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Optimization of emergy sustainability index for biodiesel supply network design

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ABSTRACT

Sustainability is an important and difficult consideration for the stakeholders/decision-makers when planning a biofuel supply network. In this paper, a Mixed-Integer Non-linear Programming (MINLP) model was developed with the aim to help the stakeholders/decision-maker to select the most sustainable design. In the proposed model, the emergy sustainability index of the whole biodiesel supply networks in a life cycle perspective is employed as the measure of the sustainability, and multiple feedstocks, multiple transport modes, multiple regions for biodiesel production and multiple distribution centers can be considered. After describing the process and mathematic framework of the model, an illustrative case was studied and demonstrated that the proposed methodology is feasible for finding the most sustainable design and planning of biodiesel supply chains.

1. Introduction

Due to the rapid depletion of fossil fuel and increasing environmental deterioration, biodiesel has emerged as a promising alternative fuel for realizing the global sustainable development due to its economical, environmental and social advantages [1–3]. However, different pathways for biodiesel production have different sustainability performance [4]. Accordingly, a variety of studies concerning the sustainability of biodiesel have been launched to promote the development of biodiesel in multiple countries such as Brazil [5] and China [6]. Furthermore, the role of biodiesel supply chains in the renewable energy sector has attracted more and more attentions from the stakeholders/decision-makers [7], consequently, effective methodologies that can guide the design of sustainable biofuel supply chains are becoming more and more important nowadays. In an integrated biodiesel system, different feedstocks can be used and various manufacture technologies/processes can be selected. And also, various transport modes can be selected for feedstock and biodiesel transportation with different targeted markets. Therefore, multiple alternative scenarios can be selected in each stage of the whole life cycle ('from cradle to gate') of biodiesel, the integration of the alternative scenarios is quite important for appropriate planning and design of supply chains for biodiesel production with a better sustainability performance.

Several methodologies and models have been developed for evaluating biofuel supply chains with different focuses, i.e. economic performances [8], energy efficiency [9], or environmental performances [10]. Recently, Corsano et al. [11] pointed out that a multidisciplinary approach is preferred for better assessment of the sustainability of biofuel supply chains, which is also an emerging trend of business supply chain [12]. In this area, some pioneer works have already been reported. Ayoub et al. [13] considered the economic performance, environmental impact, energy consumption, and labors number simultaneously for the design of bioenergy supply chains. Mele et al. [14] proposed a multi-objective model for designing sustainable biofuel supply chains by using two comprehensive metrics including Eco-indicator 99 and Global Potential Warming. Liu and Huang [15] developed a model for sustainable biodiesel system designs by integrating economic, environmental and social indices. All these models are useful for helping the decision-makers/stakeholders to design a more sustainable biodiesel supply chain, however, most of these studies focused on multi-objective programming. Although Pareto solutions could be

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Nomenclature

Indices/sets

$c \in C$ the set of feedstocks for crop production (–)
$j \in J$ transport modes for crop transportation (–)
J_{mn} the set of transport modes for the transportation of crops from the m-th crop center to the n-th plant (–)
$k \in K$ transport modes for biodiesel transportation (–)
K_{nl} the set of transport modes for the transportation of biodiesel from the n-th plant to the l-th distribution center (–)
$l \in L$ biodiesel distribution centers (–)
$m \in M$ crop centers (–)
$n \in N$ available regions for building biodiesel plants (–)
$u \in U$ the set of feedstocks for biodiesel production (–)
$s \in S$ various stages in the whole life cycle of biodiesel (–)
$v \in V$ the set of fuels (–)

Parameters

AA_m the available area of the m-th crop land (ha)
AB_m percentage of the solar energy that can be absorbed by the m-th crop (–)
AD air density (kg m^{-3})
AE_m average elevation regarding to the m-th crop land (m)
AP_m average precipitation regarding to the m-th crop land (m)
C_v^j the v-th fuel consumption using the j-th transport mode for transporting per unit crop for per mileage (kg t^{-1} km^{-1})
C_v^k the v-th fuel consumption using the k-th transport mode for transporting per unit biodiesel for per mileage (kg t^{-1} km^{-1})
C_m^{c0} the consumption of the c-th feedstock regarding to the m-th crop per area (kg)
$C_{m,n}^{u0}$ the consumption of the u-th feedstock using the m-th plant to produce per unit biodiesel (kg t^{-1} km^{-1})
CP_n^L the lower production boundary of the plant in the n-th region (t)
CP_n^U the upper production boundary of plant in the n-th region (t)
D_{mn} the distance between the m-th crop center with the n-th region for building a biodiesel plant (km)
D_{nl} the distance between the n-th region of biodiesel plant and the l-th distribution center (km)
DC drag coefficient (–)
DE water density (kg m^{-3})
DM^l the demand of the l-th distribution center (t)
EIR emergy investment ratio (–)
ELR environmental load ratio (–)
ESI emergy sustainability index (–)
EYR emergy yield ratio (–)
F_R renewable purchase inputs (sej)
F_N non-renewable purchase inputs (sej)
GR gravity (m s^{-2})
GW geostrophic wind (m s^{-1})
GFE Gibbs free energy (J kg^{-1})
IN_m solar radiation per the growth cycle of m-th crop (J m^{-2} yr^{-1})
N non-renewable environmental resources (sej)
P product (mass or energy) (kg or J)
R renewable environmental resources (sej)
r_m the conversion ratio of the m-th crop to biodiesel, and it means that per unit biodiesel requires $1/r_m$ unit of the m-th crop
RR_m rain-off rate regarding to the m-th crop land (m)
S^j the cost of service and management for transporting per unit crops for per mileage using the j-th transport mode (Yuan RMB km^{-1} t^{-1})
S^k the cost of service and management for transporting per unit biodiesel for per mileage using the k-th transport mode (Yuan RMB km^{-1} t^{-1})
T_m the growth cycle of the m-th crop (yr)
Tr transformity (sej kg^{-1} or sej J^{-1})
TCP^j the planned total transport capacity of the j-th transport mode in the prescribed time (t)
TCP^k the planned total transport capacity of the k-th transport mode in the prescribed time (t)
TLE_m topsoil loss energy per unit area corresponding to the m-th crop land (J ha^{-1})
Y_m yield of the m-th crop per unit area (t ha^{-1})
YI yield of the industrial system (sej)

Binary variables

I_m^n the binary variable (with a value 1, the n-th region is selected to build biodiesel plant using the m-th crop, and 0 means that the n-th region is not selected) (–)

Continuous variables

C_m^c the consumption of the c-th feedstock regarding to the m-th crop planting (kg)
$C_{m,n}^u$ the consumption of the u-th feedstock using the m-th plant to produce biodiesel (kg)
F_v the consumption of the v-th fuel (kg)
E_m^t topsoil loss regarding to the m-th crop land (sej)
E_m^{rcp} rain chemical potential regarding to the m-th crop land (sej)
E_m^{rgp} rain geopotential regarding to the m-th crop land (sej)
E_m^{sun} sunlight absorption by the m-th crop land (sej)
E_m^w wind energy regarding to the m-th crop land (sej)
$T_j^{m \to n}$ the amount of the crop in the m-th crop center transported by the j-th transport mode to the n-th region (t)
$T_k^{n \to l}$ the amount of the biodiesel produced transported by the k-th transport mode from the n-th plant to the l-th distribution center (t)
$TS_{m \to n}$ the cost of service and management for the transport of crops from the crop centers to the plants (Yuan RMB)
$TS_{n \to l}$ the cost of service and management for the transport of biodiesel from the crop centers to the plants (Yuan RMB)
$X_{m \to n}$ the amount of biodiesel produced by the m-th crop in the n-th region (t)

obtained, it is still difficult for the decision-makers/stakeholders to refer to or choose the most suitable scenario among various solutions. Thus, a model that uses a single objective as the sustainability measure of biodiesel supply chains is preferred for the decision-makers/stakeholders.

Two indices were widely used as the measure of sustainability, e.g. ecological footprint which is defined as a measure of the human demand for land and water areas, and compares the human consumption or resources and absorption of waste with the Earth's ecological capacity to regenerate, and it is a composite indicator that combines the built-up land footprint, carbon footprint, forest footprint, fishing-grounds footprint, grazing land footprint, and crop land footprint) [16,17] and emergy sustainability index (ESI) which is an index in emergy synthesis for measuring the