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Resilient solar photovoltaic supply chain network design under business-as-usual and hazard uncertainties

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ABSTRACT

Unlike their inherent advantageous features, photovoltaic systems have not yet penetrated the market adequately due to their high price against other electricity generation options. To propel this fledgling industry further towards commercialization, the efficient and effective design of its supply chain is of paramount importance. In this regard, this study proposes a hybrid robust-scenario based optimization model to design a resilient photovoltaic supply chain under both business-as-usual and hazard uncertainties. To capture business-as-usual uncertainty, a customized robust optimization method is developed, which is capable of tackling correlated uncertain parameters and adjusting the level of conservatism in the solutions. Likewise, a number of proactive and reactive resilience strategies are incorporated into the model to ameliorate the resilience level of the concerned supply chain in the presence of hazard uncertainty. The capabilities of the developed model are explored by discussing a real case study via which helpful managerial insights are gained.

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1. Introduction

Spurred by the severe degradation of natural resources, ever-increasing the environmental concerns and energy demand, renewable energy sources (RESs) have aroused interests worldwide (Leung and Yang, 2012; Medina-Herrera et al., 2017). Among many types of RESs, solar energy is the most promising alternative to conventional energy sources since it is relatively distributed evenly around the world (Chang, 2010). One typical way to generate solar power is employing photovoltaic (PV) systems, which harness sunlight and turn it into electricity using semiconductor devices (Desideri et al., 2012). PV systems are envisioned to play an important role in the future energy supply owing to the following advantages: (1) abundance of solar energy; (2) reduction of GHG emissions such as CO_2, NO_X and SO_2; (3) low freshwater requirement to cool mirrors, suitable for the countries facing water scarcity; (4) operating without noise and jeopardizing natural resources; (5) having prolonged shelf-life; and (6) applicable to cases where the distribution of power through the network may not be desirable (Charabi and Gastli, 2011; Fthenakis and Moskowitz, 2000; Peng et al., 2013; Sawhney et al., 2014).

Despite the aforementioned advantages, one of the underlying obstacles to prompt growth of PV power generation systems is the high establishment and operating costs (Bhutto et al., 2012). According to Garcia and You (2015) and Mohseni et al. (2016), a prerequisite for growing such a nascent industry is the efficient design of its supply chain (SC), resulted from handling the strategic and tactical decisions in an integrated manner. Generally speaking, optimizing an SC as a whole affords the optimal solution for the relevant strategic and tactical decisions and leads to escape from sub-optimal solutions (Diabat et al., 2017; Sadjadi et al., 2016). Accordingly, as a principled way, the efficient design of PV SC (PVSC) can drastically improve the cost performances of the PV industry and propel it further towards commercialization. Notwithstanding the importance of integrated design of PVSC, only a handful of studies have ever attempted to design holistic PVSCs. In other words, virtually all of them have concentrated only on optimizing the downstream part of PVSC, i.e., specifying the solar plant locations. Azadeh et al. (2008) extended a hierarchical data envelopment analysis approach to determine the appropriate locations for PV farms. A somewhat similar work was proposed by Charabi and Gastli (2011), who deployed a geographic information system to evaluate the land suitability for solar plants implementation. Applying a deterministic optimization model, Chen et al. (2017) simultaneously determined the strategic and tactical decisions in a multistage PVSC.

The long-term impact of the design decisions incurs that SCs are hemmed in by a high degree of uncertainties. That is, not

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only intrinsic variations in the input data, but also unexpected natural and man-made disasters inevitably affect the capabilities of SCs (Sadghiani et al., 2015). Furthermore, in view of the fact that today's SCs are more prone to natural and man-made disasters (Fahimnia and Jabbarzadeh, 2016; Torabi et al., 2015), it is incumbent upon to take into account such uncertainties when designing an PVSC. This is further underlined in the current circumstances since the PV industry is still in an infancy phase of development and requires private sector investments (Wüstenhagen and Menichetti, 2012). In other words, uncertain and risky environments can jeopardize future investments in the PV industry. Based on two factors, i.e., the occurrence frequency and severity level, uncertainties can be fundamentally categorized into two main classes: 1) business-as-usual; and 2) hazard (Ponomarov, 2012; Tang, 2006).

Business-as-usual uncertainty is related to inherent variations in parameters, caused by the dynamic nature of the input data during the period. From the frequency and severity of occurrence points of view, this type of uncertainty corresponds to the case where the frequency of occurrence is high and the level of impact is low. In particular, in the PVSC network design (PVSCND) problem, business-as-usual uncertainty includes, but are not limited to, fluctuations in the costs and demand, arising from some global and domestic factors (Norberto et al., 2016; Shouman et al., 2016). Under such situations, considering deterministic values for uncertain input data can eventuate in sub-optimal or infeasible solutions and undermine the quality of the decisions taken (Ben-Tal and Nemirovski, 2000; Guzman et al., 2017a). However, to the best of our knowledge, scanty modeling efforts can be found in the relevant literature that devote to business-as-usual uncertainty. Stochastic programming (SP) and robust optimization (RO) are the two main paradigms to cope with this type of uncertainty in the optimization problems (Shahabi and Unnikrishnan, 2014). In spite of being a valuable technique to deal with business-as-usual uncertainty, SP suffers from some notable drawbacks. First, it needs the probability distribution information of uncertain parameters, whilst this is predominantly not possible in the real world since the lack of reliable historical data. Second, using SP method in the large real-life problems generally imposes a high computational complexity to the optimization model. Contrariwise, RO is a distribution-free method that aims at deriving the worst-case solution based on a predefined uncertainty set. It is also able to preserve the computational tractability of the primary model (Li et al., 2011; Yuan et al., 2016). In this manner, RO can be effectively utilized to withstand the inherent uncertainty of the input data in the optimization problems. RO methods can be categorized into two main groups, namely static and adaptive methods. When all the decisions are made before the realization of uncertain parameters, static RO methods can be applied to deal with business-as-usual uncertainty. On the other hand, adaptive RO methods tackle the sequential nature of decision-making processes, where some decisions are taken before the uncertainty is unveiled (so-called "here and now" decisions), while others are postponed after the uncertainty realization (so-called "wait and see" decisions) (Ben-Tal et al., 2004; Ning and You, 2018). Here, since all the PVSC decisions are made simultaneously before the uncertainty is revealed, we utilize a static RO method to handle the inherent uncertainty of the input data. One of the earliest studies on RO was taken by Soyster (1973), who proposed a linear RO model, often leading to an overly conservative solution that may be far from the optimal solution yielded by the nominal data. Later on, Ben-Tal and Nemirovski (1998), (2000) and El Ghaoui et al. (1998) independently developed the work of Soyster (1973) for various convex uncertainty sets. The findings and results of their studies were collected and offered in the Ben-Tal et al. (2009) book that at present is one of the main sources in the field of RO theory. At the same vein, Bertsimas and Sim (2004) proposed a new RO approach, which is able to flexibly adjust the conservatism level as well as retain the linearity of Soyster (1973)'s model.

As previously noted, the second category of uncertainty is termed hazard. Broadly speaking, hazard uncertainty stems from unavoidable natural and man-made disasters such as flood, earthquake and terrorist attack that has the low occurrence frequency and high-severity impact (Torabi et al., 2016). Based on anecdotal observations, when a hazard occurs, most SCs tend to collapse during the event and many of them cannot recover. For instance, according to Eskew (2004), 150 of 350 companies working in the World Trade Centre went out of business after the 1993 bombing there. Hazard can also trigger substantial operational and financial losses to firms (Ponis and Koronis, 2012; Ponomarov and Holcomb, 2009; Stecke and Kumar, 2009). This includes reductions in return on assets, return on sales and operating income, e.g., 93, 114 and 107%, respectively (Hendricks and Singhal, 2005), plus falls in stock market value, e.g., 10% (Hendricks and Singhal, 2003). These examples underscore the importance of addressing hazard uncertainty in SCs that should be realized by organizations. To respond to this need, an SC must be designed in such a way that in the hazard occurrence, it is capable of stipulating an effective response and recovering to its initial state, known as the cores of SC resiliency (Ponomarov and Holcomb, 2009). Conventionally, a number of proactive and reactive strategies such as fortification (e.g., Hasani and Khosrojerdi, 2016; Sawik, 2013; Torabi et al., 2015), dual/multiple sourcing (e.g., Hearnshaw and Wilson, 2013; Meena and Sarmah, 2013) and backup sourcing (e.g., Ratick et al., 2008) are deployed to improve the SC resilience.

Research on the concept of the SC resilience goes back to the early 2000s as the initial definitions were made (e.g., Christopher and Peck, 2004; Rice and Caniato, 2003). To date, a considerable deal of research has been carried out implementing a variety of methodological approaches from conceptual/theoretical modeling (e.g., Boin et al., 2010; Ponis and Koronis, 2012) to case studies (e.g., Johnson et al., 2013; Leat and Revoredo-Giha, 2013) and surveys (e.g., Park, 2011; Zsidisin and Wagner, 2010). However, apart from the fact that a hazard and its drastic consequences may affect the whole or part of an SC, the body of the literature addressing SC resilience using quantitative models is still very thin. Liberatore et al. (2012) exploited a three-level model to devise fortification plans in median distribution systems. Applying several proactive mitigation strategies, Torabi et al. (2015) designed resilient supply bases for global SCs. Fahimnia and Jabbarzadeh (2016) proposed a multi-objective optimization model to investigate the relationships between sustainability and resilience in an SC network design (SCND) problem. Gong and You (2017) considered some resilience enhancement strategies in a multi-objective optimization model for process systems. They also developed a tailored solution algorithm to overcome the computational complexity of the proposed model. It should be pointed out that the impact of hazard uncertainty is typically captured by embedding disruption scenarios in the optimization models. However, employing a large number of scenarios, which may dramatically increase the computational complexity of the model, is a serious challenge that such problems are entangled with.

Motivated by the above-mentioned discussions, this paper unveils a novel hybrid robust-scenario based optimization model to design an PVSC considering both business-as-usual and hazard uncertainties concurrently. To sum up, the salient contributions that distinguish this research from the ones existed in the literature can be stated as follows:

- The current study is relatively one of the early attempts, which systematically determines decisions across PVSC. This can play a prominent role to establish the efficient and effective busi-

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