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Day-ahead spatio-temporal forecasting of solar irradiation along a navigation route

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HIGHLIGHTS

- It solves the problem of maritime spatio-temporal forecasting for the first time.
- A new method EEMD-SOM-BP is proposed for maritime forecasting of solar irradiation.
- An asymmetric four-parallel structure of SOM is proposed to mine data features.
- Three experiments are performed to determine the optimal settings of EEMD-SOM-BP.

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ABSTRACT

Owing to a shortage of fossil fuels and environmental pollution, renewable energy is gradually replacing fossil fuels in the power systems of hybrid ships. To exploit fully solar energy by the successful day-ahead scheduling of ships, this work proposes a new day-ahead spatio-temporal forecasting method. Ensemble empirical mode decomposition (EEMD) is used to extract data features and decompose original historical data into several frequency bands. After the original data are processed, data from the four land weather stations that are closest to the ship and self-organizing map-back propagation (SOM-BP) hybrid neural networks are used to forecast the solar radiation received by the ship in the next 24 h. Multiple comparative experiments are implemented. The results show that the EEMD-SOM-BP spatio-temporal forecasting method can accurately forecast the solar radiation on a ship that is sailing along a navigation route.

1. Introduction

With the depletion of fossil energy and severe environmental pollution, renewable energy generation technologies have been developed rapidly in recent years. A considerable number of ships that run on renewable energy have been constructed and most use a hybrid power system that combines solar energy with fossil fuel [1]. Solar irradiation forecasting plays a very significant role in the operation and scheduling of ships that use solar energy. Recently, interest in the development of renewable energy forecasting has been increasing [2–6]. 1. The numerical weather prediction (NWP) model, which is established from many historical data and experiences of meteorological experts, is suitable for forecasting solar irradiation over a time horizon of more than 6 h. 2. For shorter time scales of seconds to minutes, meteorological satellites and whole sky imagers can be efficiently used [7]. 3. Data-driven statistical models are the most widely used and are undergoing rapid development [8–10].

Nowadays the construction of renewable distributed power sources has motivated a rapid increase in research into the spatio-temporal forecasting of renewable energy. Spatio-temporal forecasting is the use of historical data from multiple locations close to a target location or the relationship among meteorological parameters within a region to forecast the future state at the target location. The fundamental basis of the spatio-temporal prediction of solar/wind energy is that the solar radiation/wind speed at multiple locations are always interrelated through the cloud/wind cluster in the region [11]. Currently, many spatio-temporal prediction methods are used in the field of solar irradiation/PV power prediction [12–15]. These methods fall into three categories, which are spatio-temporal statistical methods, pure data analysis methods and image processing methods. In spatio-temporal statistical methods, traditional statistical methods are used to model environmental processes in a region. After removing the diurnal trend

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Fig. 1. Nine weather stations and navigation route.

Table 1
Hourly data used in EEMD-SOM-BP method.

ANN dataset	Meteorological parameter	Location
Training and CV input Test input	Solar irradiation, wind speed, wind direction, temperature	9 land weather stations
Training and CV output Test output	Solar irradiation	Ship navigation position

of solar irradiation and deforming the geographical coordinates to establish spatial stationarity, Yang [16] used a time-forward kriging method to forecast hourly spatio-temporal solar irradiance data from ten weather stations in Singapore. Some regression models, such as the functional coefficient autoregressive model [17], the spatio-temporal ARMA (STARMA) model [18] and the spatio-temporal vector autoregressive (VAR) model [19], use separable/non-separable covariance structures or clearness index analysis to describe the spatio-temporal relationships among sites. Pure data analysis methods mine historical data and then fit spatio-temporal relationships among meteorological parameters within a region. Federica [20] transformed daily data over an eight-year period into uncorrelated data using Principal Component Analysis (PCA), revealing the effectiveness of the method. Dong [21] used a self-organizing map (SOM) ANN to divide the input space into regions based on the characteristics of the data. For image processing method, Chow [22] used the variational optical flow (VOF) method to analyze the motion of clouds using data that were obtained using a ground-based sky imaging system. However, to solve more complex and difficult spatio-temporal prediction problems, these methods should be combined with each other.

Although accurate solar energy forecasting has repeatedly been proved to improve the penetration of photovoltaic power, and to reduce system operating risks and costs [23,24], no solar forecasting method for hybrid ships yet exists. Researchers can only use land-based solar energy prediction methods to forecast maritime solar irradiation. Clearly, doing so yields inaccurate predictions, which are useless for subsequent research into marine power systems. Unlike in a land-based spatio-temporal forecasting problem, in a maritime problem, the predicted target location (vessel) is always moving. The problem is therefore more complex than a land-based renewable energy prediction problem with fixed locations/stations. Obviously, spatio-temporal statistical methods can only profile topological relationships among fixed points [25,26]. And Pure data analysis methods, which are used mainly to mine relationships within a region, are also unable to solve maritime forecasting problems independently [27]. Thus in this paper, SOM networks, a pure data analysis method, are used to split the route into multiple regions. Then BP networks, a statistical method, are utilized to fit spatio-temporal relationships among fixed points in each region. Moreover, access to maritime meteorological data is limited for reasons of national security. Most weather stations are in cities rather than at sea, and whole sky imagers cannot be used at sea, too [28]. The lack of meteorological data at sea makes the problem of maritime renewable energy forecasting challenging. Therefore, limited data must be reconstructed by EEMD method to simplify the problem.

This work proposes a new combined EEMD-SOM-BP method for solving maritime spatio-temporal solar irradiation forecasting problems. Previous research has demonstrated that artificial neural networks (ANN) are the most effective means for solving such complex hourly solar irradiation/PV power forecasting problems [29–32]. However, owing to their finite convergence ability, the primary data