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Resilience analytics with disruption of preferences and lifecycle cost analysis for energy microgrids

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ABSTRACT

Innovative technologies are presenting opportunities to improve resilience of energy plans for industrial and military installations. The investment rationale is complicated by uncertain future conditions across the system lifecycle, including technology, climate, economy, and others. This paper introduces *resilience analytics with scenario-based preferences* as follows. Risk is addressed here as the degree of disruption of priorities for investments in engineering systems. The particular concern of this paper is disruption from shifts in public values, and to evaluate the resilience of investment plans to such shifts. It recognizes resilience models as compilations of instantaneous framings of initiatives, objectives, stakeholder preferences, and uncertainties. Problem frames can be considered in series, where inputs to frames are the outputs of previous frames. Or frames can be considered in parallel, featuring joint inputs while addressing differing questions. This paper presents a case study of *resilience analytics* focusing on two quantitative frames. In the first frame, scenario-based preferences are used to identify combinations of factors disruptive to energy innovation at installations. In the second frame, estimation of lifecycle costs is performed with respect to factors that were identified as influential in the previous frame.

1. Introduction

Resilience of energy systems of military and industrial installations for a range of emergent and future conditions is important to national security and homeland defense, as well as economic development. Reliance on a publicly owned and aging grid infrastructure is a key challenge of the coming decade, and various agencies are encouraging the development of technologies that can help to assure that energy supplies meet critical demands at all times. Currently, fixed installations are 99% dependent on the commercial power grid to meet their electricity needs. The Defense Science Board [7] noted, "Critical national security and Homeland defense missions are at an unacceptably high risk of extended outage from failure of the grid," thus relating the resilience of missions to the resilience of underlying infrastructure. In this work, we emphasize energy resilience, or the assured access to reliable supplies of energy and the ability to protect and deliver sufficient energy to meet operational needs.

Resilience is generally defined as an ability to withstand, adapt to, and recover from a disruption. Resilience of a system or organization is generally measured as some function of the adverse change in performance it experiences after a disruption (its vulnerability) and its subsequent return to a desired performance level (its recoverability) [15,28]. Francis and Bekera [10] discuss the diverse definitions and usage of the term resilience and conclude that resilience analytics must include a focus on deep uncertainties and emergent conditions that bring about shifts in stakeholder preferences, methods for which are described in [39,17,13,23]. We consider *resilience analytics* as the descriptive, predictive, and prescriptive analytics to understand, design, and manage system performance across disruptive events to enhance their resilience.

When designing energy microgrids, stakeholders must prioritize the many potential design alternatives such as including natural gas microturbines, solar photovoltaics, biofuels, batteries and many others while considering multiple objectives such as reducing costs, reducing environmental impacts, and others. In this paper, we introduce *resilience analytics* of engineering systems to describe the disruption of prioritized alternatives by scenarios of emergent and future conditions. First, the focus of this paper is the *risk* defined as the degree of disruption of priorities for strategic planning. The disruption is caused

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by shifts in the preferences of stakeholders due to uncertain emergent conditions, which can be at least equal a challenge for engineering systems as physical, software, and other hazards [25,38,46]. In other words, *risk is the influence of scenarios to priorities*, referring to the ordering of initiatives or investments. A *scenario is comprised of one or more uncertain emergent conditions.* A *condition* refers to external or internal sources of risk to systems that may either adversely or favorably affect the performance of the system against a set of objectives. While it would be ideal to investigate the consequences of all of these conditions, limited time and budget necessitates the need for addressing conditions with the highest influence to prioritization. In this way, risk arises from shifts in weights of objectives, which in turn disrupts the prioritization of initiatives. For example, when considering energy investments consideration is given to multiple objectives such as reducing costs, increasing power reliability, and reducing environmental impacts, among others. The emergent conditions of stricter federal energy efficiency, conservation, and renewable energy requirements can be considered a *renewable policies* scenario under which stakeholders more strongly prefer the objective of reducing environmental impacts as compared to other objectives such as reducing costs. *Resilience analytics* thus identifies the scenarios that are potentially most disruptive to priorities. We represent the disruptiveness of scenarios through a simple metric of the shifts in rank across a set of initiatives. Thus, this paper does not deal with uncertainty in the usual way. Here, we chose to filter risk not by probability and severity but by the sensitivity of priorities to scenarios.

Second, a particular focus is considering multiple problem frames [2,36]. The paper describes how several published case studies are used to frame the same problem, and develops two additional *frames* (*Frame I* and *Frame II*, below) for illustration. The overlapping of *frames* is demonstrated to contribute to the toolkit of reliability engineering, in particular for the identification and refinement of system requirements supported by *resilience analytics*.

The overall direction of the paper is thus resilience analytics with multiple problem frames as a support for decision-making for reliability and safety of engineering systems.

2. Background

Historically, energy investment decisions were based on least-cost alternatives. However, the military now recognizes that it must incorporate other objectives or criteria into the priority-setting process. There have been several policy directives and Federal mandates in recent years that have moved Federal agencies towards energy security and environmental sustainability. These include the Energy Policy Act of 2005 [8], the Executive Order (EO) 13423 [9], the Energy Independence and Security Act of 2007 (EISA 2007), and most recently the Executive Order (EO) 13693. Some of the requirements in these policy directives include reducing facility energy intensity 30% by 2015 compared to 2003 baseline [EO 13423], reducing water consumption intensity relative to the 2007 baseline by 2% annually through the end of fiscal year 2015 [EO 13423] [9], and requiring renewable electricity consumption by the Federal government to not be less than 7.5% after 2013 [8]. To address both energy security and sustainability concerns, the 2009 Army Energy Security Implementation Strategy (AESIS) identifies the following five strategic objectives: (i) Reduce energy consumption, (ii) Increase energy efficiency across platforms and facilities, (iii) Increase use of renewable/alternative energy, (iv) Assure access to sufficient energy supplies, (v) Reduce adverse impacts on the environment [44]. Renewable and alternative energy sources such as biomass, landfill gas, municipal solid waste, hydrogen, hydropower, geo-thermal/pressure, micro-turbines, fuel cells, wind, tidal and solar are some examples of the many initiatives that military and industrial installations use to meet their energy security and sustainability objectives.

Even as energy planners for military installations address a plethora of resource options and multiple objectives, they face a dynamic, complex, and uncertain future. Emergent and future conditions related to technologies, political and regulatory changes, resource demand and supply shifts, and climatic changes, might significantly impact the resilience of energy initiatives. Of particular concern to energy planners is how current investment decisions will be impacted by future uncertainties. Changing federal, military, and business requirements will influence high-level energy security objectives, and thus the type of technologies that the installations will pursue. For example, an increase in the number and enforcement of renewable energy requirements at Federal buildings will direct attention more towards investigating renewable technologies that are feasible in the region. Changing state regulations such as renewable portfolio standards, carbon taxes, and utility tariff regulations influences the feasibility of various energy systems. Supply and demand shifts of oil and natural gas might affect availability and price of these resources. In general, emergent and future conditions can constitute deep uncertainties [17]. Deep uncertainty includes when parties to a decision do not know or cannot agree on the system model and event probabilities [24].

The above characteristics add to contentiousness of priorities across stakeholders. Recent literature has advocated the use of scenario planning and multicriteria analysis to seek resilient initiatives across scenarios of epistemic or deep uncertainty when probabilistic analysis is not practical [12,25,26,29,37]. Schroeder and Lambert [35] refine this concept with a focus on risk identification; identifying combinations of factors that are the most influential to prioritization. Their work builds on the 2009 ISO definition of risk as *the impact of uncertainties on objectives [16]*. Specifically, previous work has considered risk as how uncertain future conditions change the relative preference of objectives and consequently the prioritization of initiatives.

Catrinu and Nordgard [5] apply multicriteria decision analysis for risk analysis of electric system management subject to aleatory and epistemic uncertainties. Karvetski and Lambert [17] perform a scenario-based multicriteria analysis for selecting energy systems at a particular military base. Hamilton et al. [13] illustrate a scenario-based multicriteria analysis for evaluating research and development priorities at military installations. Tylock et al. [40] evaluate energy technology alternatives for a representative military base using a stochastic multi-attribute analytic approach to explore different priorities or weighting schemes in combination with uncertainties related to technology performance. So far, these analyses have been static views of a priority-setting problem. While they provide a systematic methodological process for identifying scenarios and resilient initiatives for a particular problem frame in time, most priority-setting situations do not start with a well-defined set of candidate initiatives, criteria, and emergent conditions. Thus existing methods need to be extended with iterations and continuity of analyses that reflect insight gained from prior iterations.

Emergent conditions for infrastructure plans can lead to changes in stakeholder preferences in several modeling frames. Examples include changes in preferences realized after major events including 9–11 (improve homeland security), Katrina (improve conditions of underrepresented groups), 2008 recession (improve fiscal accountability), Sandy (improve human migrations with respect to climate change), among others. Brito and de Almeida [3] recommend incorporating decision maker preferences into risk assessment for prioritizing energy investments.