Journal of Environmental Management 230 (2019) 319–334

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

# A facility location problem for sustainability-conscious power generation decision makers

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ARTICLE INFO

*Keywords:*
Sustainability performance measurement
Energy sector
Capacitated facility location problem
Double bootstrap data envelopment analysis

ABSTRACT

The practical implementation of a performance measurement system is an inevitable necessity for all levels of management to direct business operations towards maximal efficiency. In particular, academics' and practitioners' expectations have resulted in notable initiatives that incorporate sustainability assessment in managerial decision-making. The sustainability paradigm investigates practices and policies that simultaneously account for economic, environmental, and social aspects. Drawing on the perspective of a sustainability-conscious decision maker, this paper centers on the evaluation of logistical locations with capacitated production levels through a two-phase assessment procedure. To design a supervisory framework to measure the sustainability performance of the supplying facilities under investigation, we develop a double bootstrap data envelopment analysis model with undesirable factors in the first phase. We, then, use the obtained bias-corrected efficiency estimates in the second phase to establish sustainability-based policies in the context of facility location problems. The proposed model is applied to an energy case study of fossil fuel power plants in the United States. We present empirical evidence corroborating a considerable difference between the results of the case where the decision maker explores the environmental and social impacts of the power plants and the conventional formulation by which only financial outcomes are considered. Our numerical findings reveal that the proposed approach substantially diminishes greenhouse gas emissions at the cost of slight increases in total expenses. In addition to such an improvement in the environmental efficiency, we provide evidence of a dramatic enhancement in the social performance.

## 1. Introduction

In this study, we propose a two-phase framework that enables us to analyze a comprehensive objective function in the facility location context in the presence of variable costs, fixed costs, and sustainability considerations. The investigation of different aspects of sustainability development and integration of such practices into performance measurement models have attracted much attention. Irresponsible waste disposal, plastic pollution, water overexploitation, soot from power stations, and radioactive elements dispersed across vital ecosystems of the planet are serious threats that humankind is facing as a result of industrial activities dominating the planetary machinery.

The Intergovernmental Panel on Climate Change (IPCC) reports that the period of 1983–2012 was probably the warmest 30-year season of the last 1400 years in the Northern Hemisphere. Since the 1950's, humanity's activities profoundly have impacted the Earth such that the imminent geological epoch Anthropocene can come to bitter regret. The literature has seen a proliferation in environmental management research since the Earth Summit in Rio in 1992 (Reed et al., 2014). Consequently, international initiatives and nationwide legislation, such as the Kyoto Protocol in 1997 and more recently the Paris Agreement in 2016, have widely publicized ecological aspects. In addition to such environmental considerations, policy makers and researchers have promoted humanitarian solutions and investigated socially-friendly practices (Fry and Binner, 2016; Holguín-Veras et al., 2012; Sodhi and Tang, 2014). Accordingly, the recent research has explored many sustainability-oriented initiatives, where a three-dimensional lens outlines the impacts of business operations on the economy, the environment, and the society (Elkington, 1997). There is extensive evidence that both small and large enterprises have realized the importance of such sustainability considerations in creating new profitability streams (Hassini et al., 2012; Mincer, 2008). However, many managers still require more tangible evidence recognizing the need to account for ecological and societal concerns. Consequently, great interest in the quantitative

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https://doi.org/10.1016/j.jenvman.2018.09.066
Received 5 March 2018; Received in revised form 12 August 2018; Accepted 21 September 2018

evaluation of organizations' sustainability performance has arisen (Neely et al., 1995; Tajbakhsh and Hassini, 2015). We examine such assessment frameworks in this study and underscore the potential balance between the mentioned triple pillars.

In the current digital era, power failures can strike businesses without warning and lead to severe disruption to operations of hospitals, humanitarian camps, data centers, airports, and manufacturing facilities. The power outage occurred in the Hurricane Sandy in 2012 caused damages at the total $35.4 billion to the United States. The increasing demand from the provision of goods and services vindicates the essential need to examine energy markets' policies and operations. Accordingly, electricity is mission critical for many policy makers and organizations. Additionally, our interest in the energy sector in this article is driven by the significant pollution level of energy generation facilities. Sueyoshi et al. (2017) argue that energy efficiency solutions offer the most cost effective ways to overcome global warming issues and mitigate their severe consequences, such as heat waves, droughts, floods, and food crisis. We note that one may confuse energy efficiency with energy conservation, where the latter necessarily indicates the use of less energy rather than an optimal consumption level. IPCC releases statistics showing that massive fossil fuel consumption and land-use changes have increased $CO_2$ atmospheric concentrations by 40% since pre-industrial times, causing a more significant contrast in precipitation between wet and dry regions and between wet and dry seasons. Notably, a recent survey carried on by the World Resources Institute shows that the energy sector is the most polluting business in the world, representing 70% of global emissions over the past 10 years. More than 50% of total discharges are attributed to business operations in China, the United States, and the European Union. Green practices and outstanding achievements in Europe have encouraged international decision makers to carefully account for sustainability initiatives. The European Union Carbon Dioxide Emissions Trading Scheme is an example of such policies (Hong et al., 2016).

In this study, we look into energy production operations of the second-top global emitter, the United States, that sees 1.4% of increase in greenhouse gas emissions each year. The Environmental Protection Agency's data shows that more than 60% of greenhouse gas emissions from the US large facilities are discharged from power plants, among which fossil fuel stations are known to be major polluters. At the global level, however, greener practices have been promoted in this industry. The International Energy Outlook 2017 indicates that renewable energy (hydropower, wind, solar, and geothermal sources) and natural gas, with their combined share of global electricity generation rising to 57% in 2040, are the world's fastest growing forms of energy. Renewables are projected to provide 31% of global electricity generation in 2040, (the same share as coal), while wind and solar increase the most among non-hydroelectric renewable sources. However, developing countries' policy makers have continued to meet much of their country's energy demand by the consumption of fossil fuels. Expressly, the Energy Information Administration's recent report reveals that more than 75% of yearly energy production in the United States have been generated in fossil fuel units that consume coal, natural gas, crude oil, or natural gas plant liquids (NGPL). Fig. 1 illustrates how significantly the fossil fuel

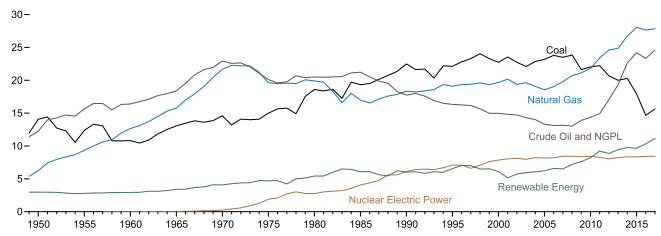


**Fig. 1.** The energy production overview by source in the United States (Quadrillion BTU/Year), extracted from the Energy Information Administration's monthly reviews.

sources have dominated the US energy generation industry since the 1950's. Despite the fact that coal overutilization has decreased, recently the country has peaked its natural gas, crude oil, and NGPL consumption. In such business environments, commonly-used efficiency metrics that support the rationality of fossil fuels mostly concentrate on economic development and financial outcomes (Jebali et al., 2017).

The primary purpose of the present study is to contribute to the sustainability performance literature. We investigate a capacitated facility location problem with multi-sourcing constraints (CFLPMS) whereby a central decision maker also pursues environmental and social objectives (Daskin, 1995). As opposed to a conventional location problem merely centering on financial objectives, a novel two-phase assessment framework is designed, whereby a data envelopment analysis (DEA) approach in the first phase measures the sustainability performance of the supply locations (Abraham et al., 1978). In the context of sustainability-oriented efficiency assessment, decision makers frequently face undesirable indicators for which higher levels of inputs and lower scales of outputs are preferred (Rolf et al., 2012; Hampf, 2014). This study is a first step toward integrating DEA frameworks with undesirable metrics and facility location problems, which takes into account environmental impacts and social aspects. Particularly, in the first phase of our assessment a double bootstrap DEA approach (Simar and Wilson, 2007) is discussed to overcome estimation issues (such as serial correlations and heterogeneity) that arise in the use of frontier methods for cross-section comparisons. In this process, we are also able to investigate the impact of explanatory variables on the sustainability-based efficiency estimates as a by-product of this methodological alternative. Consequently, a CFLPMS instance is explored in the second phase where the sustainability scores play a primary role in the assignment of the supply nodes to the demand points. Our proposed two-phase assessment framework is depicted in Fig. 2.

The practicality of the proposed model is discussed by applying the results to a power generation case. In this application, the high-ranking power units have the mission to meet the electricity requirements of demand points that represent the network locations most at risk for natural disasters. The major goal of the decision maker is to guarantee the power supply of such crucial locations while ensuring the collective impact of the selected power plants on the environment and the society is minimal. The numerical results demonstrate that the absence of a sustainable perspective in decision-making can bring forth statistically different solutions compared to the scenario of adopting a sustainability-oriented strategy. Expressly, the results strengthen the argument that environmentally- and socially-friendly decision makers can take into consideration a balance between financial outcomes and sustainability objectives.

The rest of the paper is organized as follows. In Section 2, we discuss related studies at the intersection of facility location, performance measurement, and sustainability development. Subsequently, we formulate a two-phase evaluation procedure in Section 3 that accounts for sustainability impacts of assignment decisions in CFLPMS. The computational results of applying the proposed framework to the energy sector are provided in Sections 4 and 5. Finally, Section 6 concludes this study and proposes further research questions.

## 2. Research context

Operations management researchers have characterized the sustainability paradigm from many viewpoints (Ahi and Searcy, 2013). The literature offers many applications of such a multidisciplinary context, among which are sustainability-based performance measurement, sustainable regulation, closed-loop network design, corporate social responsibility, humanitarian logistics, environmentally conscious lot-sizing, green procurement, and sustainable agricultural planning (Kleindorfer et al., 2005; Linton et al., 2007). Hassini et al. (2012) define business sustainability as "*the ability to conduct business with a long-term goal of maintaining the well-being of the economy, environment,*