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System-level energy consumption modeling and optimization for cellulosic biofuel production

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HIGHLIGHTS

- A system-level energy model for cellulosic biofuel production is proposed.
- The relationships between energy and production parameters are studied.
- A numerical case is conducted to identify the major energy drivers.
- The impacts of decision variables on energy consumption are analyzed.
- The optimization results in 21.09% reduction in total energy consumption.

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ABSTRACT

As a promising alternative to fossil fuels, cellulosic biofuel has obtained considerable interest due to its potential for mitigating global climate change and enhancing energy security. However, the widespread adoption of cellulosic biofuel is taking place in a slower pace than expected. One major challenge is that the cellulosic biofuel production is still highly energy-intensive. In fact, the energy contained in cellulosic biofuel is less than the energy required for its production. To address this issue, in this paper, an analytical system-level energy model is proposed to characterize the fundamental relationships between total energy consumption and biofuel production parameters in cellulosic biofuel production systems. Furthermore, an optimization strategy based on Particle Swarm Optimization (PSO) is adopted to minimize the energy consumption of cellulosic biofuel production while maintaining the desired biofuel yield. A baseline case is implemented for analyzing energy consumption, and the results show that pretreatment consumes most energy among all processes and the water/biomass ratio is the most significant energy driver. In addition, the optimal solution results in a 21.09% reduction in the total energy consumption compared to the baseline case.

1. Introduction

In 2017, the global greenhouse gas (GHG) emissions have reached an all-time high [1], meanwhile, 62% of these emissions are from burning fossil fuels [2]. The extensive use of fossil fuels has led to serious issues like climate change, environmental pollution, human health, and energy supply challenges associated with the irreversible depletion of fossil fuels [3]. Hence, many countries are turning their attentions to new, clean, and sustainable energy sources, e.g., solar energy, wind energy, biofuel, etc.

Biofuel, as one of the most popular renewable energy sources, is expected to play a crucial role in future global energy infrastructure. Currently, biofuel is the only viable and widely available source of renewable transportation energy [4,5]. Based on different biomass feedstocks, biofuels can be divided into several categories such as sugarcane biofuel, cellulosic biofuel, algae biofuel, etc. Among various types of biofuels, cellulosic biofuel is considered to be the most promising alternative to help mitigate the global climate change [6] due to its wide available feedstock resources and low lifecycle GHG emissions. It is reported that using cellulosic ethanol can achieve up to 90% GHG saving compared to petroleum fuels [7].

Despite the aforementioned advantages, cellulosic biomass needs to go through several energy intensive production processes before these benefits can be realized. A typical cellulosic biofuel production system usually includes size reduction, pretreatment, enzymatic hydrolysis, and fermentation process. During the size reduction process, the raw cellulosic biomass is cut and grinded into small particles for further biochemical conversions. Next, in the pretreatment process, the

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Nomenclature

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$\mathbf{S}$	solution vector to the optimization problem
$\mathbf{X}$	particle position vector
$\mathbf{V}$	particle velocity vector

Upper case

A	pre-exponential factor (1/s)
A^p	pretreatment reactor surface area (m^2)
A^h	hydrolysis reactor surface area (m^2)
A^f	fermentation reactor surface area (m^2)
C_{acid}	active acid concentration (w/w%)
C_k	Kick's constant
C_{pw}	specific heat capacity of water (KJ/mol/K)
C_{pb}	specific heat capacity of biomass (KJ/mol/K)
C_{pa}	specific heat capacity of acid (KJ/mol/K)
D_e	diffusion coefficient (m^2/s)
E_a	activation energy (kJ/mol)
H_L	latent heat of water vaporization (KJ/kg)
K_g	inhibition constant of xylose (g/L)
K_{xl}	inhibition constants of xylose (g/L)
L_1	particle size before reduction (mm)
L_2	particle size after reduction (mm)
M_g	molecular weight of glucan (g/mol)
M_{gl}	molecular weight of glucose (g/mol)
M_x	molecular weight of xylan (g/mol)
M_{xl}	molecular weight of xylose (g/mol)
M_{xo}	molecular weight of xylose oligomer (g/mol)
N_p	number of particles in the swarm
$P_{i,g}$	threshold ethanol concentration of glucose (g/mol)
$P_{i,x}$	threshold ethanol concentration of xylose (g/mol)
$P_{m,g}$	maximum ethanol concentration of glucose (g/mol)
$P_{m,x}$	maximum ethanol concentration of xylose (g/mol)
$Q_{heatloss}$	energy to balance heat loss (KJ)
$Q_{heating}$	energy for heating (KJ)
$Q_{reaction}$	reaction energy (KJ)
$Q_{recovery}$	recovered energy (KJ)
$Q_{size\ reduction}$	energy required in size reduction process (KJ)
R	gas constant
R_1	inner radius of the reactor (m)
R_2	outer radius of the reactor(m)
T_p	pretreatment temperature (°C)
T_h	enzymatic hydrolysis temperature (°C)
T_f	fermentation temperature (°C)

Lower case

a	ratio of the liquid volume and solid spheres volume
c_1	learning factor
c_2	learning factor
c_e	concentration of ethanol (kg/L)
c_g	concentration of glucose (kg/L)
c_{xl}	concentration of xylose (kg/L)
c_{xo}	concentration of xylose oligomer (kg/L)
c_z	concentration of recombinant (kg/L)
h_{out}	convection coefficient (W/m^2/°C)
m_a	mass of diluted acid (kg)
m_b	mass of biomass (kg)
m_w	mass of water (kg)
k_{pipe}	thermal conductivity of the reactor (W/m/°C)
t_p	pretreatment time (min)
t_f	fermentation time (hour)
t_h	enzymatic hydrolysis time (hour)
k	reaction rate (1/s)
$q_{emax,g}$	maximum specific ethanol production rate by glucose (g/L)
$q_{emax,x}$	maximum specific ethanol production rate by xylose (g/L)
q_n	reaction constant
$q_{smax,g}$	maximum specific glucose utilization rate (g/L)
$q_{smax,x}$	maximum specific xylose utilization rate (g/L)
p_g	mass of glucan in feedstock (kg)
p_x	mass of xylan in feedstock (kg)

Greek

ρ_w	density of water (kg/m^3)

recalcitrant structure of the lignocellulosic material is weakened and most hemicellulose carbohydrates (i.e., xylan, galactan, arabinan, mannan) are converted into soluble sugars. In the enzymatic hydrolysis process, cellulose is catalyzed by enzymes to release shorter chains and ultimately soluble sugars. Finally, these sugars are converted into ethanol in the fermentation process.

In the current literature, numerous studies have been carried out on different aspects of biofuel production. For biomass processing, the effects of various factors on biofuel production are investigated including biomass type [8–11], biomass size [12–14], biomass particle properties [15,16], etc. For biofuel conversion processes, research efforts have been devoted to the improvement of the pretreatment process [17–19], the development of cellulase enzyme [20,21], and genetically modification of fermentation microbe [22,23], etc. Furthermore, lifecycle analysis [24,25] and economic performance evaluations of biofuel production [26,27] have also been conducted.

The aforementioned studies provide considerable knowledge and innovative technological advancements in biofuel production. However, the challenge regarding the high energy demand in producing cellulosic biofuel still exists. It is reported that 1.27 MJ of energy are required to produce 1 MJ ethanol, where 63% is consumed in the production processes [28]. Currently, most studies on the energy analysis of biofuel production adopt the Life Cycle Assessment (LCA) approach to estimate the energy usage and analyze the environmental impacts [7,24,25,29,30]. However, LCA models are typically linear steady-state models [31], and thus cannot be used to reduce the production energy usage by identifying the optimum system production parameters (e.g., pretreatment temperature, feedstock particle size, fermentation time, etc.). Therefore, more detailed energy modeling and analyses that consider the relationships between these production parameters and energy consumption are emerging, which can be classified into two main categories: simulation-based and analytical studies.

The majority of simulation-based studies use Aspen software to simulate biofuel conversion in single or multiple processes [32–38]. The advantage of simulation-based methods is that they can capture system performance in the quite complex biofuel production systems. However, like LCA models, they are not able to reveal the fundamental mathematical relationships between system parameters and performance measures. Furthermore, the development and execution of simulation models to obtain statistically useful results may be prohibitively expensive and slow, which makes it quite difficult to find optimal solutions.

Compared to simulation-based studies, much less research uses analytical modeling methods due to the difficulties in establishing mathematical relationships between biofuel production parameters and energy consumption. Only a few papers that use analytical modeling