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An EEMD-based multi-scale fuzzy entropy approach for complexity analysis in clean energy markets

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ABSTRACT

To measure the efficiency of clean energy markets, a multi-scale complexity analysis approach is proposed. Due to the coexisting characteristics of clean energy markets, the "divide and conquer" strategy is introduced to provide a more comprehensive complexity analysis framework for both overall dynamics and hidden features (in different time scales), and to identify the leading factors contributing to the complexity. In the proposed approach, ensemble empirical mode decomposition (EEMD), a competitive multi-scale analysis tool, is first implemented to capture meaningful features hidden in the original market system. Second, fuzzy entropy, an effective complexity measurement, is employed to analyze both the whole system and inner features. In empirical analysis, the nuclear energy and hydropower markets in China and US are investigated, and some interesting results are obtained. For overall dynamics, the US clean energy markets appear a significantly higher complexity level than China's markets, implying market maturity and efficiency of US clean energy relative to China. For inner features, similar features (in terms of similar time scales) in different markets present similar complexity levels. For different inner features, there are some distinct differences in clean energy markets between US and China. China's markets are mainly driven by upward long-term trends with a low-level complexity, while short-term fluctuations with high-level complexity are the leading features for the US markets. All these results demonstrate that the proposed EEMD-based multi-scale fuzzy entropy approach can provide a new analysis tool to understand the complexity of clean energy markets.

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1. Introduction

Confronted with double pressures of resource shortage and environment destruction, clean energy has been playing an increasingly important role in the energy system [1–3]. As one of the largest developing country, China has designed a series of clean energy programs to develop a low-carbon economy. According to the Twelfth Five-Year Plan, China's non-fossil fuels are expected to reach 15% of total primary energy consumption by 2020. However, China's clean energy is still at a relatively low-level development stage, accounting for approximately 24.4% of total domestic electricity production in 2014, according to China Statistical Yearbook. In contrast, the US clean energy has otherwise undergone a longer development history, accounting for about 32.5% of total domestic electricity production in 2014, according to International Energy Agency (IEA). Furthermore, US became one of the largest clean energy producers, with approximately 32.8% of global nuclear electricity generation and 7.1% of global hydropower generation in 2014. Due to the importance of clean energy, this study tends to analyze clean energy markets, especially the two typical discrepant markets (i.e., China's and US clean energy markets), which can further offer helpful insights into policy designs for clean energy development.

As for energy market analyses, numerous studies have been initiated by using the complexity characteristic as a vivid estimator responding to market performance, e.g., market efficiency [4,5] and long-term memory [6]. On the one hand, the complexity can be viewed as one of the most essential measurements, which covers or is at least closely related to all the other data characteristics especially within the nonlinear system theory [7]. On the other hand, energy markets have been fully shown to be typical complex systems, presenting coexisting characteristics of nonstationarity, nonlinearity, chaos, fractality, cyclicity, seasonality, saltation, stochasticity, etc. [8]. Accordingly, the complexity

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can provide an overall description for such a market situation. Generally, a higher-level complexity indicates a more intricate, disordered, irregular market system, responding to market efficiency and maturity [9]. Therefore, this study tends to analyze the clean energy markets in China and US in terms of complexity, to explore and compare their market efficiency and long-range correlations.

Generally, the complexity measurements fall into three groups, i.e., fractality, chaos and entropy [9]. Among them, entropy, a thermodynamic statistic, can provide a vivid description directly for system disorder [10]. Generally, a larger value of entropy refers to a higher level of complexity, in which more irregular factors exist impacting the data dynamics. Due to such a merit of visualization, diverse entropies have been developed for energy market analyses, e.g., approximate entropy (ApEn) [11], sample entropy (SampEn) [12], Fuzzy entropy (FuzzyEn) [13,14], permutation entropy [15], etc. Particularly, FuzzyEn has been widely employed as a promising measurement for market efficiency, with its unique merits of continuity and convexity [10]. Unlike SampEn and ApEn with Heaviside function, FuzzyEn employs a fuzzy membership function to measure the diversity across hidden patterns, which allows a much more stable result and effectively avoids super-sensitivity to the tolerance parameter. Due to these virtues, FuzzyEn has been applied to different data dynamics such as biogeographic data [17] and medical data [18]. However, to the best of our knowledge, there were few studies on energy market analysis using FuzzyEn, not mention to clean energy markets. Therefore, this study especially introduces this stable and effective estimator, FuzzyEn, for clean energy markets, which helpfully fills in such a gap with its application to energy markets.

Due to the coexisting characteristics of market dynamics, the interesting concept of “divide and conquer” has recently been introduced to propose multi-scale entropies for investigating inner features on different time scales. For fault diagnosis, Liu and Han [18] employed a time-frequency method to decompose the non-stationary vibration signal of a roller bearing into a number of product functions at different frequency-bands, and formulate a multi-scale entropy using SampEn across scales. Zheng et al. [19] developed a multi-scale FuzzyEn for rolling bearing fault diagnosis, in which coarse grained vectors with different scale factors are generated and FuzzyEn is employed for complexity measurements. Liu et al. [20] applied empirical mode decomposition (EMD) and entropy to diagnose circuit breaker faults. Similarly, Zhao et al. [21] applied EMD and FuzzyEn to high-speed rail fault diagnosis. Wang et al. [22] formulate an EMD-based multi-scale entropy for analyzing traffic signals. However, to the best of our knowledge, such emerging multi-scale complexity analysis approaches have not yet been applied to energy market analysis. For multi-scale analysis tool, given that EEMD is an improved EMD effectively addressing the mode mixing problem [23,24], EEMD is especially introduced here to formulate a novel multi-scale complexity analysis approach—EEMD-based FuzzyEn which is a reasonable extension to the works in Refs. [20–22] using EMD.

Generally speaking, due to the coexisting characteristics of clean energy markets, a novel EEMD-based multi-scale fuzzyEn approach is proposed for complexity analysis based on the strategy of “divide and conquer”, which provides a more comprehensive analysis for not only the overall market dynamics but also different inner features (on different time scales). In the proposed approach, EEMD is first implemented to capture meaningful hidden features from the original clean energy markets. And then FuzzyEn is applied to the complexity measurement of both the overall system and the inner features.

The main purpose of this paper is to propose a novel EEMD-based multi-scale fuzzy entropy approach to investigate the complexity of clean energy markets in China and US, due to the coexisting characteristics of clean energy markets. The remainder of the paper is organized as follows. Section 2 formulates the novel EEMD-based multi-scale complexity analysis approach. For illustration, the clean energy markets in China and US are thoroughly analyzed, as the empirical results discussed in Section 3. Section 4 concludes the paper and outlines the major directions for future research.

2. Methodology formulation

Due to the coexisting characteristics of clean energy markets, this section formulates a novel EEMD-based multi-scale fuzzy entropy (FuzzyEn) approach based on the strategy of “divide and conquer”, to provide a more comprehensive complexity analysis for both the whole data dynamics and various inner features (on different time scales). In the first step, EEMD, a competitive multi-scale analysis tool, is first implemented to decompose the clean energy data into meaningful, independent components on different time scales. In the second step, FuzzyEn, an effective, stable complexity measurement, is applied to the whole clean energy market dynamics and the various hidden features. Accordingly, the general framework of the proposed appraoch can be formulated, as illustrated in Fig. 1.

Two major steps are involved in the proposed approach, i.e., multi-scale analysis and complexity analysis.

Step 1: Multi-scale analysis

The original series data of clean energy market are first decomposed by using the EEMD algorithm into a set of intrinsic mode functions (IMFs) and one residue, responding to different specific features on different time scales. Furthermore, given that some specific components with similar time scales respond to a similar meaningful factor, the fine-to-coarse (F2C) reconstruction is further implemented to integrate similar features into main components, including a short-term fluctuation on a relatively short time scale, a medium-term process on a relatively long time scale, and a long-term trend with the time scale in the above sample period [8].

Step 2: Complexity analysis

The FuzzyEn statistic, an effective complexity measurement, is utilized to analyze both the overall dynamics (i.e., the original series data) and various inner features (i.e., the extracted components on different time scales), to provide a comprehensive complexity analysis for clean energy markets and to identify the leading features contributing to complexity.

The following two subsections describe the corresponding techniques, i.e., EEMD and FuzzyEn, respectively.

2.1. Ensemble empirical mode decomposition (EEMD)

EEMD was proposed by Wu and Huang [25] to effectively overcome the intrinsic drawbacks of EMD, i.e., mode mixing. Different from traditional multi-scale analysis tools (e.g., Fourier and wavelet decomposition), the EMD family are empirical, intuitive, direct, self-adaptive data processing techniques, and have been repeatedly proven to be powerful for nonlinear, non-stationary and complex systems [23,24].

The original EMD, developed by Huang et al. (1998) [26], assumes that data with high-level complexity might possess many different coexisting modes of oscillations in terms of IMFs at the same time. The main purpose of EMD is to extract these IMFs from the original time series. Mathematically, IMFs must meet the following two conditions: (1) in each function, the numbers of extrema and zero-crossings are the same or different at the most by one; and (2) each function is symmetric with respect to local zero mean. Furthermore, the decomposition process is performed under the following assumptions: (1) there exist at least one maximum

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