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An information theory based robustness analysis of energy mix in US States

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ABSTRACT

In this study, we use Shannon entropy to study the evolution of the 50 United States (US) states electricity grid mix to identify regime shifts and steady transitions away from fossil fuels. In particular, a series of major events in the 1970s led most states in the US to look for partial alternatives to fossil fuels for electricity generation. We notably observe changes for 26 states between the years 1968 and 1980. Starting with the premise that a more diversified grid mix is preferable from a robustness viewpoint, and by using 2015 data, we then evaluate the response of all states under multiple energy source disruption scenarios and detect three different classes of states: vulnerable (10 states), moderately robust (17 states), and robust (23 states). Expectedly, some states are particularly vulnerable as they depend predominantly on a single energy source (e.g., West Virginia with 95% coal usage). In contrast, we find seven states (i.e., South Dakota, Illinois, Vermont, Connecticut, Maine, New York, and New Jersey) that have particularly robust energy mix, while having fossil fuel shares below 50% in 2015.

1. Introduction

Fossil fuels have traditionally been the primary energy source for electricity generation in the United States (US). Before 1970, fossil fuels were used to generate about 80% of the electricity. This proportion dropped to 71% by 1978. Two economic recessions (1973 and 1980), partly triggered by the two oil crises in the 1970s (Hamilton, 2011; Kerr, 1998; Schurr, 1983), resulted in a negative growth in the US gross domestic product (GDP) and a high unemployment rate ("Bureau of Labor Statistics, ", 2018). In 2015, after more than three decades, fossil fuels still accounted for 65% of all energy sources for electricity generation.

The events of the 1970s therefore had a substantial impact on the energy mix for electricity generation in a relatively short period of time—we quantify how much of an impact in this study. In particular, uncertainties linked with the availability of fossil fuels, the availability of cheaper fuels, accompanied by significant technological innovation, drove electric utility companies to diversify their energy source (Dooley, 1998; Estanqueiro, 2010; Margolis and Kammen, 1999; Weijermars et al., 2012). It is therefore not unreasonable to image that similar events could occur in the future. More generally, we need to recognize that states that rely on a single or few energy sources can be inherently more vulnerable to external shocks. This applies both to fossil fuel and non-fossil fuel energy sources; for example, fossil fuels can be vulnerable to shortages of supply (e.g., because of a war or economic crisis) and non-fossil fuel sources can be vulnerable to climate change (e.g., rainfall patterns for hydroelectric power). At the same time, severe external shocks and crises are highly uncertain by nature; some even occur in a cascading or escalating form (Petit et al., 2015). This uncertainty remains a vital challenge for robustness or vulnerability analysis (Ben-Haim, 2012; Kermanshah et al., 2017; Kermanshah and Derrible, 2017, 2016; Park et al., 2013; Wisetjindawat et al., 2017), and various models have been developed to understand uncertainty in any system (Dempster, 1967; Edwards, 1969; Ferson, 2002; Klir, 2005; Miranda, 2008; Shafer et al., 1976; Wald, 1945; Walley, 1996; Zadeh, 1965). In addition, and partly because of this uncertainty, the preferred approach in robustness analysis is often to analyze the worst case or extreme scenarios (Ben-Haim, 2012; Wald, 1945). For example, electric power networks have been analyzed comprehensively to assess their vulnerability to any type of failure (Cao et al., 2006; Carreras et al., 2001; Ding and Han, 2008, 2006; Mei et al., 2011), often using network science or graph models (Arianos et al., 2009; Chassin and Posse, 2005; Holmgren, 2006; Pagani and Aiello, 2013; Sun, 2005) to capture complex properties of urban infrastructure systems that have often evolved over long periods of time (Derrible, 2016a; Derrible, 2016b). In this article, we analyze the robustness of the electricity grid by focusing on the proportion of energy sources used for electricity generation, and we start from the premise that a more diverse energy mix is generally desirable from a robustness viewpoint. More precisely, as a state with a more diverse energy mix is more robust

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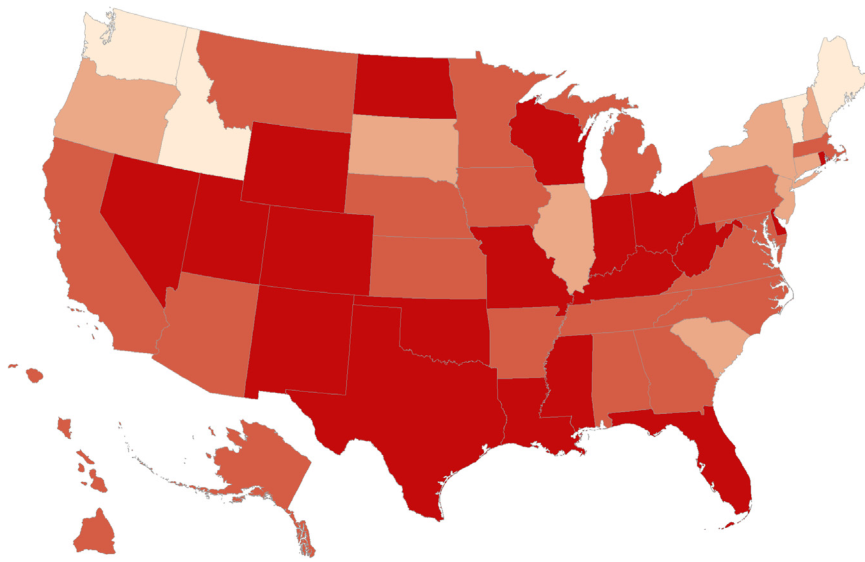

Fig. 1. Fossil Fuel Usage for Electricity Generation in the USA in 2015.

Table 1
Computation of Entropy for California in 2015.

Energy source	Usage in %	$p(x_i)$	$p(x_i)\cdot log(p(x_i))$
Nuclear	12	0.12	−0.25
Hydropower	8	0.08	−0.20
Geothermal	7	0.07	−0.19
Solar	9	0.09	−0.22
Wind	7	0.07	−0.19
Biomass	5	0.05	−0.15
Natural Gas	52	0.52	−0.34
Total	100	H = 1.53	

Table 2
Computation of ΔH for a disruption of 50% in California.

Energy source	$H(x)$	$H(x\Delta p, j)$	$\Delta H_{\Delta p,j}$
Nuclear	1.53	1.48	−0.055
Hydropower	1.53	1.48	−0.053
Geothermal	1.53	1.48	−0.051
Solar	1.53	1.48	−0.055
Wind	1.53	1.48	−0.051
Biomass	1.53	1.49	−0.045
Natural Gas	1.53	1.78	0.252
ΔH_R			−0.058

than a state relying on a single energy source, the main goal of this study is to numerically measure the diversity of each U.S. state energy mix. Towards that end, we define a measure of robustness using Shannon entropy and analyze the impact of several extreme energy mix scenarios for all US states.

According to Energy Information Administration (EIA), in 2016, 4.08 trillion kilowatt-hours (kWh) of electricity were generated at utility-scale facilities in the US; an electric utility-scale facility is defined as "a corporation, person, agency, authority, or other legal entity or instrumentality aligned with distribution facilities for delivery of electric energy for use primarily by the public" (EIA, 2017). This electricity was generated from nine sources of energy: 1) coal, 2) natural gas, 3) distillate fuel oil and kerosene-type jet fuel, 4) nuclear, 5) hydropower, 6) geothermal, 7) photovoltaic and solar thermal, 8) wind, and 9) wood and waste (biomass). In 2015, about 65% of the electricity was generated from fossil fuels (sources 1–3), 22% from nuclear energy (source 4), and 13% from renewable energy sources (sources 5–9). These proportions vary greatly from state to state, however. On the one hand, some states (e.g., Utah, Missouri) depend predominantly on fossil fuel sources, and on the other hand, some states (e.g., Vermont) depend almost entirely on renewable energy sources. Fig. 1 shows a map of the 50 US states grouped based on their fossil fuel usage for electricity generation in 2015, where we find that only 5 states used less than 25%, 7 states used 25–50%, 20 states used 50–75%, and 18 states used more than 75% fossil fuel to generate their electricity. In particular, 12 states used less than 50% fossil fuel sources to generate their electricity: South Dakota, Illinois, Vermont, Connecticut, South Carolina, Maine, New Hampshire, Washington, Oregon, New York, New Jersey, and Idaho. We note, however, that these 12 states used to rely mostly on fossil fuel sources to generate electricity, but they went through significant changes, either regime shifts or steady transitions, that we study in this article.

The main goal of this study is to measure and track changes in energy sources used for electricity generation in all 50 US states (excluding the District of Columbia (DC)) using EIA data (EIA, 2017) for the period spanning from 1960 to 2015. In particular, we use Shannon entropy to quantify electricity grid diversity, which we can then use to analyze the impact of major disruptions on the robustness of an electricity grid. More specifically, the objectives are to:

1. Define a measure of energy mix diversity using concepts of Shannon entropy,
2. Study the evolution of the 50 US states and identify regime shifts and steady transitions in their energy grid mix,
3. Evaluate the robustness of the 50 US states under multiple energy source disruption scenarios.

Briefly, among the 50 US states, we observe noticeable changes for 28 states with a change in entropy of 0.25 or more from the previous year. Moreover, most significant changes are observed for 8 states before 1968, 26 states from 1968 to 1980, and 17 states after 1980, indicating the significant impact of major events in the 1970s. Finally, in the robustness analysis, we find that 10 US states are particularly vulnerable as they depend on a single fossil fuel source for electricity generation. In contrast, we also detect 7 US states whose energy mixes are well distributed while having less than 50% fossil fuels.