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Oscillation characteristic study of wind speed, global solar radiation and air temperature using wavelet analysis

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HIGHLIGHTS

- Wind speed, solar radiation and temperature are investigated using wavelet analysis.
- All the three time series used show significant correlation with annual period.
- Wind energy and solar energy can play complementary role in power generation.
- The research idea can be extended when designing energy project across regions.

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ABSTRACT

In this paper, 10-year meteorological data observed at Taipei, Taiwan, from 2006 to 2015, are studied to investigate the inherent correlation between renewable resources. The data are investigated in the time-frequency space using wavelet analysis including wind speed, global solar radiation and air temperature. Through the wavelet transform of the time series, the related cross wavelet transform, wavelet coherence and phase angle are obtained. The results show that the wavelet power spectra exhibit prominent oscillations at annual and half-year periods for the three kinds of meteorological data, while some oscillations for other periods do not show a regular pattern. Wind speed spectrum is more irregular than the other two types of data due to climatic and geographic factors, whereas temperature has the most regular form. From the cross wavelet transform of data pairs, it is seen wind speed and solar radiation have an anti-phase correlation, implying that wind and solar energy can be used in complementary roles in electricity generation in this region. The results of wavelet analysis coincide with the variation trend of the monthly mean of the meteorological data over the 10-year period. Wavelet analysis is a robust tool for the oscillation characteristic study on time series data.

1. Introduction

Keeping in view the imminent shortage of fossil fuels and environmental concerns related to their use, the development and utilization of renewable energy has assumed great importance around the world [1–6]. Wind energy and solar energy are the most important renewable resources being developed today. Wind and solar energy can be converted to electrical power by wind turbines and photovoltaic (PV) cells, respectively [5–10]. The power generated by wind turbines and PV cells is generally delivered to the national grid. Using both simultaneously can enhance the grid system's reliability and performance. Therefore, it is crucial for engineers to understand their inherent characteristics in the design of energy projects [11–15].

For a time series, the Fourier transform or short-time Fourier transform can be applied to study its oscillation characteristics such as periodicity, amplitude magnitude and phase angle [16,17]. As reported in literature [18–23], geophysical time series are complex and are considered non-stationary processes. In this context, the wavelet transform method competes with traditional mathematical tools used in spectral analysis. Wavelet transform represents convolution between wavelet coefficients and time series of the signal. After wavelet transformation, the internal characteristics of the signal are spread to the time–frequency domain, called scalogram, by which the local feature for any time and frequency can be detected.

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Nomenclature

a	scale parameter
b	translation parameter
COI	cone of influence
$P_x(\cdot)$	wavelet power spectrum
t	time
$W_x(\cdot)$	wavelet transform
$W_y(\cdot)$	wavelet transform
$W_{xy}(\cdot)$	cross wavelet transform
$WC_{xy}(\cdot)$	wavelet coherence
$\overline{W}_x(\cdot)$	smoothed wavelet spectrum
$\overline{W}_y(\cdot)$	smoothed wavelet spectrum
$\overline{W}_{xy}(\cdot)$	smoothed cross wavelet spectrum
$x(\cdot)$	time series
$y(\cdot)$	time series
Greek letters	
$\psi(t)$	mother wavelet
$\psi(\frac{t-b}{a})$	daughter wavelet
ω	modulation frequency
$\theta_{xy}(\cdot)$	phase angle

Wavelet transformation has been used in various fields of research [18–35]. Torrence and Compo [18] applied the wavelet transform to analyse the inherent correlation between El Nino sea surface temperature and Southern oscillation index; they concluded that these data reveal higher power during the periods 1880–1920 and 1960–90, as well as a 15-year modulation of variance. They also discussed mother wavelet functions, cross wavelet transform, coherence and phase angle. Grinsted et al. [19] studied the geophysical time series data, i.e. the Arctic oscillation index (from December 1851 to February 1997) and the Baltic maximum sea ice extent record (from 1720 to 2000), through cross wavelet transform and wavelet coherence. They asserted that phase angle can be used to examine the mechanistic models of physical relationships between the time series. Velasco and Mendoza [20] used wavelet analysis to study the relationship between solar activity and climatic oscillation over a long-time scale. They found that climatic oscillations and solar phenomena show clear coherence for different periods, which may imply a modulation of solar activity. Jose et al. [21] applied wavelet analysis to study wind velocity and temperature data measured in 1999, in the Amazon forest to investigate the turbulence interaction between them. Chellali et al. [22] studied the wavelet power spectrum for both wind speed and temperature data observed at Adrar, Algeria, from 2005 to 2008. They concluded that the wind and temperature data reveal great coherence in synoptic and intra-seasonal bands. Avdakovic et al. [23] employed the wavelet transform to analyse the wind speed's characteristics and concluded that it is a useful tool for wind energy's potential assessment. Siddiqi et al. [24] decomposed the wind speed time series to several sublevels through wavelet transform to remove noise from it and figured its inherent content. Hussain and Al-Alili [25] presented a new approach for model validation in solar radiation by using wavelet phase and frequency coherence analysis and concluded that the wavelet transform can be used to capture transient features in a signal. Mohammadi et al. [26] proposed a hybrid approach by combining the support vector machine with wavelet transform to predict horizontal global solar radiation in Iran and concluded that the wavelet-combined approach outperforms other approaches. Deo et al. [27] adopted a wavelet-coupled support vector machine model to analyse global incident solar radiation based on six types of meteorological measurements in Australia and found that the adopted model shows high performance considering various statistical parameters. Other wavelet-based studies related to the topic of renewable energy are also available in the literature, but they mainly focus on the forecasting of time series by using wavelet theory, e.g. for wind speed time series [36–40] or for solar radiation [41,42]. They also suffer from the drawback that they focus only on a single kind of renewable energy.

In this paper, a new idea to the research field is proposed; we simultaneously study three kinds of meteorological data, wind speed, global solar radiation and air temperature, through wavelet analysis. The meteorological data were observed every 10 min at Taipei, from 1 January 2006 to 31 December 2015, by the Central Weather Bureau, Taiwan. Taipei is selected here as case study to show the research idea. The 10-min data were transformed to daily data by taking the arithmetic average in the subsequent analysis. It should be mentioned here that the air temperature in Taiwan reflects the demand of electricity as illustrated in [43]. The electricity demand is high when the air temperature is high in summer and it reduces when the temperature is low in winter. Meanwhile, for a particular region, wind and solar energy may have some specific correlation that has not been reported in the literature. Investigating how the three kinds of meteorological data correlate with each other could help engineers integrate wind and solar power generation in a hybrid system. The main purpose of the present study is to carry out a comparative analysis of renewable resources using wavelet analysis. To our knowledge, this is the first study of its kind.

2. Wavelet analysis

The wavelet transform of a time series $x(t)$ is calculated as [18,22]:

$$W_x(a,b) = \int x(t)\psi\left(\frac{t-b}{a}\right)dt \tag{1}$$

where $\psi(t)$ is called the mother wavelet. It has a finite duration, a finite energy and zero mean. $\psi(t)$ can be dilated and shifted along the time axis by using the scale parameter a and the translation parameter b, respectively; it is then expressed as $\psi(\frac{t-b}{a})$, which is called the daughter wavelet. The wavelet power spectrum (i.e. scalogram) is defined as the square of the wavelet transform:

$$P_x(a,b) = |W_x(a,b)|^2 \tag{2}$$

Note that the scale parameter relates to the frequency or period on the scalogram, while the translation parameter stands for the location on the time axis.

Many wavelet functions are available in the literature. The Morlet wavelet is selected in this paper because it consists of both real and imaginary parts that enable it to investigate a signal's coherence and phase angle. Morlet wavelet is expressed as

$$\psi(t) = \pi^{-1/4}\exp\left(-\frac{t^2}{2}\right)\exp(i\omega t) \tag{3}$$