pro}	GWP of production process (kg CO_2 eq.)
G_{up}	GWP of upstream activities (kg CO_2 eq.)
L_{site}	annual labor cost for a defined site, e.g., collection, staging, refinery, or storage ($)
L_{truck}	annual labor cost of a defined truck, e.g., single-trailer, double-trailer, or tanker trucks ($)
M_{mass}	mass of available biomass (metric tons)
M_{pro}	mass of processed biomass (metric tons)
N	base number of collection sites
PY	percentage yield of converting biomass to bio-oil
O_{pro}	mass of bio-oil produced (metric tons)
q_{ij}	biomass quality rate
RCO_2	CO_2 emissions rate (kg CO_2 eq./kg CO_2)
RCH_4	CH_4 emissions rate (kg CO_2 eq./kg CH_4)
RN_2O	N_2O emissions rate (kg CO_2 eq./kg N_2O)
U_c	annual utilization of a forwarder (metric tons per year)
U_{dt}	annual utilization of a double-trailer truck (metric tons per year)
U_f	annual processing of a fixed bio-refinery (metric tons per year)
U_m	annual processing of a portable bio-refinery (metric tons per year)
U_p	annual utilization of a grinder (metric tons per year)
U_{st}	annual utilization of a single-trailer truck (metric tons per year)
U_{tt}	annual utilization of a tanker truck (metric tons per year)
V_{site}	annual variable cost for a defined site, e.g., collection, staging, refinery, or storage ($ per year)
V_{truck}	annual variable cost of a defined truck, e.g., single-trailer, double-trailer, or tanker trucks ($ per year)
α	quality rate of processed biomass
β	accessibility rate of processed biomass
θ	annual available mass of biomass (metric tons per year)

Continuous variables

X_{ijt}	mass of biomass (metric tons) transported from site i to site j during time period t
X_{ikt}	mass of biomass (metric tons) transported from site i to site k during time period t
X_{jlt}	mass of biomass (metric tons) transported from site j to site l during time period t

Integer variables

Y_{kst}	mass of bio-oil (metric tons) transported from site k to site s during time period t
Y_{lst}	mass of bio-oil (metric tons) transported from site l to site s during time period t

Binary variables

B_{ijt}	binary variable for transportation from site i to site j during time period t

significant opportunities for domestic job creation. For instance, it is estimated that the transportation sector accounts for two-thirds of U.S. oil consumption and generates one-third of U.S. greenhouse gas (GHG) emissions [3], which can be reduced through the increased production and use of bio-oil.

The need for scaling up bioenergy production derives from national