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A modeling framework for design of nonlinear renewable energy systems through integrated simulation modeling and metaheuristic optimization: Applications to biorefineries

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ABSTRACT

This study presents the development and implementation of a novel framework for optimal design of new and emerging renewable energy production systems by considering an iterative strategy which integrates the Net Present Value optimization along with detailed mechanistic modeling, simulation, and process optimization which yields optimal capacity plan, and operating conditions for the process. Due to the non-linear nature of process conversion mechanisms, metaheuristic algorithms are implemented in the framework to optimize operating conditions of process. Further, to apply complex kinetics in the process, we have made a linkage between process simulator (Aspen Plus) and Matlab. To demonstrate the effectiveness of the proposed methodology, a hypothetical case study of a lignocellulosic biorefinery is utilized. The proposed framework results reveal a deviation in optimal process yields and production capacities from initial literature estimates. These results indicate the importance of developing a multi-layered framework to optimally design a renewable energy production system.

1. Introduction

Over the past decade, world energy consumption has increased progressively owing to the growing demand by burgeoning industrial societies in emerging markets and the rising world population. The current global state of energy supply is highly dependent on fossil fuels. Owing to finite nature of fossil fuels, rapid increase in their prices and concerns about their environmental impact, efforts around the world to develop and commercialize renewable transportation fuels and biobased chemicals have intensified (Cardona & Sanchez, 2007). As the world has recognized the importance of diversifying its energy resource portfolio away from fossil resources and more toward renewable resources, the focus has shifted from recognizing the importance of the renewable resources sector toward designing sustainable value chains that can be scaled up efficiently and provide tangible net environmental benefits from renewable energy utilization. Still, the commercialization of conversion technologies has been hampered by a multitude of endogenous and exogenous factors including unavailability of appropriate feedstock supply systems, lack of capital and investment risk appetite, and inefficient feedstock conversion systems. Out of all issues mentioned, optimizing conversion systems can have a tremendous impact on the overall profitability of renewable transportation fuels and biobased chemical value chains.

Renewable energy in its broad sense is energy that is derived from natural resources such as sunlight, wind, water, and geothermal heat; these resources have shorter cycles of replenishment and are provided by nature on a “near-continuous” basis. Renewable energy, as a final product, comes in 2 essential forms; (1) electricity that is transported geographically using fixed transportation mediums such as utility grids and wires, and (2) transportation fuels, such as biodiesel, ethanol and butanol, whose mediums (vehicles) are mobile in nature. Once we have categorized the type of renewable energy, we can start to focus on the renewable resources that are currently utilized to produce these energies. Solar, wind, water, and hydrothermal sources in their native forms are used mostly to produce electricity. In order to democratize the use of renewable energy specifically as transportation fuels, a seamless transformation where the renewable resources are converted from their native forms to a more usable and convertible form, is necessary. Fortunately nature provides such a transformative process through the use of photosynthesis, where carbon inputs are chemically altered into organic compounds using energy from sunlight. These compounds, primarily in the form of sugars and lipids, are used to form the structure and backbone of almost all plants and trees we see around us. The question then becomes, what processes and technologies are needed to harvest this natural energy and convert them into usable forms for use as portable,

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transportation fuels in an economically viable and environmental and socially responsible manner.

The concept of a biobased facility had been prevalent in the United States and the world in general, for hundreds of years. Paper and sugar mills are quintessential examples of bio-facilities where renewable raw materials such as wood pulp and sugarcane are converted to value-added products. The use of composting facilities and waste digesters in farms and rural areas around the world has been a source of sustainable generation of electric power from renewable resources for decades. In recent times, the emphasis on biobased production using renewable resources has significantly broadened its footprint to incorporate production of fuels, power and chemicals derived from a wider variety of renewable resources. Some renewable transportation fuels that are already in the commercial production phase include first generation ethanol (corn ethanol) and biodiesel (from vegetable oils and animal fats).

Recent ventures into renewable energy have been fraught with corporate failures. A driving reason for these unsuccessful ventures, in part is governed by the lack of proper planning in designing renewable energy plants and supply networks. Often exuberant forecasts of market evolution and insufficient levers in plant and supply chain design for risk mitigation have led to companies failing to maintain solvency when lab- and bench-scale innovations are commercialized for the production of renewable products. An essential part of the planning process is garnering sufficient decision support to guide long-term strategic actions in the face of process and policy uncertainty, and market and competitive risks.

Decision modeling frameworks are ubiquitously classified as decision support systems in a variety of industry verticals. In its most basic form, a decision support system is used to help value chain actors make mission-critical decisions that have an economic, social, or environmental impact on the stakeholders of the value chain. Additionally, the nature of the decisions can be (1) strategic in nature leaning toward longer term decisions that will have an extended impact on stakeholders, (2) tactical which help stakeholders develop tactics to execute the strategies that are developing through strategic planning, or (3) operational in nature where the daily or weekly management of value chain functioning is emphasized.

Within the renewable products industry, decision support systems are relatively new, somewhat driven by the nascence of the industry itself. Owing to the complex nature of supply chains, conversion processes, and product markets, the use of decision support to aid in decision-making seems appropriate and in many cases it does lead more sound actions being taken by stakeholders based on a more complete picture of what is actually happening around them. Most decision support systems use complex mathematical formulations to model the interactions and interplay of actual physical phenomena that may go unaccounted for in case of ad-hoc decision making; consequently they are considered a valuable tool for any decision maker to compliment the “due diligence process” that they would go through before finalizing and executing critical decisions that would impact stakeholders over the short, medium, and long terms. Table 1 shows a list of renewable product industries and corresponding support functions for a prototypical decision support framework.

Table 1
Decision support functions in renewable energy production systems.

Renewable energy sub-industry	Decision support functions
Solar	Solar resource assessment; Power market analysis (supply, demand, price), load forecasting
Wind	Wind resource assessment, load and power forecasting, discrete parts' inventory management
Biomass (electricity)	Regional feedstock inventory analysis (GIS), feedstock logistics management, emissions management
Hydropower	Water resource assessment and planning, Hydropower forecasting, environmental management

From the perspective of new renewable product value chains, we have to be cognizant of the fact that most of these endeavors are still in their design and pre-feasibility study phase, wherein, the processes that execute the purpose of the value chain are still non-existent. For example, 2nd and 3rd generation biofuels including cellulosic ethanol and butanol, and algae oil are still in the research, development and demonstration (RD&D) phase in their commercialization cycle, where feedstock supplies, processing technology yields, and product markets are still being studied and developed. When developing a decision support framework for such enterprises, the initial functions of the framework should therefore focus on aiding stakeholders in the intelligent design of the supply and production chains that will impact all actors and participants over strategic time horizons (10–30 years).

The inception of decision support tools and frameworks is a relatively new concept in the field of renewable energy and biochemicals and is gaining attention. Ramachandra, Jha, Krishna, and Shruthi (2005) presented a model based decision support tool that helped solar power companies estimate the probable amount of solar energy regionally. Ouammi, Ghigliotti, Robba, Mimet, and Sacile (2012) published a model based environmental decision support system that stressed optimal technology selection and site location for wind power generation. In recent times, several analytical models have been suggested to study the effect of biomass species, technology choices, plant capacities, and process operating conditions on the production and profitability of cellulosic ethanol. The National Renewable Energy Laboratory (NREL) has developed several analytical models (Aden, 2008; Dutta & Phillips, 2009; Kazi, Fortman, & Anex, 2010) that analyze different process configurations for the production of cellulosic ethanol. A technical report by *Minnesota Technical Assistance Program* (2008) investigates ethanol production and introduces potential improvements in energy and water requirement as well as environmental impacts reduction. In this report a comparison of newer and older facilities in Minnesota for ethanol production is also provided. Sammons, Eden, Yuan, Cullinan, and Aksoy (2007) developed a general systematic framework for optimizing product allocation and process configuration for a flexible biorefinery. Their methodology provides a framework for process design and product selection based on optimization. In their model, process integration methods such as pinch analysis are employed to optimize the plant. Production pathway and product portfolio are selected based on economic and environmental criteria. Zondervan, Nawaz, de Haan, Woodley, and Gani (2011) proposed a model to compute the optimal processing routes in a biorefinery by considering different feedstock and products. Bao, Ng, Tay, Jimenez-Gutierrez, and El-Halwagi (2011) developed a systematic optimization framework by integrating multiple conversion technologies. In this model the optimization problem is formulated as a linear program. Karuppiah et al. (2008) and Martin and Grossmann (2011) showed a superstructure optimization model which incorporates heat integration inside the plant. The optimization problem is formulated as a mixed-integer nonlinear programming problem involving short-cut models for all the units in the system that consist of mass and energy balances, and design equations. Pham and El-Halwagi (2012) proposed a systematic two-stage approach to the synthesis and optimization of biorefinery configurations with the available feedstocks and desired products. A “forward–backward” approach is introduced for synthesizing possible pathways. An increased emphasis on efficient supply chain management and Net Present Value optimization has yielded substantial literature concerning supply chain