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Modeling the development and utilization of bioenergy and exploring the environmental economic benefits

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ABSTRACT

This paper outlines a complete bioenergy flow incorporating bioresource procurement, feedstock supply, conversion technologies and energy consumption to industrialize the development and utilization of bioenergy. An input–output optimization simulation model is developed to introduce bioenergy industries into the regional socioeconomy and energy production and consumption system and dynamically explore the economic, energy and environmental benefits. 16-term simulation from 2010 to 2025 is performed in scenarios preset based on bioenergy industries, carbon tax-subsidization policy and distinct levels of greenhouse gas emission constraints. An empirical study is conducted to validate and apply the model. In the optimal scenario, both industrial development and energy supply and demand are optimized contributing to a 8.41% average gross regional product growth rate and a 39.9% reduction in accumulative greenhouse gas emission compared with the base scenario. By 2025 the consumption ratio of bioenergy in total primary energy could be increased from 0.5% to 8.2%. Energy self-sufficiency rate could be increased from 57.7% to 77.9%. A dynamic carbon tax rate and the extent to which bioenergy industrial development could be promoted are also elaborated. Regional economic development and greenhouse gas mitigation can be potentially promoted simultaneously by bioenergy utilization and a proper greenhouse gas emission constraint. The methodology presented is capable of introducing new industries or policies related to energy planning and detecting the best tradeoffs of economy–energy–environment.

1. Introduction

Driven by the necessity to reduce dependence on conventional fossil energy and mitigate the greenhouse effect, countries all over the world are prompted to explore and utilize renewable energy for achieving future energy security [1–3]. Biomass systems operating at a steady state are considered as being inherently carbon neutral, since carbon fixation during plant growth largely offsets the carbon emissions generated during biomass combustion [4]. The substitution of conventional fossil energy with bioresources through bioenergy technologies results both in a net reduction in greenhouse gas (GHG) emission and the prospect of regional energy consumption structure adjustment. Furthermore, development of bioresource-related industries is promising to be moved forward by providing raw materials for bioenergy production [5].

To facilitate scaled and efficient bioenergy utilization, various ideas for the development and conversion of bioenergy have been investigated. Numerous studies have analyzed factors such as natural conditions, transportation and technological equipments to design and optimize an integrated and efficient bioenergy system and simulate the whole logistics process making use of modeling approach [6–11]. Besides, the environmental impacts and economic performances of a certain bioenergy system and the introduced management and economic policies have been evaluated to explore the best way to promote regional bioenergy utilization [5,12–16].

The reviewed studies revealed that discontinuous availability and relatively higher logistics cost generally confine bioenergy

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Abbreviations: GHG, greenhouse gas; I–O, input–output; DOSM, dynamic optimization simulation model; AR, agricultural residue; FR, forestry residue; LM, livestock manure; MSW, municipal solid waste; GRP, gross regional product; GHGEC, GHG emission constraint; UIs, usual industries; CEIs, conventional energy industries; BEIs, bioenergy industries; EIs, energy industries; CNY, Chinese yuan; tce, tonnes of standard coal equivalent; CO_2-e, CO_2 equivalent; GHGEGR, GHG emission growth rate; ESSR, energy self-sufficiency rate.

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Nomenclature

Subscript

1	usual industries
2	conventional energy industries
3	bioenergy industries
e	energy industries
p	private consumption
g	government consumption
*B*1	biomass combustion power generation industry
*B*2	biomass gasification power generation industry
*B*3	biomass solid molding fuel industry
*B*4	livestock manure biogas power generation industry
*B*5	MSW incineration power generation industry

Variables (In the formulas, the variables in bold denote vectors or matrices; (t) denotes an endogenous variable)

$X_i(t)$	output of industry i ($i = 1, 2, 3, e$)
A_{ij}	input coefficients from industry i to industry j (i = 1,e; $j = 1, 2, 3$)
$D_i(t)$	final demand of industry i ($i = 1, 2, 3$)
$P_i(t)$	private consumption for purchasing commodities or services (energy) ($i = 1, e$)
G_i	government consumption for purchasing commodities or services (energy) ($i = 1, e$)
$\Delta K_i(t)$	capital formation provided by industry i ($i = 1, 2, 3, e$)
$N_i(t)$	net export of industry i ($i = 1, e$)
ℓ	unit row vector
Ep_i^m	production coefficient of the m-th energy of industry i ($i = 2, 3$)
Ec_i^m	consumption coefficient of the m-th energy of industries or private (government) energy consumption ($i = 1, 2, 3, p, g$)
$R_e^m(t)$	the m-th energy imported from or exported to other regions;
$M_{Bi}(t)$	the number of bioenergy projects of Bi ($Bi = B1–B5$)
$C_{Bi}(t)$	the amount of ARs utilized by Bi ($Bi = B1–B3$)
$F_{Bi}(t)$	the amount of FRs utilized by Bi ($Bi = B1–B3$)
CF_{Bi}^s	the amount of ARs or FRs utilized by unit bioenergy project of Bi ($Bi = B1$–B3)
$D_{B4}(t)$	the amount of cattle (hog) manure utilized by $B4$
D_{B4}^s	the amount of cattle (hog) manure utilized by unit bioenergy project of $B4$
$SW_{B5}(t)$	the amount of MSW utilized by $B5$
SW_{B5}^s	the amount of MSW utilized by unit bioenergy project of $B5$
$Q_C(t)(Q_F(t), Q_D(t), Q_W(t))$	total collectable and utilizable amount of ARs (FRs, LM, MSW)
qc_j	generation coefficient of AR from crop j (corresponding to UIs)
qf_j	generation coefficient of FR from forestry j (corresponding to UIs)
$qd_c(qd_h)$	generation coefficient of cattle (hog) manure (corresponding to UIs)
$qw_1(qw_p)$	generation coefficient of MSW (corresponding to UIs and private consumption)
Z_{Bi}	output of unit bioenergy project of Bi ($Bi = B1–B5$)
$Y_d(t)$	disposable income
τ_d	direct tax rate
y_i	income rate of industry i ($i = 1, 2, 3$)
β	private saving rate
α_i	share in total private consumption ($i = 1, e$)
$S_p(t)$	private saving
$S_g(t)$	government saving
τ_i	indirect tax rate of industry i ($i = 1, 2, 3$)
$Sub(t)$	total subsidies for BEIs
$\tau_s(t)$	carbon tax rate
$I_i(t)$	net investment of industry i ($i = 1, 2, 3$)
δ_i	capital depreciation rate of industry i ($i = 1, 2, 3$)
$K_i(t)$	capital stock of industry i ($i = 1, 2, 3$)
γ_i	capital production coefficient of industry i ($i = 1, 2, 3$)
w_i	GHG emission coefficient of industries, private and government energy consumption ($i = 1, 2, 3, p, g$)
v_i	value added rate of industry i ($i = 1, 2, 3$)

utilization at a regional level. Most of the approaches reviewed were developed specifically for a given bioenergy system, and not designed to be generic and easily extendable. Many efforts have been made to identify the feasibility of a bioenergy system itself or environmental economic policies proposed. However regarding overall evaluation of benefits from bioenergy utilization for energy consumption structure adjustment and environmental impact mitigation at a regional level, limited extended work has been undertaken.

Input–output (I–O) analysis was developed by Leontief as a framework for the analysis of highly interconnected economic systems allowing for intersectoral interdependencies in a country or a region to be investigated [17]. Recently, I–O analysis has been extensively applied to assess the interactions among economy, energy and environment. Oliveira and Antunes [18] developed a multi-objective linear programming model based on I–O analysis to analyze the changes in the economic structure and energy system, as well as to assess the corresponding environmental impacts in Portugal. Fu et al. [19] established an energy I–O model to quantify China's investment-driven energy consumption and carbon emissions in 2007 and discussed how to determine energy-saving potentials by improving the utilization of the investment-driven energy consumption. Llop and Pie [20] defined a price model based on the traditional I–O model and applied it to the production system in Catalonia, Spain to analyze the economic impacts of various policies implemented in energy activities. Specifically, studies for the optimization of biomass-related activities to promote regional bioenergy utilization with I–O model have been carried out. Tan et al. [21] developed a multi-regional fuzzy I–O model to optimize biomass production and trade under resource availability and environmental footprint constraints. Cruz et al. [4] presented a novel multi-time-stage I–O-based modeling framework for simulating the dynamics of bioenergy supply chains. Madlener and Koller [22] summarized the methodology and results of an I–O study on the economic impacts and CO_2 mitigation effects of promoting biomass district heating systems in Vorarlberg, Austria. Compared with other applied methods for the assessment of energy and environmental impacts of socioeconomic activities such as life cycle assessment and system dynamics [14,23–25], I–O analysis does has advantages in offering an approach to embedding energy activities, environmental impacts and environmental economic policies into complex interrelations of all sectors and solving a systematical optimization problem at aggregated macro and sectorally disaggregated micro levels [26,27].

Considering the deficiency in the assessment of the whole bioenergy utilization process at a regional level in the reviewed studies, this study tries to involve all the necessary factors from the harvesting to the end use of various types of bioenergy to form a complete