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Probabilistic multi-disruption risk analysis in bioenergy parks via physical input–output modeling and analytic hierarchy process

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ABSTRACT

Bioenergy parks are integrated energy systems developed based on material and energy synergies among bioenergy and auxiliary plants to increase efficiency and reduce carbon emissions. However, the resulting high interdependence between component units results to a vulnerable network upon capacity disruptions (i.e., plant inoperability). Inoperability of one or more plants within a bioenergy park results in a deviation from an initial network configuration because of failure propagation. The consequences of such disruptions depend upon which component units caused the failure. In this work, a probabilistic multi-disruption risk index is developed to measure the net output change of a bioenergy park based on exogenously-defined plant disruption scenarios, whose probabilities are estimated using the analytic hierarchy process (AHP). This network index is an important measure of the system's robustness to an array of probabilistic perturbation scenarios. Such risk-based information can be used for developing risk management measures to reduce network vulnerability through increasing system redundancy and diversity. A bioenergy park case study is presented to demonstrate the computation of the multi-disruption risk index.

Keywords: Probabilistic risk analysis; Bioenergy parks; Physical input–output model; Analytic hierarchy process; Multi-disruption scenarios

1. Introduction

The increasing energy demands as well as rising carbon dioxide (CO_2) emissions are driven by the growing world population coupled with rising standards of living. Annual CO_2 emission from energy-related activities is projected to reach 37.0 Gt/yr by 2035 which is about a 20% increase since 2011 (IEA, 2012). In addition, the atmospheric CO_2 concentration already exceeds 400 ppm, which is well above the 350 ppm safe boundary level proposed by Rockström et al. (2009). Researchers address these issues by focusing on low-carbon technologies, particularly on the utilization of biofuels in the transportation and industrial sectors (Liew et al., 2014). Although biofuels are renewable resources and their production is viewed as nearly "carbon neutral", they still raise other sustainability issues. Studies show that "carbon debts" are incurred when natural ecosystems are converted for biofuel crop production (Fargione et al., 2008), production processes are water-intensive (Jeswani and Azapagic, 2011) and land-intensive (Ponton, 2009), and there may be energy inefficiency resulting in significant greenhouse gas emissions (De Castro et al., 2014). A sustainability indicator developed by De Benedetto and Klemeš (2009) is a useful tool to assess the influence of these factors, including costs, in

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the sustainability of biofuel production. Aside from these, other lesser known factors such as the nitrogen footprint must be considered as it is also now being used to measure sustainability in general (Čuček et al., 2012a) and specifically for biomass supply chains (Čuček et al., 2012b); in particular, the benefits of reduced carbon footprint must be balanced with increased nitrogen footprint (Čuček et al., 2014). Razon (2015) also emphasized the need for developing alternative means of nitrogen fixation for the sustainability of biofuels and other nitrogen-dependent processes. The recent work by Azapagic (2014) meanwhile outlines key sustainability issues that must be addressed related to biofuel production using integrated biorefineries. One way to deal with these critical issues is to maximize the use of biofuel products, by-products, and production wastes (Martin et al., 2014).

The creation of "bioenergy parks" offers the prospect of sustainability through increased efficiency and reduced carbon emissions compared to stand-alone bioenergy plants by using concepts drawn from industrial ecology (IE). IE was proposed by Frosch and Gallopoulos (1989) as a strategy for achieving industrial sustainability by mimicking cyclic flows in natural ecosystems. Developing synergistic waste exchanges among process plants via industrial symbiosis (IS) is considered as one of the major means of implementing IE. Examples of IS networks include the Kalundborg industrial complex in Denmark (Jacobsen, 2006) and the Ulsan eco-industrial park in South Korea (Behera et al., 2012). A bioenergy park is a specific type of an IS network that is developed based on material (or energy) synergies, as in the case of the Handelö bioenergy cluster in Sweden (Martin and Eklund, 2011). Such systems offer potential economic gains (Gonela and Zhang, 2014) between bioenergy plants. The bioenergy park concept is related to integrated renewable energy parks (Subhadra and Edwards, 2010) and multi-functional bioenergy systems (Ubando et al., 2014).

Sustainability is achieved in IS networks through product, by-product, and utility exchanges among separate component plants by cooperating or collocating (Chertow, 2000). A similar integration technique such as the "total sites" concept was introduced earlier by Dhole and Linnhoff (1993) to plan energy integration and utility sharing in clusters of process plants. Meanwhile, the concept of locally integrated energy systems developed by Perry et al. (2008) and adapted by Kostevšek et al. (in press) in conjunction with a renewables-based network is a useful approach in developing optimum synergistic exchanges (e.g., heat and power) when designing bioenergy parks. The advantages of utilizing IS networks include the following: reduction of waste generated by maximizing by-product usage (Martin et al., 2014), optimal allocation of product resources (Aviso, 2014), negative carbon emissions through CO_2 sequestration (Ubando et al., 2014), increased economic gains for each component plant (Ng et al., 2014a), and equitable distribution of costs and benefits among bioenergy park members (Ng et al., 2015). Optimum economic performance was also demonstrated for single (Ng and Ng, 2013) or multiple owners of IS networks (Ng et al., 2013). Conversely, there are also inherent disadvantages of such network configuration which include increase in system complexity (Domenech and Davies, 2011), lack of flexibility due to technological lock-in (Boons et al., 2011), strong interdependence among component plants (Zhu and Ruth, 2013), diverse interests (i.e., economic and inherent safety) of plant owners (Ng et al., 2014b), and high vulnerability to system disruptions (Chopra and Khanna, 2014).

Bioenergy parks are highly-efficient and highly-integrated energy systems composed of stand-alone bioenergy plants. However, the resulting strong interdependency among component plants decreases network robustness (or increases vulnerability) against system perturbations (e.g., plant capacity disruption) (Chopra and Khanna, 2014). In this work, capacity disruption is defined as the reduction in the "as planned" production levels of the bioenergy plants and is similar to the concept of sectoral inoperability used in economic systems (Santos and Haimes, 2004). Disruption in one or more plants within a bioenergy park will result in a deviation from a baseline network configuration due to the rippling effects of failure (Haimes and Jiang, 2001). Propagation of failure occurs in interdependent and integrated networks such as in economic systems (Santos, 2006), eco-industrial parks (Zeng et al., 2013), and multi-functional energy systems (Kasivisvanathan et al., 2013). The work of Hsu and Rohmer (2010) primarily focused on the effects of disruption in the storage and manufacturing departments of a company involved in an industrial synergistic network. Disruptions or failures can be classified as cascading (i.e., disruption in one component causes the failure of another component), escalating (i.e., disruption in one component aggravates the failure of another independent disruption), and common cause (i.e., multi-component disruption) (Rinaldi et al., 2001). Specifically for IS networks, disruptions are initiated through changes in technology, relocation or eventual plant closure, catastrophic events, and changes in production levels. The consequences of such disruption depend upon the degree of interdependency between components plants, network topology (i.e., system connectivity), and the location of the failure in the network (Zhu and Ruth, 2013). Plant disruptions in a bioenergy park may result in an overall decrease in economic and environmental gains of the network. The consequences of disruptions are demonstrated to be greater if the source of failure originates from the critical component plants in the bioenergy park (Benjamin et al., 2015). These aforementioned risks necessitate the need to develop a framework to quantify and analyze the consequences of plant disruptions within a bioenergy park. The lack of integration of such risk analysis in biofuel and bioenergy supply chains is viewed by Seay and Badurdeen (2014) as a major barrier to achieving sustainability. This work is intended primarily to address this research gap.

Risk analysis is a qualitative and quantitative framework that can be used to provide risk-based information to IS network owners and decision makers about the overall risk in a bioenergy park. Kaplan and Garrick (1981) defined risk as the triplet of scenario, likelihood, and consequence. Recent works expanded the risk definition by incorporating a systems engineering approach (Haimes, 2009) and the concept of uncertainty (Aven, 2011). Probabilistic risk analyses (PRA) particularly focus on the use of probabilities (i.e., likelihood) in quantifying system risk (Aven and Reniers, 2013). PRA is a framework used to study the quality and quantity failure of drinking water systems (Lindhe et al., 2009), predict bioterrorism attacks in conjunction with event trees (Ezell et al., 2010), and in analyzing low probability but high consequence industrial disasters (Zio and Aven, 2013). A simplified expression of risk is presented in Eq. (1) which is based on the summary of risk definitions by Veland and Aven (2013),

$$\text{Risk} = P(A) \times C, \tag{1}$$

where $P(A)$ is the probability of an event (or scenario) A to occur and C is the corresponding consequence of that event,