The Electricity Journal 30 (2017) 55–66

Contents lists available at ScienceDirect

The Electricity Journal

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

Quantifying diversity of electricity generation in the U.S.

Tiffany Yue-wei Wu[a,b], Varun Rai[a,c,*]

[a] LBJ School of Public Affairs, The University of Texas at Austin, Austin, TX 78712, United States
[b] Jackson School of Geosciences, The University of Texas at Austin, Austin, TX 78712, United States
[c] Mechanical Engineering Department, The University of Texas at Austin, Austin, TX 78712, United States

ARTICLE INFO

Keywords:
Electricity
Diversity
Resilience
Redundancy
Path-dependence
Uncertainty
Evolutionary economics

ABSTRACT

Applying the Shannon-Wiener Index, Simpson Index and Stirling Index to primary energy source data from the U.S. Energy Information Agency reveals that the major drivers of diversity change have been the adoption of wind and natural gas.

1. Introduction

How should societies allocate their resources to ensure economic growth and development, while being sustainable and resilient? Conventional economics offers a broad response, contending that optimal allocation of resources through markets at all junctures should do the trick. But often there are externalities − factors that are not priced in goods and services transacted in the market − associated with the normal functioning of the economic system. For externalities, too, the standard response in the conventional approach is to internalize them through price adjustments *once the externalities are discovered*. For example, in the case of local air pollution, this involves putting a price on emissions of pollutants such as sulfur dioxide, particulate matter, etc. However, one criticism of such approaches is that they assume too much information availability and are built upon relatively rigid trajectories about the future technological state and the relevant knowledge space that inform policy design, whereas in reality *unknown* impacts of past technologies and technological change continuously surprise us. Overall, these arguments contend that, in the long run, policies relying entirely on markets and prices could lock us into sub-optimal outcomes.

As an alternative to the conventional economics approach, and partly inspired by the biological and ecological sciences, a strand of literature has emerged over the past couple of decades arguing that *diversity* is one of the central features for achieving long-term resilience even in socioeconomic systems. In this view, while price signals try to alleviate known system issues (i.e., *after* externalities have been discovered), diversity can help mitigate risks completely unknown to society now. Thus, broadly speaking, diversification "is what we can do when we don't know what we don't know (Stirling, 2010)."

The purpose of this study is not to address the debate between conventional and evolutionary economic approaches. Rather, we seek to address a much simpler empirical question: from a historical perspective, what does diversity look like in the U.S. electricity sector? Besides some thoughtful broad analysis (Hanser and Graves, 2007), we found the literature to be largely silent on this question, especially from an empirical perspective. Accordingly, the purpose of this article is to set an empirically-derived diversity baseline for the electricity sector in the U.S. and to qualitatively assess what has driven changes in diversity. Accordingly, we quantify diversity for each state in the U.S. based on the primary energy sources (PESs) used to generate electricity, offering a systematic U.S.-wide quantification of diversity and its evolution in the electricity generation sector. As older generation plants begin to retire, new generation technologies mature, and local and global environmental impacts of electricity generation and use become more prominent, we hope that our analysis would provide an empirical basis for considering how diversity might play a role in our energy infrastructure moving forward.

2. Background and related literature

When resilience becomes the focus, scholars who emphasize the ecological, evolutionary, and system dynamics aspects of economic systems contend that just markets and price signals are insufficient and

* Corresponding author at: LBJ School of Public Affairs, The University of Texas at Austin, Austin, TX 78712, United States.
E-mail address: raivarun@gmail.com (V. Rai).

http://dx.doi.org/10.1016/j.tej.2017.09.001

Available online 13 October 2017
1040-6190/

other system properties, such as thresholds (for transitions, tipping points, etc.) and diversity, become highly relevant (Rammel and van den Bergh, 2003; Perrings, 2006). While acknowledging the importance of price signaling from an economic perspective, Perrings points to the shortsighted actions market signals can force firms to make. For example, in some cases, market signals reward actions taken after a disaster rather than rewarding more economical preventative measures prior to a disaster (Perrings, 2006). Perrings offers two strategies to help decision-makers create policies that promote resilience and sustainability. First, it is important to understand system dynamics when implementing sustainable management system to prevent unwanted outcomes when market controls are implemented (for example, in the face of a disaster). Complete understanding, however, is difficult to obtain, thus policies and program implementation must continue to “experiment” with the system to keep learning about its internal dynamics and interactions with external factors. The second strategy is that of diversification. In ecology, diversity builds in functional redundancy that can help under various conditions, even when those conditions are unanticipated. Likewise, diversity can also help build redundancy in socioeconomic systems under various social and environmental conditions (Perrings, 2006).

Rammel and van den Bergh further discuss the benefits of diversity as it pertains to socioeconomic systems (Rammel and van den Bergh, 2003). First, diversity can enhance adaptive flexibility, i.e., the ability to adapt to changing conditions. That is because diversity in the system could help maintain functions that may be deemed unimportant under one set of social and environmental conditions but may become important and necessary as those underlying conditions change. Second, diversity can help mitigate path-dependence and lock-in. Most new technologies are based on existing technologies: “Technologies are born from technologies (Arthur, 2009).” This creates a certain trajectory for technology development (Dosi, 1982); as development along a certain technological trajectory deepens, other alternative trajectories become distant and less feasible, thereby giving rise to path-dependence. While not problematic under normal conditions, path-dependence can make altering the technological trajectory difficult at best and impossible at worst when such a need arises because of fundamentally new important information learned in the system. Path-dependence can be mitigated, however, through policies that focus on diversity to help promote development of technologies placed along different technological trajectories (Nill and Kemp, 2009). Third, diversity can help address unknown risks. Since socioeconomic systems are complex and evolving, many risks are unpredictable. A diversified system could help with adapting to these unknown risks (Rammel and van den Bergh, 2003). Stirling argues that diversification can be used as the main response against ignorance (Stirling, 1994). As Perrings states that decision-makers should strive for greater understanding of system dynamics and diversity (Perrings, 2006), Stirling contends that diversification could fill in the blanks that understanding leaves out (Stirling, 1994).

2.1. Diversity and resilience in the electricity sector

Energy security is often defined as “availability of energy *at all times* [emphasis added] in various forms in sufficient quantities and at affordable prices (Umbach, 2004).” Rather than focusing on long-term resilience, decision-makers often find themselves grappling with myriad near-term and known threats to energy security such as inefficient markets, poor planning, geopolitical unrest, dwindling fuel stocks, etc. These threats and their solutions are not trivial issues and play a major role in ensuring reliability of the system. However, addressing them is no substitute for long-term resilience planning, which entails dealing with unknown risks. Diversification can, therefore, play a complementary role for ensuring energy security by addressing unknown threats (Stirling, 2010).

Diversification of the electricity system can be very complicated due to the complex nature of the system. Utilities must supply reliability, quick response to changes in supply and demand at multiple locations, and increasingly cleaner power sources. Electricity systems also require large amounts of capital for construction of generators and other infrastructure. This requires long time horizons, involving financial institutions, regulators, utilities and other firms, and end users across multiple sectors. As a result of this complexity, diversity may be thought of being applicable in a variety of ways at multiple levels of planning (Hanser and Graves, 2007). Diversification can be applied to a number of factors such as technologies, manufacturers, and suppliers, PESs, and workforce. Limiting ourselves to any one factor misses the point of diversification (Stirling, 2010). However, as these systems are very complicated, this study aspires only to present a quantification of diversification and qualitatively assessing how diversification has changed over the years for states and regional entities in the U.S. We limit the scope to applying the methodology to PESs only, rather than the multitude of other relevant factors. Diversity in the electricity sector is regularly limited to only PESs since PESs are often used as a proxy to capture differences in flexibility of operation, intermittency of generation, environmental effects, technology maturity, supply chain characteristics, and others (Cooke et al., 2013).

2.2. Pitfalls of adopting diversity indices

Similar to a strictly neoclassical approach, a more evolutionary approach also has its own set of challenges. Diversity tends to cost more and may not pass muster in a traditional cost-benefit approach. That is because while lock-in and path-dependence could reduce adaptability and resilience in the long run, they also contribute to “economies of scale and scope, cumulative technological change, learning, network externalities, and complementary production factors (Rammel and van den Bergh, 2003).”

Implementing diversity can also be challenging because of subjectivities involved in the process. One issue with putting diversity to practice is that often options are prioritized based on desirable traits and selective distinction and not necessarily on purely objective constructs of diversity (Stirling, 2007; Yoshizawa et al., 2009). Stirling points to three traits of diversity: variety, balance, and disparity. Variety refers to the number of options. Balance refers to how proportionally reliant a system is on a particular option. Disparity refers to how different each option is (Stirling, 2010, 2007, 1994; Cooke et al., 2013). In all three diversity traits there is a hint of subjectivity, although more in some traits than others (Stirling, 1994; Cooke et al., 2013).

2.3. Diversity calculation methods

There are multiple *diversity indices* for calculating the diversity of various systems. These indices generally consider some portion of the three attributes of diversity: variety, balance, and disparity (Stirling, 1994; Cooke et al., 2013). For example, the UK currently uses the Shannon-Wiener Index to measure diversity of the electricity sector in the UK. The Shannon-Wiener Index − originally introduced by Claude Shannon to quantify information uncertainty − is given by the following equation:

$$H = -\sum_{i=1}^{n} (p_i \ln p_i),$$

where n is the number of options or categories (i.e., variety) and p_i is the proportion of option i among all options (i.e., balance). The quantity H is also known as the information entropy. The corresponding diversity is calculated as e^H. The maximum value of the Shannon-Wiener Index increases with increasing n and (for a given number of categories) occurs when $p_i = 1/n$ for all i.

The Shannon-Wiener Index places emphasis on variety and balance, but, compared to the other indices, it gives greater weight to the