



Short-term global horizontal irradiance forecasting based on a hybrid CNN-LSTM model with spatiotemporal correlations

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ABSTRACT

Accurate short-term solar irradiance forecasting is crucial for ensuring the optimum utilization of photovoltaic power generation sources. This study addresses this issue by proposing a spatiotemporal correlation model based on deep learning. The proposed model first applies a convolutional neural network (CNN) to extract spatial features from a two-dimensional matrix composed of meteorological parameters associated with a target site and its neighboring sites. Then, a long short-term memory (LSTM) network is applied to extract temporal features from historical solar irradiance time-series data associated with the target site. Finally, the spatiotemporal correlations are merged to predict global horizontal irradiance one hour in advance. The prediction performance and generalization ability of the proposed CNN-LSTM model are evaluated within a whole year, under diverse seasons and sky conditions. Three datasets are involved for case studies, which are collected from 34 locations spread across three different climate zones in Texas, USA. Moreover, the performance of the CNN-LSTM model is compared with those obtained using the CNN, LSTM, and other benchmark models based on five evaluation metrics. The results indicate that the proposed model has advantages over the other models considered and provides a good alternative for short-term solar radiation prediction.

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1. Introduction

The rapid development of the global economy has increasingly relied on fossil fuels such as oil and coal, resulting in heavy environmental pollution and greenhouse effects [1]. Hence, the exploitation of renewable energy sources has generated increasing interest in pursuit of environmental protection worldwide [2]. Among these energy sources, solar energy represents one of the most promising options, particularly its use in photovoltaic (PV) power generation [3]. However, solar irradiance can be heavily influenced by rapid changes in cloud conditions, and is therefore stochastic in nature [4]. This variability can have a substantial impact on power grid security when connected with large scale PV generation. Therefore, developing accurate short-term solar irradiance forecasting models is crucial for ensuring the optimum dispatch and management of power systems, particularly with increasing penetration of PV power generation [5].

A considerable amount of research has been devoted to

developing solar irradiance forecasting models. From the literature, these forecasting models can be divided into four main categories based on the input data adopted [6–9]: (1) numerical weather prediction (NWP) models based on atmospheric data [10–12]; (2) image-based models [13]; (3) statistical models based on historical data [14,15]; (4) hybrid models based on multiple types of input data [16–19].

Local cloud cover information is inferred by NWP models through the dynamic modeling of the atmosphere [20]. This method has been widely used for solar radiation forecasting 6–48h ahead [21]. However, this approach is typically ill-suited for conducting short-term solar irradiance prediction due to the high calculation costs involved [22]. In addition, NWP models do not readily capture real-time temporal relationships between solar irradiance and meteorological factors, which further limits their short-term solar irradiance prediction capabilities [23].

Unlike NWP models, image-based models directly capture cloud cover information from satellite or ground-based sky images for conducting solar irradiance forecasting. The high spatial and temporal resolutions of satellite and ground-based images facilitate the detailed tracking of cloud motion [6,21]. As such, image-based

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Nomenclature

| | | | |
|-------|--|-------|--|
| ARMA | auto-regressive moving average | PSM | physical solar model |
| ANN | artificial neural network | PW | precipitable water (cm) |
| BSh | hot semi-arid climate | RMSE | root mean square error (W/m ²) |
| BSk | cold semi-arid climate | RH | relative humidity (%) |
| CNN | convolutional neural network | ReLU | rectified linear unit |
| CARDS | coupled autoregressive and dynamical system | RNN | recurrent neural network |
| Cfa | humid subtropical climate | R | correlation coefficient |
| DPT | dew point temperature (°C) | SVM | support vector machine |
| GHI | global horizontal irradiance (W/m ²) | SZA | solar zenith angle (degrees) |
| LSTM | long short-term memory | T | temperature (°C) |
| ML | machine learning | WS | wind speed (m/s) |
| MAE | mean absolute error (W/m ²) | WD | wind direction (degrees) |
| MSE | mean square error | 2D | two-dimensional |
| NWP | numerical weather prediction | μ | mean value of the global horizontal irradiance (W/m ²) |
| nMAE | normalized MAE (%) | S | number of sites |
| nRMSE | normalized RMSE (%) | F | number of meteorological parameters |
| PV | photovoltaic | k_t | clearness index |

models provide an effective solar irradiance forecast horizon ranging from minutes to several hours in advance [13,24]. Nevertheless, the high cost of image capture facilities limits the widespread use of image-based models.

In contrast to the previous two models, statistical models are based on historical solar irradiance data, and are usually applied to forecasting timescales ranging from 5 min up to 6 h [6,25,26]. Typical examples of statistical models include the auto-regressive moving average (ARMA) model [14] and the coupled autoregressive and dynamical system (CARDS) model [15]. The ARMA model is a good choice for predicting the future values of a specific solar irradiance time series, but the time series must be stationary. The CARDS model has been demonstrated over the past several decades to capture the linear relationships between historical data and future irradiance values accurately [26]. However, the CARDS model fails to capture complex nonlinear relationships accurately, which can greatly detract from its prediction performance when these conditions arise in historical data.

Although statistical models are often a good choice for conducting solar irradiance forecasting based on time series data, they can only consider historical data, and other relevant weather conditions affecting solar irradiance cannot be included within the forecasting process. This shortcoming can be overcome by integrating different types of input data in hybrid models via machine learning (ML) approaches. ML approaches possess the advantage of extracting complex nonlinear features from multiple inputs [27]. A number of ML models, such as artificial neural network (ANN) [28–30] and support vector machine (SVM) [29], have been widely used in solar radiation forecasting due to their relatively good performance when employed with small data sample sizes. In Ref. [29], ANN and SVM are adopted for 1h-ahead solar radiation forecasting, which possess root mean square error (RMSE) values ranging 84.21 W/m² ~ 124.77 W/m² and 85.36 W/m² ~ 123.33 W/m², respectively. However, conventional ML models can only extract shallow features, and usually require complex feature engineering operations [23].

This issue associated with conventional ML models has been addressed in recent years by the development of deep learning, such as convolutional neural network (CNN) and long short-term memory (LSTM) network, that rely on the representation learning of data [31]. Deep learning models improve the accuracy of classification or prediction by using deep nonlinear network structures

to realize complex function approximation, as well as by the use of deep features from massive samples [32–38]. These models can extract features spontaneously through multiple stacked hidden layers, and therefore alleviate the need for complex feature engineering operations. For example, the application of an LSTM network to solar irradiance forecasting based on historical time series data was demonstrated to obtain good prediction performance [36]. In addition, the superiority of CNN for extracting spatial correlations was demonstrated by adopting a CNN to extract cloud cover features [39]. With an increasing amount of spatiotemporal-correlated data, solar radiation prediction requires further research with a comprehensive consideration of spatiotemporal correlation.

Meanwhile, although CNN and LSTM have been widely studied for solar radiation prediction, they are mainly designed for spatial and temporal computations, respectively. Researches should be further carried out on the rational combinations of the two state-of-the-art models, in order to fully integrate their respective merits [23]. Motivated by this, the present study proposes a hybrid CNN-LSTM model that seeks to take full advantages of the superiority of CNN for extracting spatial features and the superiority of LSTM network for extracting time-series features to improve the accuracy of global horizontal irradiance (GHI) prediction. The main contributions of the present study are given as follows.

- (1) Meteorological parameters and historical solar irradiance are innovatively reconstructed to better extract spatiotemporal features. First, the meteorological parameters of a target site and its surrounding sites are reconstructed into a two-dimensional (2D) matrix to extract spatial features. Then, historical irradiance time-series data associated with the target site are reconstructed to extract temporal features.
- (2) The CNN and LSTM models are innovatively integrated into a new CNN-LSTM model. The hybrid CNN-LSTM model combines spatial and temporal correlations by merging the spatial features extracted by the CNN and the temporal features extracted by the LSTM network. Then, the GHI is predicted 1 h in advance through the dense layer of the hybrid network structure.
- (3) The prediction performance and generalization ability of the CNN-LSTM model are rigorously evaluated by analyzing the prediction results in a whole year, different seasons and sky

conditions when applied to three datasets composed of spatiotemporal data collected from 34 locations spread across three different climate zones. Meanwhile, the CNN-LSTM model is compared with seven benchmark methods based on five evaluation metrics.

The remainder of this paper is organized as follows. Section 2 introduces the datasets used in this study. Section 3 describes the working principles of the basic networks used in the present study in detail. Section 4 presents the processing flow of the proposed hybrid CNN-LSTM model, the process employed for performance evaluation, and the performance evaluation metrics used in the process. In Section 5, we present results and discussions related to the model performance evaluation based on the datasets introduced in Section 2 in comparison with other benchmark models. Finally, Section 6 summarizes the information presented in this article and proposes future work.

2. Datasets

The details for each of the 34 locations in Texas, USA are listed in Table 1. These details include the humid subtropical climate (Cfa), hot semi-arid climate (BSh), and cold semi-arid climate (BSk) climate zones [40], latitude, longitude and the statistical mean value (μ) of the GHI at each location based on physical solar model (PSM) data obtained from the National Solar Radiation Data Base developed by the National Renewable Energy Laboratory [21,41]. Additional data for each location include the hourly GHI, dew point temperature (DPT), solar zenith angle (SZA), wind speed (WS), wind direction (WD), precipitable water (PW), relative humidity

(RH), and temperature (T) observed from January 1, 2006 to December 31, 2012. Because the GHI drops to zero at night, only data observed from 6:00 to 18:00 per day are selected for training and testing. The data of each climate zone constitute a dataset and each dataset is divided into a training set comprising data ranging from January 1, 2006 to December 31, 2011 and a testing set comprising data ranging from January 1, 2012 to December 31, 2012. The target site is randomly selected from all the sites in a given dataset. Multiple target sites are selected within a dataset. When a target site is selected, the rest of the sites in the dataset are neighboring sites. Each testing only targets at one target site (i.e., only solar radiation of this target site are predicted). The target sites selected for each dataset are marked in bold and the number of values and the percents corresponding to each training and testing sets are also given in Table 1.

3. Principles of basic methods

3.1. Convolutional neural network

A CNN is a feedforward neural network proposed by LeCun [42]. As shown in Fig. 1, the architecture of a typical CNN consists of a convolutional layer, pooling layer, and fully connected layer [43]. In essence, a CNN seeks to construct multiple filters capable of extracting hidden features through a layer-by-layer convolution and pooling of input data. Finally, these abstract features are merged through the fully connected layer, and an activation function is used to solve the classification or regression problem.

In the convolution layer, feature maps of the previous layer are convolved with a convolution kernel and the output feature maps

Table 1
Geographic parameters and solar irradiance datasets of the 34 locations in Texas, USA employed in the present study.

| Dataset | Location | Latitude (N) | Longitude (E) | μ (W/m ²) | Training period | Testing period |
|---------|--------------------|--------------|---------------|---------------------------|-----------------|----------------|
| 1 (Cfa) | Liberty | 30°29' | −94°94' | 368.87 | 28483 (86%) | 4758 (14%) |
| | Dallas | 32°93' | −97°02' | 384.24 | 28483 (86%) | 4758 (14%) |
| | Shackelford | 32°77' | −99°38' | 398.87 | 28483 (86%) | 4758 (14%) |
| | Nacogdoches | 31°77' | −94°74' | 371.68 | 28483 (86%) | 4758 (14%) |
| | Burnet | 30°65' | −98°34' | 390.57 | 28483 (86%) | 4758 (14%) |
| | Bee | 28°41' | −97°86' | 387.15 | 28483 (86%) | 4758 (14%) |
| | Baylor | 33°73' | −99°34' | 393.56 | 28483 (86%) | 4758 (14%) |
| | Jack | 33°29' | −98°38' | 390.23 | 28483 (86%) | 4758 (14%) |
| | Dewitt | 29°13' | −97°06' | 380.66 | 28483 (86%) | 4758 (14%) |
| | Rains | 32°89' | −95°94' | 367.45 | 28483 (86%) | 4758 (14%) |
| | San Jacinto | 30°81' | −95°26' | 370.45 | 28483 (86%) | 4758 (14%) |
| | Goliad | 28°57' | −97°70' | 384.61 | 28483 (86%) | 4758 (14%) |
| 2 (BSh) | Upton | 31°49' | −102°26' | 437.59 | 28483 (86%) | 4758 (14%) |
| | Pecos | 31°09' | −102°62' | 441.56 | 28483 (86%) | 4758 (14%) |
| | Terrell | 30°13' | −101°98' | 431.97 | 28483 (86%) | 4758 (14%) |
| | Val Verde | 29°65' | −101°02' | 407.40 | 28483 (86%) | 4758 (14%) |
| | Reagan | 31°13' | −101°34' | 402.22 | 28483 (86%) | 4758 (14%) |
| | Kinney | 29°09' | −100°42' | 399.78 | 28483 (86%) | 4758 (14%) |
| | Zapata | 26°89' | −99°02' | 411.36 | 28483 (86%) | 4758 (14%) |
| | Crockett | 31°05' | −101°70' | 426.02 | 28483 (86%) | 4758 (14%) |
| 3 (BSk) | Dallam | 36°29' | −102°54' | 410.50 | 28483 (86%) | 4758 (14%) |
| | Sherman | 36°29' | −101°66' | 403.50 | 28483 (86%) | 4758 (14%) |
| | Ochiltree | 36°25' | −100°62' | 396.09 | 28483 (86%) | 4758 (14%) |
| | Hartley | 35°93' | −102°54' | 414.95 | 28483 (86%) | 4758 (14%) |
| | Moore | 35°85' | −101°66' | 406.71 | 28483 (86%) | 4758 (14%) |
| | Oldham | 35°45' | −102°74' | 416.75 | 28483 (86%) | 4758 (14%) |
| | Carson | 35°33' | −101°58' | 411.33 | 28483 (86%) | 4758 (14%) |
| | Wheeler | 35°41' | −100°46' | 400.66 | 28483 (86%) | 4758 (14%) |
| | Randall | 34°93' | −101°78' | 414.10 | 28483 (86%) | 4758 (14%) |
| | Collingsworth | 34°93' | −100°50' | 406.10 | 28483 (86%) | 4758 (14%) |
| | Lamb | 34°13' | −102°22' | 422.83 | 28483 (86%) | 4758 (14%) |
| | Briscoe | 34°33' | −101°14' | 408.81 | 28483 (86%) | 4758 (14%) |
| | Cottle | 34°25' | −100°14' | 399.15 | 28483 (86%) | 4758 (14%) |
| | Martin | 32°09' | −101°90' | 410.86 | 28483 (86%) | 4758 (14%) |

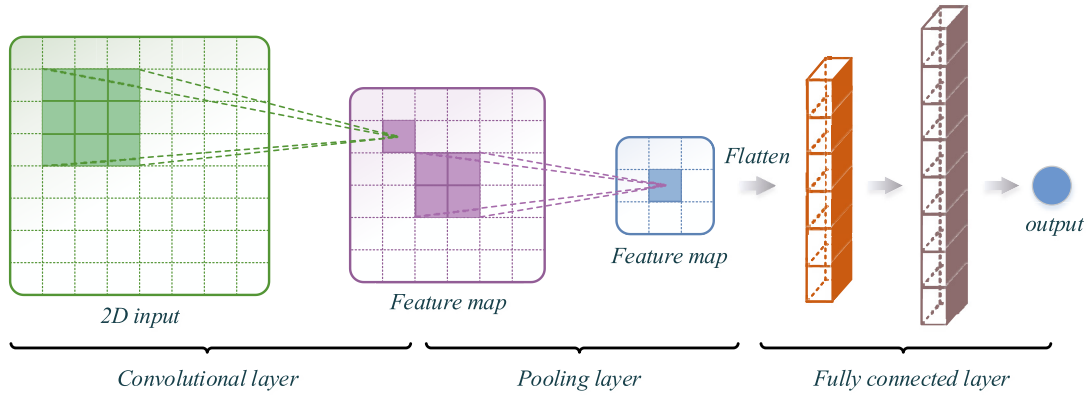


Fig. 1. Basic architecture of a CNN.

are generated by an activation function. The operation of the convolutional layer can be depicted as follows [44]:

$$x_j^l = f \left(\sum_{i \in M_j} x_i^{l-1} * k_{ij}^l + b_j^l \right), \quad (1)$$

where x_j^l represents the j th output feature map of the l th layer, x_i^{l-1} represents the i th output feature map of the $(l-1)$ th layer, M_j represents the selection of input maps, k_{ij}^l represents the weights between the i th input map and the j th output map, $*$ represents the convolution operation, b_j^l represents the bias, and $f(\cdot)$ represents the rectified linear unit (ReLU) activation function.

The pooling layer is employed to reduce the number of CNN parameters. This is realized by calculating the average (average pooling) or maximum (maximum pooling) value of a given area in a feature map. The operation of the pooling layer can be depicted as follows:

$$x_j^l = f \left(\beta_j^l \text{down}(x_j^{l-1}) + b_j^l \right), \quad (2)$$

where $\text{down}(\cdot)$ represents the maxpooling subsampling function, x_j^{l-1} represents the j th input feature map of the l th layer, and β_j^l is the bias.

Finally, the feature maps obtained by calculations of multiple convolutional and pooling layers are taken as the inputs of the fully connected layer, which then calculates the final output vector as follows:

$$x^l = f \left(K^l x^{l-1} + b^l \right), \quad (3)$$

where x^l represents the final output vector, x^{l-1} represents the input vector, K^l represents the weights between the $(l-1)$ th layer and the l th layer, and b^l represents the bias.

3.2. Long short-term memory network

An LSTM network is an enhanced recurrent neural network (RNN) that has the ability to automatically store and remove temporal state information. This ability solves the gradient disappearance problem of the RNN in dealing with long-term sequences and facilitates the extraction of complex time-series features [45]. As shown in Fig. 2, a complete LSTM network contains an input gate, output gate, and forget gate.

The operations of the forget gate f_t , input gate i_t , and output gate o_t at time step t can be depicted respectively as follows [36,46].

$$f_t = \sigma(W_f \cdot [h_{t-1}, x_t] + b_f) \quad (4)$$

$$i_t = \sigma(W_i \cdot [h_{t-1}, x_t] + b_i) \quad (5)$$

$$o_t = \sigma(W_o \cdot [h_{t-1}, x_t] + b_o) \quad (6)$$

here, x_t denotes the input at time step t , h_{t-1} denotes the output at time step $t-1$, W_f , W_i , and W_o denote the weight matrices of the forget gate, input gate, and output gate, respectively, b_f , b_i , and b_o are the biases of the forget gate, input gate, and output gate, respectively, and $\sigma(\cdot)$ is the sigmoid activation function. The final output of an LSTM network h_t is jointly determined by o_t and the memory cell state c_t at t . The relevant calculations are as follows.

$$\tilde{c}_t = \tanh(W_c \cdot [h_{t-1}, x_t] + b_c) \quad (7)$$

$$c_t = c_{t-1} * f_t + i_t * \tilde{c}_t \quad (8)$$

$$h_t = o_t * \tanh(c_t) \quad (9)$$

here, $\tanh(\cdot)$ denotes the tanh activation function, W_c denotes the weight matrix of the memory cell, b_c denotes the bias of the memory cell, and \tilde{c}_t denotes the temporary memory cell state at t .

4. Processing flow of the proposed hybrid model and its evaluation process

The processing flow of the proposed GHI prediction method based on the hybrid CNN-LSTM model is illustrated in Fig. 3(1) and (2), while the process employed for evaluating its prediction performance is illustrated in Fig. 3(3). Input dimension reconstruction is first conducted to better extract spatial and temporal features (Fig. 3(1)). The hourly meteorological parameters of all sites are reconstructed (i.e., input 1) to obtain spatial features, while the historical irradiance data of the target site are reconstructed (i.e., input 2) to obtain temporal features. Inputs 1 and 2 are then used as the inputs of the proposed hybrid CNN-LSTM model to predict the GHI of each target site 1 h in advance (Fig. 3(2)). The three datasets corresponding to the three climate zones are employed for evaluating the performances of the CNN-LSTM, persistence model, SVM, ANN, CNN, LSTM, CNN-ANN, and ANN-LSTM in terms of year, seasons and sky conditions based on the mean absolute error (MAE),

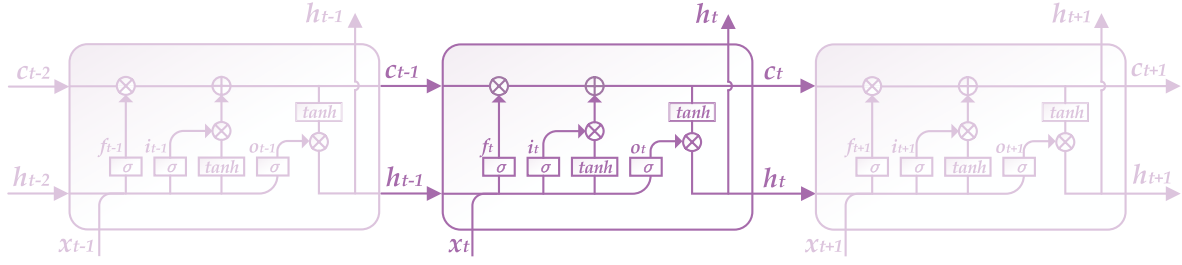


Fig. 2. Basic architecture of an LSTM network.

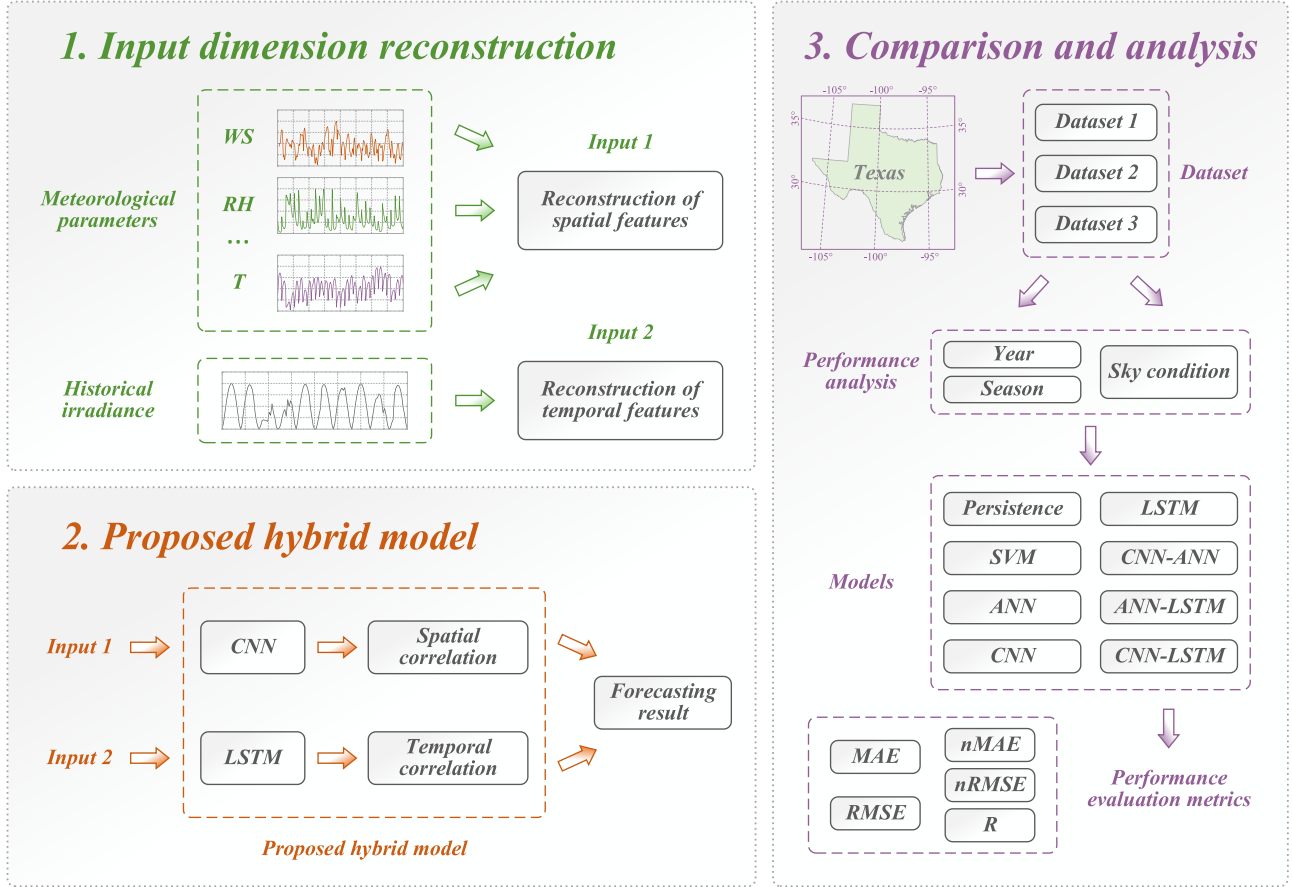


Fig. 3. Flow chart of the proposed GHI prediction method based on the hybrid CNN-LSTM model and the process employed for evaluating its prediction performance.

normalized MAE (nMAE), RMSE, normalized RMSE (nRMSE) and correlation coefficient (R) (Fig. 3(3)). The details regarding each of these processes are discussed in the following subsections.

4.1. Input dimension reconstruction

4.1.1. Reconstruction of spatial features

In the spatial reconstruction process, all meteorological parameters of the target site and neighboring sites at the target time t are formed into a 2D matrix, as illustrated in Fig. 4, which is then used to extract the spatial correlations between sites. Here, each row contains all meteorological parameters of a given site at the target time, and each column contains the same meteorological parameters for all sites. Accordingly, the 2D matrix is composed of elements $f_{i,j}$ ($i = 1, 2, \dots, S$ and $j = 1, 2, \dots, F$), where S represents the number of sites and F represents the number of meteorological

parameters. As shown in Fig. 4, a given meteorological parameter exhibits correlations between different sites, which are specifically manifested in the correlations between two adjacent elements in the same column. This site correlation $corr_1$ is defined as follows:

$$corr_1 = g(f_{i,j}, f_{i+1,j}), \quad (10)$$

where $g(\cdot)$ represents the pearson correlation function. Meanwhile, correlations also exist between different meteorological parameters for the same site, which is specifically manifested in the correlations between two adjacent elements in the same row. This parameter correlation $corr_2$ is defined as follows:

$$corr_2 = g(f_{i,j}, f_{i,j+1}), \quad (11)$$

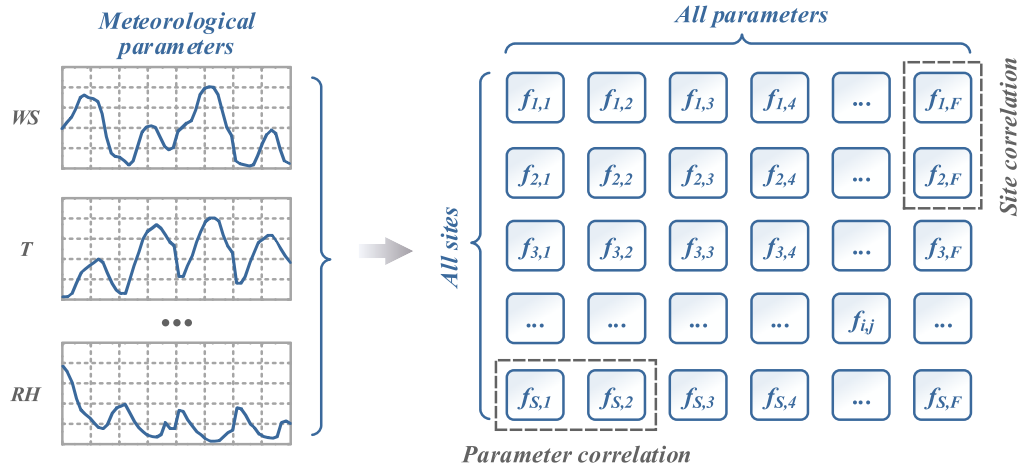


Fig. 4. Spatial feature reconstruction process for input 1 of the proposed hybrid model.

4.1.2. Reconstruction of temporal features

In the temporal reconstruction process illustrated in Fig. 5, the historical GHI sequence x_i ($i = 1, 2, \dots$) for a given target site is a discrete time series, and each hour corresponds to a time step, as shown by the purple circles in the figure, which represent the GHI distribution over time. The GHI values of each time step are sequentially sent to a single LSTM unit (see Subsection 3.2). The connected LSTM units on the right represent the expansion of the leftmost LSTM unit in the time domain and y_i ($i = 1, 2, \dots$) represents the output of each time step. Accordingly, the status of each LSTM unit is updated at each time step. In this study, the GHI values of the previous 10 h are taken as the inputs of the LSTM network (i.e., the LSTM unit holds this information in memory) to predict the GHI 1 h in advance. This construction fully reveals the implied temporal correlations in historical GHI sequences.

4.2. Proposed hybrid model

The structure of the proposed hybrid CNN-LSTM model for combining the spatial and temporal correlations is illustrated in Fig. 6. All meteorological parameters DPT, SZA, WS, WD, PW, RH, and T of the target site and neighboring sites at the target time step t (obtained by weather forecast) are reconstructed as the input 1, the historical irradiance values of the target site from time step $t-10$ to $t-1$ are reconstructed as the input 2, and the output is the GHI of the target site at time step t . The hybrid model is divided into spatiotemporal feature extraction, which merges the spatial features extracted by the CNN from input 1 and the temporal features extracted by the LSTM from input 2 via a concatenation operation, and GHI prediction in the final fully connected layer. The benchmark models CNN-ANN and ANN-LSTM for comparison replace LSTM and CNN with ANN, respectively. The inputs and outputs of

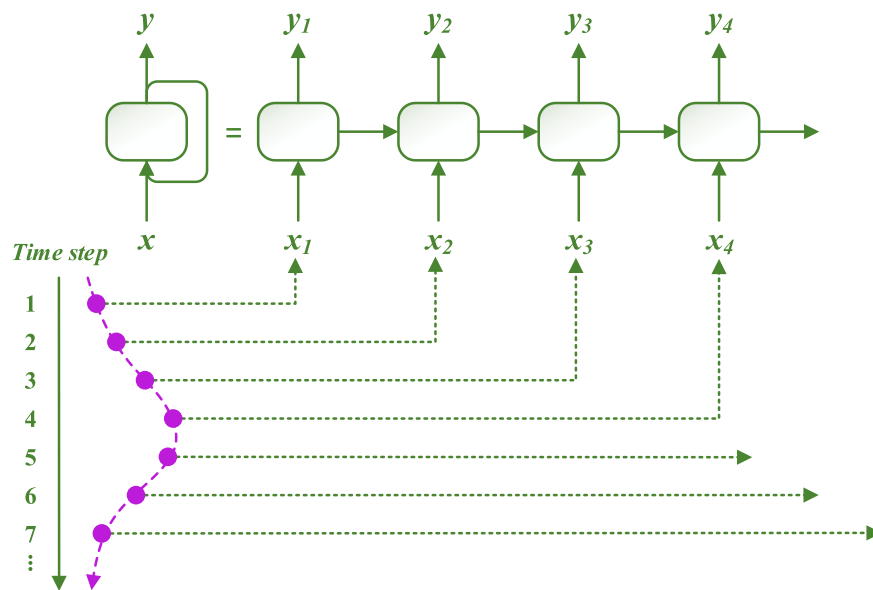


Fig. 5. Temporal feature reconstruction process for input 2 of the proposed hybrid model.

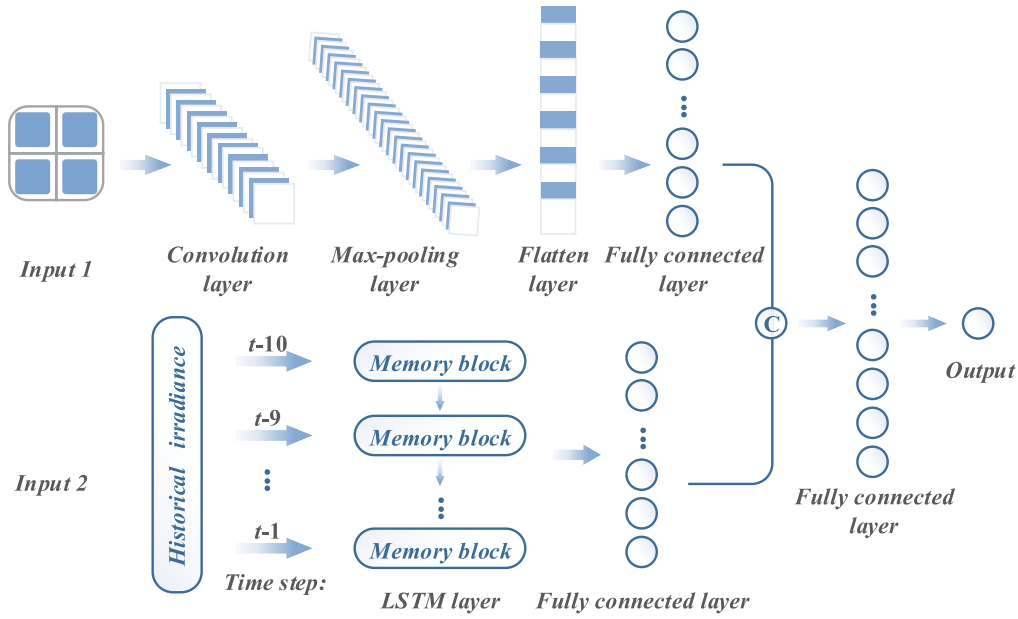


Fig. 6. Structure of the proposed hybrid CNN-LSTM model.

CNN-ANN, ANN-LSTM, SVM and ANN are the same as those of CNN-LSTM (i.e., the inputs are meteorological parameters and historical irradiance, the output is the forecasted GHI of the target site). The difference is that the data are directly input to the ANN parts of CNN-ANN and ANN-LSTM, SVM and ANN without reconstruction. The CNN model only considers spatial correlation and takes input 1 as input. The LSTM model only considers temporal correlation and takes input 2 as input. The persistence model supposes that the GHI value at the target time t is best predicted by its previous value at time $t-1$. The outputs of CNN, LSTM and persistence model are also the same as that of CNN-LSTM.

4.3. Performance evaluation metrics

No standard presently exists for conducting model performance evaluation, which increases the difficulty of model comparison. Therefore, the present work adopts five performance evaluation metrics, including the MAE, nMAE, RMSE, nRMSE, and R , to evaluate the prediction performances of the models adequately. These metrics are computed as follows [47].

$$\text{MAE} = \frac{1}{N} \times \sum_{i=1}^N |\hat{y}_i - y_i| \quad (12)$$

$$\text{nMAE} = \frac{\frac{1}{N} \times \sum_{i=1}^N |\hat{y}_i - y_i|}{y_a} \times 100\% \quad (13)$$

$$\text{RMSE} = \sqrt{\frac{1}{N} \times \sum_{i=1}^N (\hat{y}_i - y_i)^2} \quad (14)$$

$$\text{nRMSE} = \frac{\sqrt{\frac{1}{N} \times \sum_{i=1}^N (\hat{y}_i - y_i)^2}}{y_a} \times 100\% \quad (15)$$

$$R = \frac{\left| \sum_{i=1}^N (\hat{y}_i - \hat{y}_a) \cdot (y_i - y_a) \right|}{\sqrt{\left[\sum_{i=1}^N (\hat{y}_i - \hat{y}_a)^2 \right] \left[\sum_{i=1}^N (y_i - y_a)^2 \right]}} \quad (16)$$

here, \hat{y}_i and y_i represent the i th forecasted and measured values, respectively. \hat{y}_a and y_a are the averaged forecasted and measured values, respectively. N is the total number of observations. The prediction performance of a given model increases with decreasing values of MAE, nMAE, RMSE and nRMSE and increasing values of R .

5. Results and discussion

The performance of the proposed GHI prediction method is analyzed for each target site of the three datasets listed in Table 1 within a whole year, under diverse seasons and sky conditions. The proposed hybrid model is built in Python using Keras, which is a deep learning library that is capable of running on TensorFlow, Theano, and CNTK. Fairness in the testing results is ensured by employing equivalent parameters for all models in each experiment. The models use Adam optimizer to optimize parameters and mean square error (MSE) as the loss function. Each model uses early stopping with the number of iterations set to 100. The initial learning rate and batch size are set to 0.001 and 512, respectively. All experiments are conducted on a personal computer equipped with the Windows 7 operating system, 8.00 GB RAM, and an Intel® Core™ i5-6400 CPU operating at 2.70 GHz.

5.1. Annual performance

The evaluation metric values obtained for annual prediction testing of the eight models at the five target sites considered (i.e., Dallas, San Jacinto, Zapata, Moore, and Lamb) are listed in Table 2. The values given in bold represent the best values obtained for all models. In addition, the MAE values obtained for the CNN-LSTM model at all target sites are compared with those of the other models in Fig. 7, while this is presented in terms of the RMSE in Fig. 8. Finally, the percentile improvements in all annual

Table 2

Annual prediction results of different models for the three datasets listed in Table 1.

| Metric | Model | Cfa | | BSh | BSk | |
|--------------------------|-------------------|---------------|---------------|---------------|---------------|---------------|
| | | Dallas | San Jacinto | Zapata | Moore | Lamb |
| MAE (W/m ²) | Persistence model | 119.80 | 123.05 | 127.91 | 122.00 | 126.24 |
| | SVM | 65.43 | 72.00 | 67.34 | 60.79 | 61.42 |
| | ANN | 46.78 | 54.77 | 47.19 | 43.73 | 40.85 |
| | CNN | 55.75 | 66.86 | 59.52 | 52.15 | 52.29 |
| | LSTM | 46.71 | 57.54 | 48.75 | 41.03 | 40.01 |
| | CNN-ANN | 43.22 | 54.29 | 44.52 | 38.28 | 37.87 |
| | ANN-LSTM | 43.99 | 54.21 | 45.58 | 38.00 | 37.85 |
| | CNN-LSTM | 41.88 | 52.00 | 43.66 | 37.26 | 37.20 |
| nMAE (%) | Persistence model | 30.27 | 32.57 | 30.76 | 29.20 | 29.34 |
| | SVM | 16.53 | 19.06 | 16.19 | 14.55 | 14.28 |
| | ANN | 11.82 | 14.50 | 11.35 | 10.47 | 9.49 |
| | CNN | 14.09 | 17.69 | 14.31 | 12.48 | 12.15 |
| | LSTM | 11.80 | 15.23 | 11.72 | 9.82 | 9.30 |
| | CNN-ANN | 10.92 | 14.37 | 10.71 | 9.16 | 8.80 |
| | ANN-LSTM | 11.12 | 14.35 | 10.96 | 9.10 | 8.80 |
| | CNN-LSTM | 10.58 | 13.76 | 10.50 | 8.92 | 8.65 |
| RMSE (W/m ²) | Persistence model | 149.81 | 153.67 | 158.14 | 149.41 | 153.74 |
| | SVM | 87.94 | 96.27 | 90.26 | 81.28 | 83.64 |
| | ANN | 80.12 | 86.83 | 80.65 | 72.25 | 72.95 |
| | CNN | 97.10 | 104.37 | 97.86 | 90.42 | 95.43 |
| | LSTM | 82.86 | 91.93 | 83.55 | 74.28 | 75.49 |
| | CNN-ANN | 78.45 | 87.36 | 79.04 | 69.75 | 71.83 |
| | ANN-LSTM | 77.45 | 86.66 | 79.98 | 69.94 | 71.84 |
| | CNN-LSTM | 78.17 | 86.33 | 78.49 | 69.26 | 71.61 |
| nRMSE (%) | Persistence model | 37.86 | 40.67 | 38.03 | 35.76 | 35.74 |
| | SVM | 22.22 | 25.48 | 21.70 | 19.46 | 19.44 |
| | ANN | 20.24 | 22.98 | 19.39 | 17.29 | 16.96 |
| | CNN | 24.53 | 27.62 | 23.53 | 21.64 | 22.18 |
| | LSTM | 20.94 | 24.33 | 20.09 | 17.78 | 17.55 |
| | CNN-ANN | 19.82 | 23.12 | 19.01 | 16.69 | 16.70 |
| | ANN-LSTM | 19.57 | 22.93 | 19.23 | 16.74 | 16.70 |
| | CNN-LSTM | 19.75 | 22.85 | 18.87 | 16.58 | 16.65 |
| R | Persistence model | 0.8797 | 0.8654 | 0.8747 | 0.8864 | 0.8827 |
| | SVM | 0.9600 | 0.9471 | 0.9597 | 0.9676 | 0.9665 |
| | ANN | 0.9650 | 0.9561 | 0.9669 | 0.9732 | 0.9733 |
| | CNN | 0.9482 | 0.9361 | 0.9510 | 0.9575 | 0.9541 |
| | LSTM | 0.9625 | 0.9506 | 0.9644 | 0.9715 | 0.9713 |
| | CNN-ANN | 0.9665 | 0.9555 | 0.9683 | 0.9749 | 0.9741 |
| | ANN-LSTM | 0.9673 | 0.9563 | 0.9676 | 0.9748 | 0.9741 |
| | CNN-LSTM | 0.9667 | 0.9566 | 0.9688 | 0.9753 | 0.9742 |

performance metrics obtained by the proposed model relative to those of the other models at the different target sites are listed in Table 3.

According to Table 2, the annual prediction performance of the CNN-LSTM model is best for all datasets in terms of the MAE and nMAE. In addition, the annual prediction performance of the proposed model is best for all datasets in terms of the RMSE, nRMSE and R, except for the Dallas target site, where the ANN-LSTM model provides slightly better prediction results.

The improved annual prediction performances obtained by the proposed model relative to the other models at all target sites are intuitively obvious from the MAE and RMSE data respectively presented in Figs. 7 and 8, while the specific improvements are listed in Table 3. According to the figures and tables, the performance improvement of CNN-LSTM is the biggest compared with the persistence model with percentile improvements in the R ranging from 9.89% to 10.76%. The annual performance of the CNN-LSTM model is substantially better than those obtained by the SVM and ANN models, demonstrating the superiority of the proposed model over conventional machine learning models. This is particularly the case when compared with the prediction results of the SVM model. Taking the MAE as an example, we note that the values

of this performance metric obtained by the CNN-LSTM model are decreased in percentiles ranging from 27.78% to 39.43% when compared with SVM. However, when compared with ANN, the percentile performance increases of the CNN-LSTM model range from 5.06% to 14.80%. Moreover, the proposed hybrid CNN-LSTM model also yields prediction results that are far superior to those of the CNN model, which only considers spatial correlations, with percentile improvements in the MAE ranging from 22.23% to 28.86%, while improvements relative to the results of the LSTM model, which only considers temporal correlations, are much more modest (i.e., percentile improvements ranging from 7.02% to 10.44%). When compared with results obtained from the hybrid CNN-ANN and ANN-LSTM models, the increased performance of the proposed hybrid CNN-LSTM model is not so obvious. In terms of the nMAE, the percentile performance increase of the CNN-LSTM model ranges from 1.70% to 4.24% when compared with the CNN-ANN model and from 1.70% to 4.86% when compared with the ANN-LSTM model. Although the prediction performance of the CNN-LSTM model is not the best in three of the 25 total cases (i.e., five target sites and five evaluation metrics), the proposed model is still the best choice overall, demonstrating the superiority of the CNN-LSTM combination strategy.

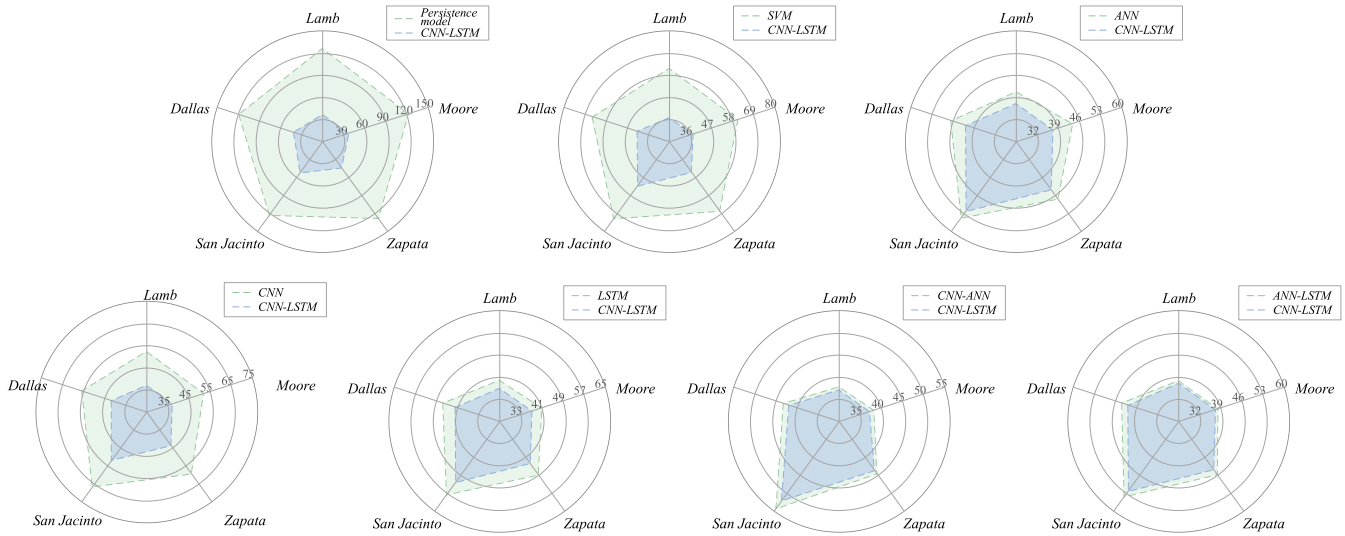


Fig. 7. Comparison of the annual prediction results of the CNN-LSTM model and those of the other models in terms of the MAE.

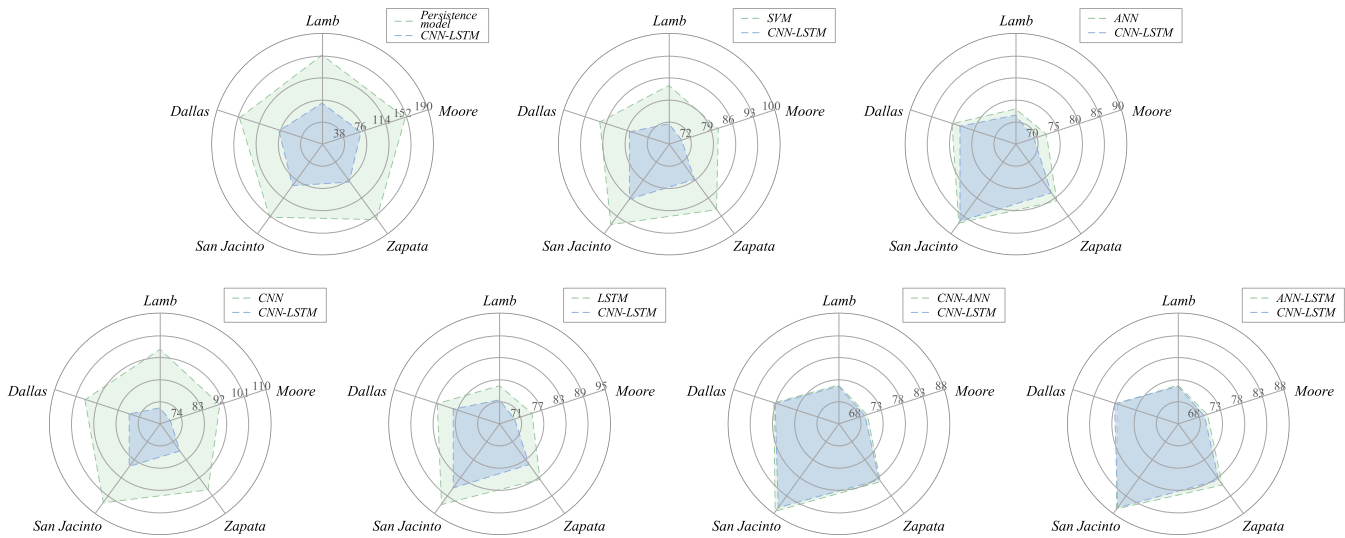


Fig. 8. Comparison of the annual prediction results of the CNN-LSTM model and those of the other models in terms of the RMSE.

5.2. Seasonal performance

The seasonal prediction performance results for the eight models at the five target sites considered are listed in Table 4, where the values given in bold represent the best performance evaluation metric values of all models. In addition, the results in Table 4 for the normalized evaluation metrics are replicated graphically in Fig. 9 along with the seasonal GHI distribution curves for each of the five target sites. The normalized metrics are applied in the figure to facilitate comparisons between the seasonal results because the MAE and RMSE values differ for different seasons owing to differences in solar intensity. According to the prediction results listed in Table 4, the proposed hybrid CNN-LSTM model achieves the best prediction performance in most cases, regardless of the season. We also note from the GHI distribution curves in Fig. 9 that the curve predicted by the CNN-LSTM model is generally closer to the actual values than those curves obtained from the other models. Nevertheless, we note that the prediction performance of the CNN-LSTM model varies from season to season

depending on the target site considered.

The results in Table 4 and Fig. 9 indicate that the normalized prediction errors for the Dallas and San Jacinto target sites are smaller in spring and summer, slightly greater in autumn, and greatest in winter. The results for the two sites are similar because Dallas and San Jacinto are both in the Cfa climate zone. A comprehensive analysis of the nMAE and nRMSE results for these target sites indicates that the prediction performance of the CNN-LSTM model is more greatly improved relative to the performances of the other models in autumn and winter, but less so in the other two seasons. Taking the Dallas target site as an example, the nMAE value obtained by the CNN-LSTM model in winter is less than those obtained by the persistence model, SVM, ANN, CNN, LSTM, CNN-ANN, and ANN-LSTM models by 21.35%, 7.09%, 1.92%, 4.81%, 2.36%, 0.60%, and 0.86%, respectively. However, the nMAE value obtained by the CNN-LSTM model in spring, where performance improvements are not so obvious, is less than those obtained by the persistence model, SVM, ANN, CNN, LSTM, CNN-ANN, and ANN-LSTM models by 17.24%, 4.55%, 0.76%, 3.38%, 0.77%, 0.43%, and

Table 3

Percentile improvements in the annual performance metrics obtained by the proposed model relative to those of the other models at the different target sites.

| Models | Sites | MAE | nMAE | RMSE | nRMSE | R |
|-------------------------------|-------------|--------|--------|--------|--------|--------|
| CNN-LSTM vs Persistence model | Dallas | 65.04% | 65.05% | 47.82% | 47.83% | 9.89% |
| | San Jacinto | 57.74% | 57.75% | 43.82% | 43.82% | 10.54% |
| | Zapata | 65.87% | 65.86% | 50.37% | 50.38% | 10.76% |
| | Moore | 69.46% | 69.45% | 53.64% | 53.64% | 10.03% |
| | Lamb | 70.53% | 70.52% | 53.42% | 53.41% | 10.37% |
| CNN-LSTM vs SVM | Dallas | 35.99% | 36.00% | 11.11% | 11.12% | 0.70% |
| | San Jacinto | 27.78% | 27.81% | 10.33% | 10.32% | 1.00% |
| | Zapata | 35.16% | 35.15% | 13.04% | 13.04% | 0.95% |
| | Moore | 38.71% | 38.69% | 14.79% | 14.80% | 0.80% |
| | Lamb | 39.43% | 39.43% | 14.38% | 14.35% | 0.80% |
| CNN-LSTM vs ANN | Dallas | 10.47% | 10.49% | 2.43% | 2.42% | 0.18% |
| | San Jacinto | 5.06% | 5.10% | 0.58% | 0.57% | 0.05% |
| | Zapata | 7.48% | 7.49% | 2.68% | 2.68% | 0.20% |
| | Moore | 14.80% | 14.80% | 4.14% | 4.11% | 0.22% |
| | Lamb | 8.94% | 8.85% | 1.84% | 1.83% | 0.09% |
| CNN-LSTM vs CNN | Dallas | 24.88% | 24.91% | 19.50% | 19.49% | 1.95% |
| | San Jacinto | 22.23% | 22.22% | 17.28% | 17.27% | 2.19% |
| | Zapata | 26.65% | 26.62% | 19.79% | 19.80% | 1.87% |
| | Moore | 28.55% | 28.53% | 23.40% | 23.38% | 1.86% |
| | Lamb | 28.86% | 28.81% | 24.96% | 24.93% | 2.11% |
| CNN-LSTM vs LSTM | Dallas | 10.34% | 10.34% | 5.66% | 5.68% | 0.44% |
| | San Jacinto | 9.63% | 9.65% | 6.09% | 6.08% | 0.63% |
| | Zapata | 10.44% | 10.41% | 6.06% | 6.07% | 0.46% |
| | Moore | 9.19% | 9.16% | 6.76% | 6.75% | 0.39% |
| | Lamb | 7.02% | 6.99% | 5.14% | 5.13% | 0.30% |
| CNN-LSTM vs CNN-ANN | Dallas | 3.10% | 3.11% | 0.36% | 0.35% | 0.02% |
| | San Jacinto | 4.22% | 4.24% | 1.18% | 1.17% | 0.12% |
| | Zapata | 1.93% | 1.96% | 0.70% | 0.74% | 0.05% |
| | Moore | 2.66% | 2.62% | 0.70% | 0.66% | 0.04% |
| | Lamb | 1.77% | 1.70% | 0.31% | 0.30% | 0.01% |
| CNN-LSTM vs ANN-LSTM | Dallas | 4.80% | 4.86% | −0.93% | −0.92% | −0.06% |
| | San Jacinto | 4.08% | 4.11% | 0.38% | 0.35% | 0.03% |
| | Zapata | 4.21% | 4.20% | 1.86% | 1.87% | 0.12% |
| | Moore | 1.95% | 1.98% | 0.97% | 0.96% | 0.05% |
| | Lamb | 1.72% | 1.70% | 0.32% | 0.30% | 0.01% |

0.25%, respectively.

The seasonal trends of the prediction results obtained for the Dallas and San Jacinto target sites differ somewhat for the Zapata target site in the BSh climate zone, where the normalized prediction errors are relatively small in spring and summer, and relatively large in autumn and winter. However, while the normalized prediction errors of the CNN-LSTM model are large in autumn and winter, the performance improvement of the CNN-LSTM model relative to the performances of the other models is greater. For example, the nMAE value obtained by the CNN-LSTM model in spring is reduced by −0.10% compared with that of the CNN-ANN model and 0.04% compared with that of the ANN-LSTM model. However, the nMAE value of the CNN-LSTM model in winter is reduced by 0.49% compared with that of the CNN-ANN model and 0.80% compared with that of the ANN-LSTM model.

In contrast to the Dallas and San Jacinto target sites, the seasonal trends of the prediction results obtained for the Moore and Lamb target sites are different even though both of these sites reside in the BSk climate zone. For Moore, the normalized prediction errors are relatively small in summer and relatively large in winter, while the prediction errors in spring and autumn are similarly in between the values obtained during summer and winter. In addition, the performance improvement of the CNN-LSTM model relative to the performances of the other models varies from season to season, where the proposed model provides the smallest improvement in summer and slightly greater improvement in the other three seasons. Meanwhile, the seasonal prediction error trends for Lamb are similar to those obtained for Dallas and San Jacinto, where the

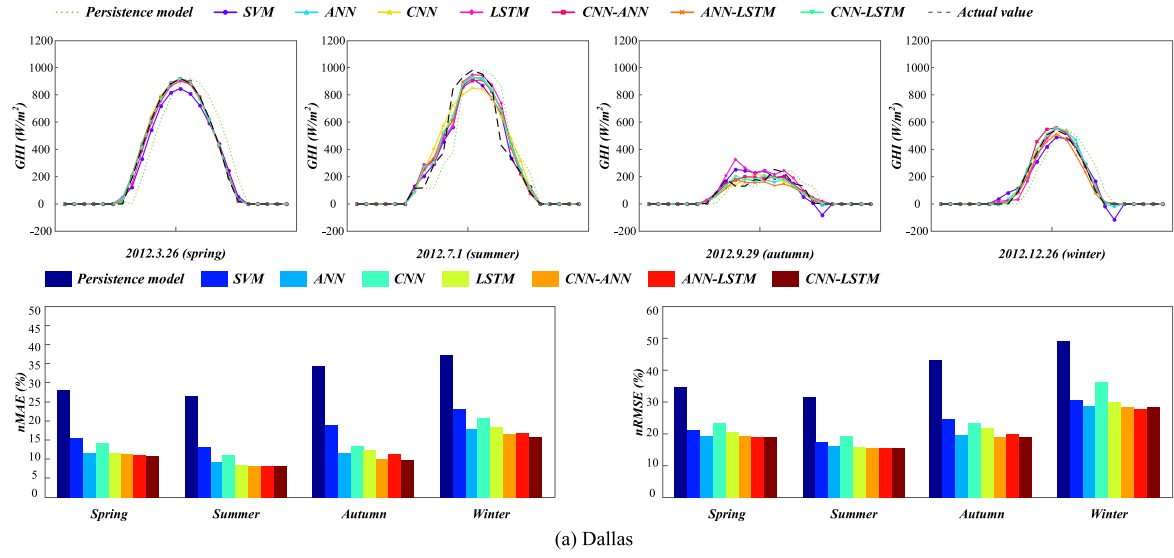
normalized prediction errors of spring and summer are similarly moderate and the prediction errors are slightly greater in autumn and greatest in winter. Moreover, it is once again noted that the performance improvement of the CNN-LSTM model is greater in autumn and winter when the prediction errors are greater. For example, the nMAE value of the CNN-LSTM model in summer is reduced by 0.16% compared with that of the CNN-ANN model and 0.07% compared with that of the ANN-LSTM model, while the nRMSE value of the CNN-LSTM model is reduced by 0.29% compared with that of the CNN-ANN model and 0.16% compared with that of the ANN-LSTM model. Meanwhile, the nMAE value of the CNN-LSTM model in autumn is reduced by 0.16% compared with that of the CNN-ANN model and 0.44% compared with that of the ANN-LSTM model, while the nRMSE value of the CNN-LSTM model is reduced by 0.41% compared with that of the CNN-ANN model and 0.46% compared with that of the ANN-LSTM model.

5.3. Performance under different sky conditions

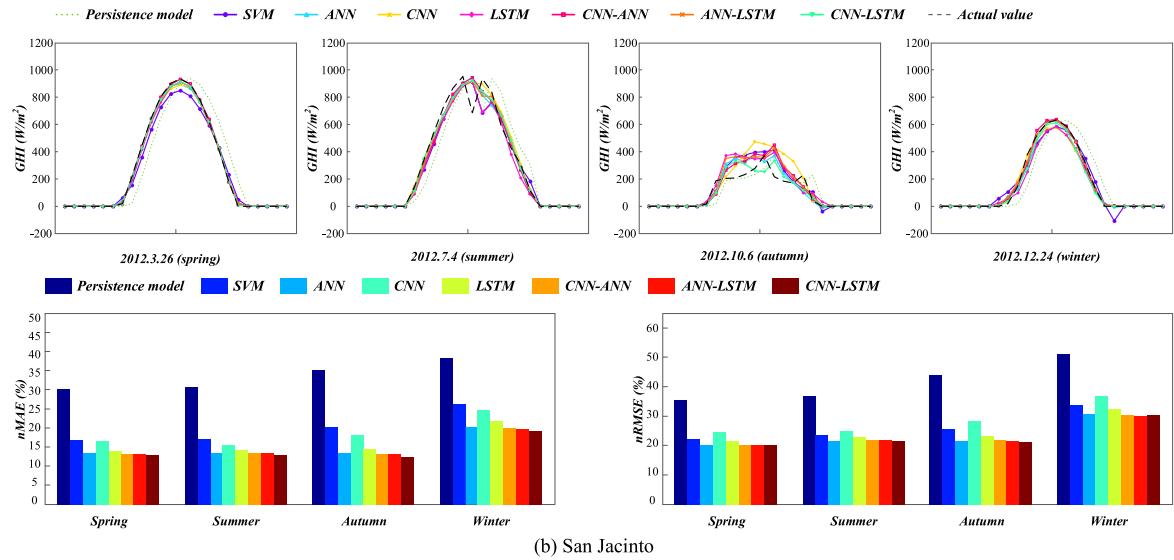
Clearness index (k_t) is a good proxy to sky condition. The percents of cloudy ($0 \leq k_t \leq 0.3$), partly cloudy ($0.3 < k_t \leq 0.7$) and cloudless ($0.7 < k_t \leq 1$) hours for each target site on the testing set are given in Table 5. According to the distribution of sky conditions for each site in Table 5, prediction results of eight models for five target sites under three different sky conditions are calculated and listed in Table 6, where the values given in bold represent the best performance metric values of all models. The number of times each model obtains the best performance metric values in terms of three

Table 4
Seasonal prediction results of the different models at the five target sites.

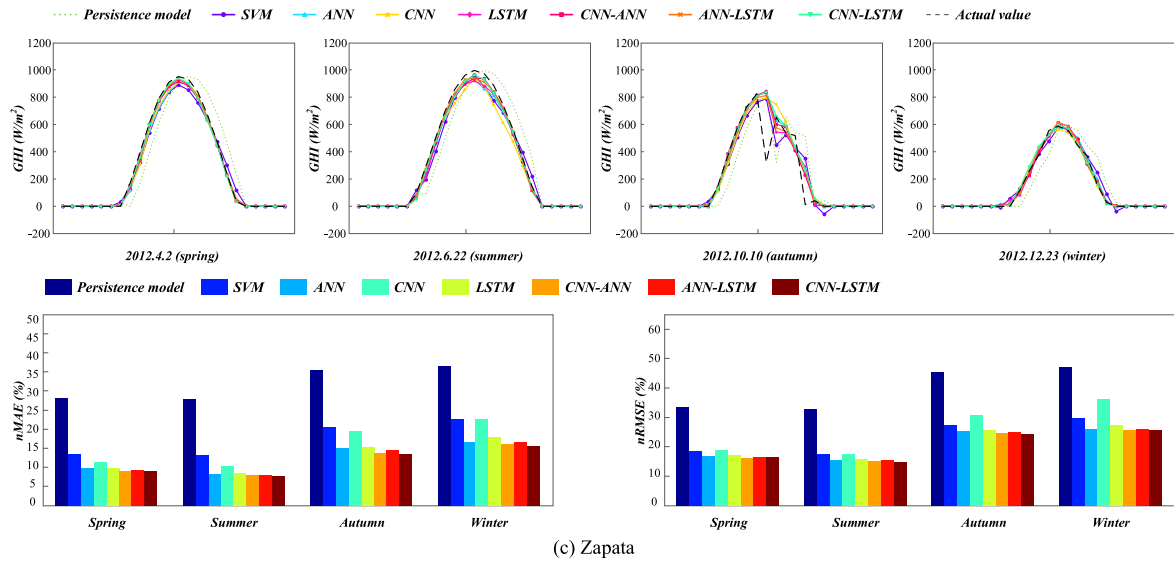
| Season | Model | Dallas | | | | | San Jacinto | | | | | Zapata | | | | | Moore | | | | | Lamb | | | | |
|--------|-------------------|-------------------------|-------|-------------------------|-------|--------|-------------------------|-------|-------------------------|-------|--------|-------------------------|-------|-------------------------|-------|--------|-------------------------|-------|-------------------------|-------|--------|-------------------------|-------|-------------------------|-------|--------|
| | | MAE | nMAE | RMSE | nRMSE | R | MAE | nMAE | RMSE | nRMSE | R | MAE | nMAE | RMSE | nRMSE | R | MAE | nMAE | RMSE | nRMSE | R | MAE | nMAE | RMSE | nRMSE | R |
| | | (W/ m ²) | (%) | (W/ m ²) | (%) | | (W/ m ²) | (%) | (W/ m ²) | (%) | | (W/ m ²) | (%) | (W/ m ²) | (%) | | (W/ m ²) | (%) | (W/ m ²) | (%) | | (W/ m ²) | (%) | (W/ m ²) | (%) | |
| Spring | Persistence model | 139.74 | 28.13 | 171.59 | 34.54 | 0.8539 | 146.55 | 29.99 | 174.58 | 35.73 | 0.8396 | 148.01 | 28.10 | 176.23 | 33.46 | 0.8491 | 145.23 | 27.26 | 172.80 | 32.44 | 0.8570 | 147.87 | 26.84 | 173.27 | 31.45 | 0.8609 |
| | SVM | 76.71 | 15.44 | 104.01 | 20.94 | 0.9493 | 81.61 | 16.70 | 108.20 | 22.15 | 0.9394 | 70.99 | 13.48 | 96.22 | 18.27 | 0.9561 | 75.42 | 14.16 | 100.56 | 18.88 | 0.9533 | 70.86 | 12.86 | 94.10 | 17.08 | 0.9617 |
| | ANN | 57.86 | 11.65 | 96.43 | 19.41 | 0.9533 | 65.15 | 13.34 | 98.91 | 20.24 | 0.9475 | 51.45 | 9.77 | 87.92 | 16.69 | 0.9619 | 54.76 | 10.28 | 93.38 | 17.53 | 0.9574 | 49.32 | 8.95 | 84.37 | 15.32 | 0.9667 |
| | CNN | 70.91 | 14.27 | 116.66 | 23.48 | 0.9302 | 80.03 | 16.38 | 120.03 | 24.57 | 0.9224 | 59.54 | 11.31 | 99.93 | 18.98 | 0.9503 | 67.41 | 12.66 | 118.00 | 22.15 | 0.9321 | 64.16 | 11.65 | 110.31 | 20.02 | 0.9426 |
| | LSTM | 57.92 | 11.66 | 101.42 | 20.41 | 0.9476 | 67.44 | 13.80 | 105.04 | 21.50 | 0.9402 | 51.96 | 9.87 | 91.03 | 17.29 | 0.9590 | 56.43 | 10.59 | 97.18 | 18.24 | 0.9537 | 50.16 | 9.11 | 87.79 | 15.94 | 0.9637 |
| | CNN-ANN | 56.23 | 11.32 | 96.00 | 19.32 | 0.9533 | 64.12 | 13.12 | 98.89 | 20.24 | 0.9473 | 47.17 | 8.96 | 85.05 | 16.15 | 0.9643 | 50.97 | 9.57 | 90.96 | 17.08 | 0.9596 | 48.09 | 8.73 | 83.75 | 15.20 | 0.9670 |
| | ANN-LSTM | 55.34 | 11.14 | 93.63 | 18.85 | 0.9556 | 64.18 | 13.14 | 98.70 | 20.20 | 0.9476 | 47.92 | 9.10 | 86.41 | 16.41 | 0.9632 | 51.10 | 9.59 | 92.65 | 17.39 | 0.9582 | 46.64 | 8.47 | 83.63 | 15.18 | 0.9673 |
| | CNN-LSTM | 54.11 | 10.89 | 94.95 | 19.11 | 0.9542 | 62.39 | 12.77 | 98.43 | 20.15 | 0.9478 | 47.73 | 9.06 | 85.83 | 16.30 | 0.9636 | 50.49 | 9.48 | 90.77 | 17.04 | 0.9598 | 46.65 | 8.47 | 84.06 | 15.26 | 0.9668 |
| Summer | Persistence model | 137.53 | 26.53 | 163.29 | 31.50 | 0.8623 | 147.30 | 30.78 | 177.13 | 37.02 | 0.8218 | 147.93 | 27.89 | 174.18 | 32.84 | 0.8525 | 143.18 | 26.03 | 164.67 | 29.94 | 0.8609 | 148.73 | 27.61 | 173.81 | 32.27 | 0.8511 |
| | SVM | 67.84 | 13.09 | 90.52 | 17.46 | 0.9615 | 82.21 | 17.18 | 112.70 | 23.55 | 0.9267 | 69.63 | 13.13 | 93.51 | 17.63 | 0.9594 | 61.21 | 11.13 | 81.56 | 14.83 | 0.9690 | 69.22 | 12.85 | 99.14 | 18.41 | 0.9529 |
| | ANN | 47.27 | 9.12 | 84.28 | 16.26 | 0.9629 | 64.73 | 13.53 | 103.47 | 21.62 | 0.9374 | 43.18 | 8.14 | 81.04 | 15.28 | 0.9676 | 42.18 | 7.67 | 68.74 | 12.50 | 0.9766 | 46.81 | 8.69 | 88.79 | 16.48 | 0.9605 |
| | CNN | 56.90 | 10.98 | 100.24 | 19.34 | 0.9467 | 73.57 | 15.37 | 118.34 | 24.73 | 0.9176 | 53.64 | 10.11 | 92.16 | 17.38 | 0.9578 | 50.27 | 9.14 | 86.47 | 15.72 | 0.9614 | 61.33 | 11.39 | 119.47 | 22.18 | 0.9282 |
| | LSTM | 43.49 | 8.39 | 81.81 | 15.78 | 0.9650 | 67.25 | 14.05 | 108.47 | 22.67 | 0.9311 | 44.70 | 8.43 | 84.15 | 15.87 | 0.9650 | 35.21 | 6.40 | 68.87 | 12.52 | 0.9756 | 44.57 | 8.27 | 91.14 | 16.92 | 0.9582 |
| | CNN-ANN | 42.74 | 8.25 | 80.43 | 15.52 | 0.9660 | 65.01 | 13.59 | 105.28 | 22.00 | 0.9350 | 41.96 | 7.91 | 80.45 | 15.17 | 0.9681 | 36.59 | 6.65 | 65.74 | 11.95 | 0.9778 | 45.09 | 8.37 | 89.16 | 16.55 | 0.9602 |
| | ANN-LSTM | 42.52 | 8.20 | 79.22 | 15.28 | 0.9671 | 64.73 | 13.53 | 103.99 | 21.73 | 0.9366 | 42.12 | 7.94 | 80.98 | 15.27 | 0.9677 | 35.02 | 6.37 | 64.76 | 11.77 | 0.9784 | 44.62 | 8.28 | 88.44 | 16.42 | 0.9609 |
| | CNN-LSTM | 41.96 | 8.09 | 80.41 | 15.51 | 0.9660 | 62.02 | 12.96 | 103.44 | 21.62 | 0.9374 | 40.35 | 7.61 | 78.30 | 14.76 | 0.9698 | 35.78 | 6.51 | 65.78 | 11.96 | 0.9777 | 44.21 | 8.21 | 87.61 | 16.26 | 0.9615 |
| Autumn | Persistence model | 101.66 | 34.50 | 127.59 | 43.31 | 0.8695 | 103.80 | 35.14 | 130.14 | 44.05 | 0.8697 | 110.62 | 35.33 | 141.91 | 45.32 | 0.8621 | 99.64 | 33.64 | 124.58 | 42.05 | 0.8751 | 105.21 | 33.38 | 130.17 | 41.30 | 0.8732 |
| | SVM | 55.55 | 18.85 | 71.87 | 24.39 | 0.9586 | 60.04 | 20.32 | 76.07 | 25.75 | 0.9553 | 63.81 | 20.38 | 86.26 | 27.55 | 0.9485 | 49.56 | 16.73 | 63.03 | 21.28 | 0.9683 | 48.95 | 15.53 | 63.67 | 20.20 | 0.9698 |
| | ANN | 34.21 | 11.61 | 57.68 | 19.58 | 0.9730 | 39.72 | 13.45 | 63.21 | 21.40 | 0.9688 | 46.73 | 14.92 | 78.58 | 25.10 | 0.9573 | 34.66 | 11.70 | 53.43 | 18.04 | 0.9769 | 29.89 | 9.48 | 52.01 | 16.50 | 0.9796 |
| | CNN | 39.55 | 13.42 | 68.98 | 23.41 | 0.9612 | 53.16 | 17.99 | 83.44 | 28.25 | 0.9450 | 60.45 | 19.30 | 95.94 | 30.64 | 0.9355 | 41.61 | 14.05 | 68.14 | 23.00 | 0.9620 | 36.22 | 11.49 | 60.67 | 19.25 | 0.9725 |
| | LSTM | 36.58 | 12.42 | 63.92 | 21.69 | 0.9668 | 42.50 | 14.39 | 68.07 | 23.04 | 0.9639 | 47.18 | 15.07 | 80.09 | 25.58 | 0.9551 | 31.90 | 10.77 | 53.76 | 18.15 | 0.9765 | 29.14 | 9.25 | 53.48 | 16.97 | 0.9784 |
| | CNN-ANN | 29.61 | 10.05 | 55.87 | 18.96 | 0.9747 | 39.10 | 13.24 | 64.30 | 21.76 | 0.9678 | 43.00 | 13.73 | 76.43 | 24.41 | 0.9596 | 29.20 | 9.86 | 51.46 | 17.37 | 0.9785 | 25.77 | 8.17 | 49.41 | 15.68 | 0.9816 |
| | ANN-LSTM | 33.20 | 11.27 | 58.68 | 19.92 | 0.9721 | 39.19 | 13.27 | 63.58 | 21.52 | 0.9685 | 45.48 | 14.52 | 77.65 | 24.80 | 0.9583 | 29.11 | 9.83 | 52.11 | 17.59 | 0.9779 | 26.64 | 8.45 | 49.57 | 15.73 | 0.9814 |
| | CNN-LSTM | 28.75 | 9.76 | 56.14 | 19.05 | 0.9745 | 36.31 | 12.29 | 62.36 | 21.11 | 0.9697 | 41.98 | 13.41 | 75.72 | 24.18 | 0.9605 | 28.03 | 9.46 | 50.72 | 17.12 | 0.9791 | 25.24 | 8.01 | 48.13 | 15.27 | 0.9825 |
| Winter | Persistence model | 99.03 | 37.27 | 130.44 | 49.09 | 0.8575 | 92.97 | 38.45 | 123.19 | 50.95 | 0.8598 | 103.74 | 36.31 | 134.59 | 47.10 | 0.8637 | 98.48 | 34.67 | 128.02 | 45.07 | 0.8725 | 101.67 | 32.96 | 130.16 | 42.19 | 0.8815 |
| | SVM | 61.15 | 23.01 | 81.49 | 30.67 | 0.9435 | 63.47 | 26.25 | 81.73 | 33.80 | 0.9369 | 64.73 | 22.65 | 84.17 | 29.46 | 0.9456 | 56.46 | 19.88 | 74.64 | 26.28 | 0.9570 | 56.08 | 18.18 | 71.34 | 23.13 | 0.9665 |
| | ANN | 47.40 | 17.84 | 76.33 | 28.73 | 0.9505 | 48.79 | 20.18 | 74.13 | 30.66 | 0.9481 | 47.39 | 16.58 | 74.18 | 25.96 | 0.9581 | 42.99 | 15.14 | 66.95 | 23.57 | 0.9646 | 36.88 | 11.96 | 58.62 | 19.00 | 0.9758 |
| | CNN | 55.08 | 20.73 | 95.57 | 35.97 | 0.9220 | 60.01 | 24.82 | 89.31 | 36.94 | 0.9248 | 64.63 | 22.62 | 103.17 | 36.11 | 0.9188 | 48.84 | 17.20 | 80.59 | 28.37 | 0.9483 | 46.75 | 15.16 | 77.65 | 25.17 | 0.9571 |
| | LSTM | 48.58 | 18.28 | 79.31 | 29.85 | 0.9460 | 52.32 | 21.64 | 78.56 | 32.49 | 0.9415 | 51.20 | 17.92 | 78.04 | 27.31 | 0.9534 | 40.25 | 14.17 | 69.91 | 24.61 | 0.9613 | 35.67 | 11.56 | 61.38 | 19.90 | 0.9734 |
| | CNN-ANN | 43.90 | 16.52 | 75.51 | 28.42 | 0.9516 | 48.24 | 19.95 | 73.08 | 30.23 | 0.9496 | 45.94 | 16.08 | 73.52 | 25.73 | 0.9587 | 36.00 | 12.67 | 64.18 | 22.59 | 0.9675 | 31.96 | 10.36 | 55.47 | 17.98 | 0.9782 |
| | ANN-LSTM | 44.58 | 16.78 | 73.55 | 27.68 | 0.9540 | 48.06 | 19.88 | 72.49 | 29.98 | 0.9505 | 46.83 | 16.39 | 74.10 | 25.93 | 0.9582 | 36.44 | 12.83 | 63.05 | 22.20 | 0.9686 | 32.99 | 10.69 | 56.78 | 18.41 | 0.9772 |
| | CNN-LSTM | 42.31 | 15.92 | 75.49 | 28.41 | 0.9516 | 46.57 | 19.26 | 73.17 | 30.26 | 0.9495 | 44.55 | 15.59 | 73.29 | 25.65 | 0.9588 | 34.35 | 12.09 | 62.87 | 22.14 | 0.9688 | 32.16 | 10.42 | 57.51 | 18.64 | 0.9766 |



(a) Dallas



(b) San Jacinto



(c) Zapata

Fig. 9. Seasonal GHI distribution curves and the normalized evaluation metric values obtained by the different models at the five target sites.

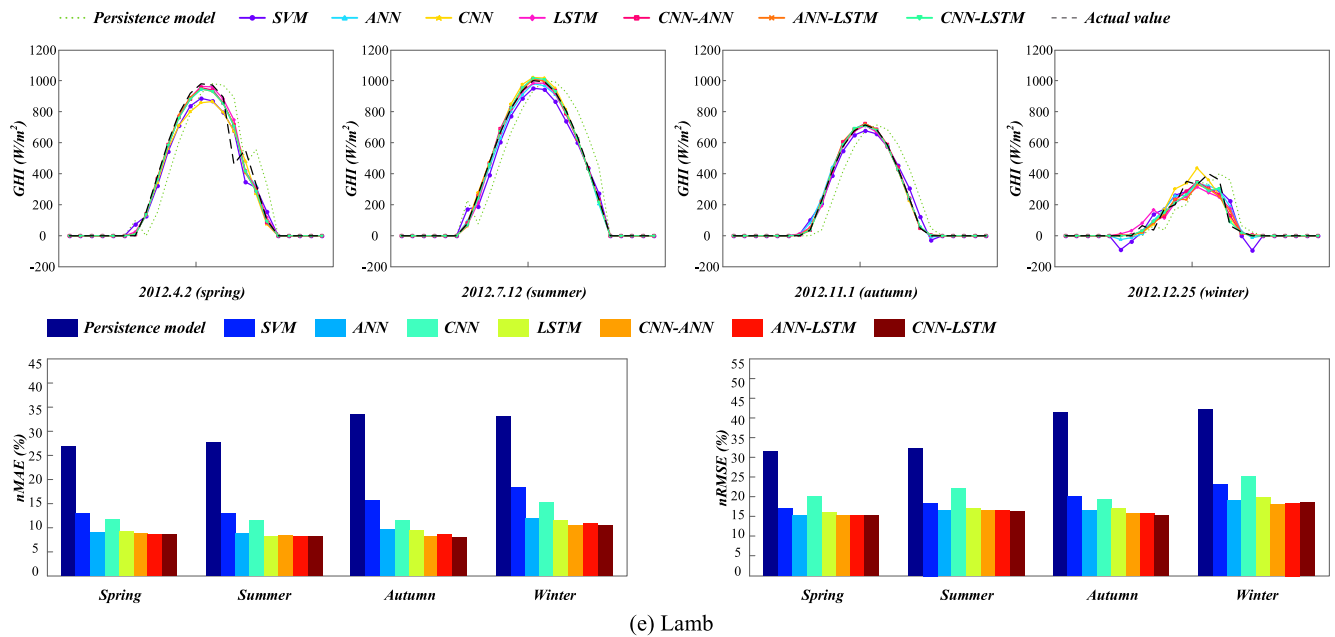
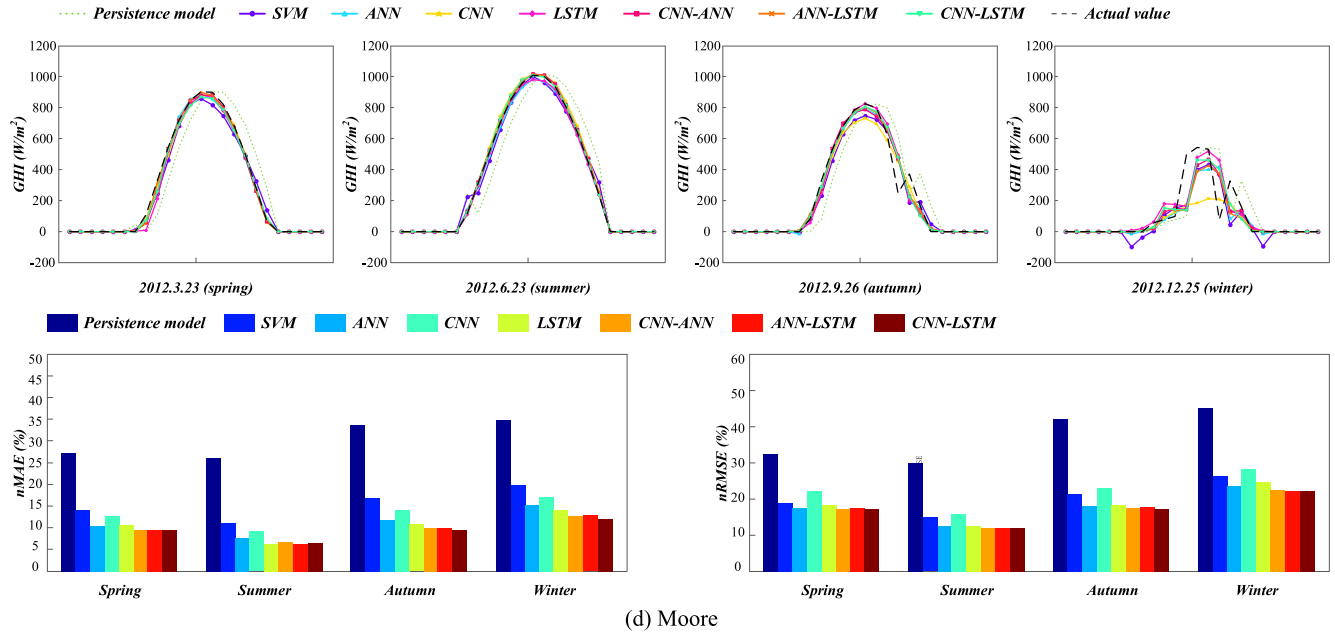


Fig. 9. (continued).

sky conditions is shown in Fig. 10.

For cloudy sky conditions, various models obtain the best performance metric values according to the Table 6 and Fig. 10. Meanwhile, the CNN-LSTM model performs best in 9 of total 25 cases. For instance, the MAE and nMAE values of CNN-LSTM are best in Zapata and the values are 44.56 W/m² and 145.02 W/m² respectively. This number 9 is highest of all models, demonstrating the superiority of the proposed hybrid model under cloudy sky conditions.

When the sky condition is partly cloudy, the SVM model achieves the best prediction performances in most cases according to Table 6 and Fig. 10. Although the CNN-LSTM model only performs best in 4 of total 25 cases, the prediction performance of the proposed model is also good in the remaining cases.

Under cloudless sky conditions, the CNN-LSTM model performs best in 17 of total 25 cases and this number is the highest of all eight models as well. For instance, the CNN-LSTM model owns the best prediction results of all eight models regardless of the performance evaluation metrics in San Jacinto and Moore. The MAE, nMAE, RMSE, nRMSE and R values of CNN-LSTM in San Jacinto are 44.26 W/m², 8.91%, 69.86 W/m², 14.07% and 0.9734 respectively, and the MAE, nMAE, RMSE, nRMSE and R values of CNN-LSTM in Moore are 30.50 W/m², 5.76%, 50.95 W/m², 9.62% and 0.9854 respectively, indicating the good prediction performance of the proposed hybrid model.

Table 5

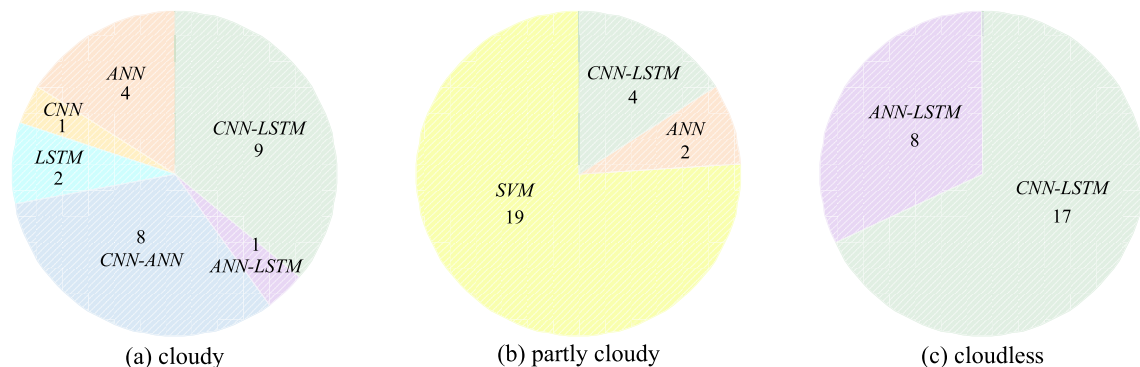
The percents of cloudy, partly cloudy and cloudless hours for each target site on the testing set.

| Site | $0 \leq k_t \leq 0.3$ (cloudy) | $0.3 < k_t \leq 0.7$ (partly cloudy) | $0.7 < k_t \leq 1$ (cloudless) |
|-------------|--------------------------------|--------------------------------------|--------------------------------|
| Dallas | 797h (16.75%) | 635h (13.35%) | 3326h (69.90%) |
| San Jacinto | 849h (17.84%) | 781h (16.41%) | 3128h (65.74%) |
| Zapata | 667h (14.02%) | 732h (15.38%) | 3359h (70.60%) |
| Moore | 704h (14.80%) | 590h (12.40%) | 3464h (72.80%) |
| Lamb | 688h (14.46%) | 522h (10.97%) | 3548h (74.57%) |

Table 6

Prediction results of different models under three sky conditions.

| Site | Model | $0 \leq k_t \leq 0.3$ (cloudy) | | | | | $0.3 < k_t \leq 0.7$ (partly cloudy) | | | | | $0.7 < k_t \leq 1$ (cloudless) | | | | |
|-------------|-------------------|--------------------------------|---------------|-----------------------------|---------------|---------------|--------------------------------------|--------------|-----------------------------|--------------|---------------|--------------------------------|-------------|-----------------------------|--------------|---------------|
| | | MAE (W/m ²) | nMAE (%) | RMSE (W/m ²) | nRMSE (%) | R | MAE (W/m ²) | nMAE (%) | RMSE (W/m ²) | nRMSE (%) | R | MAE (W/m ²) | nMAE (%) | RMSE (W/m ²) | nRMSE (%) | R |
| Dallas | Persistence model | 55.69 | 172.88 | 106.14 | 329.52 | 0.6185 | 120.25 | 48.91 | 158.19 | 64.34 | 0.6370 | 135.08 | 26.41 | 156.94 | 30.68 | 0.8500 |
| | SVM | 71.02 | 220.49 | 106.76 | 331.46 | 0.8282 | 81.42 | 33.11 | 109.89 | 44.69 | 0.8394 | 61.03 | 11.93 | 77.63 | 15.18 | 0.9711 |
| | ANN | 54.48 | 169.15 | 102.08 | 316.91 | 0.8374 | 90.25 | 36.70 | 122.73 | 49.91 | 0.8058 | 36.63 | 7.16 | 61.72 | 12.07 | 0.9782 |
| | CNN | 52.27 | 162.28 | 119.16 | 369.94 | 0.8309 | 112.13 | 45.60 | 152.59 | 62.06 | 0.7660 | 45.82 | 8.96 | 75.09 | 14.68 | 0.9702 |
| | LSTM | 54.63 | 169.62 | 106.45 | 330.48 | 0.8194 | 88.70 | 36.08 | 125.18 | 50.91 | 0.8129 | 36.80 | 7.19 | 64.15 | 12.54 | 0.9775 |
| | CNN-ANN | 41.46 | 128.71 | 97.94 | 304.07 | 0.8204 | 87.86 | 35.73 | 123.61 | 50.27 | 0.8127 | 35.13 | 6.87 | 59.91 | 11.71 | 0.9804 |
| | ANN-LSTM | 46.35 | 143.90 | 99.35 | 308.46 | 0.8297 | 87.66 | 35.65 | 120.93 | 49.18 | 0.8258 | 35.09 | 6.86 | 58.52 | 11.44 | 0.9813 |
| | CNN-LSTM | 41.62 | 129.21 | 99.58 | 309.17 | 0.8213 | 87.64 | 35.65 | 122.84 | 49.96 | 0.8155 | 33.21 | 6.49 | 59.02 | 11.54 | 0.9807 |
| San Jacinto | Persistence model | 63.26 | 156.41 | 114.68 | 283.55 | 0.6434 | 125.66 | 46.78 | 160.99 | 59.93 | 0.7301 | 138.63 | 27.91 | 160.87 | 32.39 | 0.8395 |
| | SVM | 79.59 | 196.79 | 114.06 | 282.02 | 0.8478 | 82.67 | 30.77 | 112.35 | 41.82 | 0.8800 | 67.27 | 13.54 | 86.11 | 17.34 | 0.9633 |
| | ANN | 56.64 | 140.03 | 103.50 | 255.91 | 0.8385 | 84.24 | 31.36 | 118.25 | 44.02 | 0.8725 | 46.90 | 9.44 | 71.21 | 14.34 | 0.9725 |
| | CNN | 66.88 | 165.35 | 126.85 | 313.63 | 0.8427 | 97.23 | 36.20 | 134.33 | 50.01 | 0.8401 | 59.27 | 11.93 | 87.73 | 17.66 | 0.9602 |
| | LSTM | 61.07 | 150.99 | 112.50 | 278.15 | 0.8308 | 89.40 | 33.28 | 123.52 | 45.98 | 0.8662 | 48.63 | 9.79 | 74.90 | 15.08 | 0.9696 |
| | CNN-ANN | 53.37 | 131.95 | 106.16 | 262.48 | 0.8432 | 83.48 | 31.08 | 118.00 | 43.93 | 0.8762 | 47.25 | 9.51 | 71.22 | 14.34 | 0.9721 |
| | ANN-LSTM | 54.37 | 134.43 | 104.26 | 257.78 | 0.8445 | 83.41 | 31.05 | 117.62 | 43.79 | 0.8775 | 46.88 | 9.44 | 70.83 | 14.26 | 0.9728 |
| | CNN-LSTM | 52.06 | 128.71 | 104.41 | 258.16 | 0.8483 | 82.93 | 30.87 | 118.36 | 44.06 | 0.8744 | 44.26 | 8.91 | 69.86 | 14.07 | 0.9734 |
| Zapata | Persistence model | 51.73 | 168.34 | 107.06 | 348.40 | 0.5932 | 127.11 | 48.94 | 164.22 | 63.23 | 0.6767 | 143.21 | 27.21 | 165.14 | 31.37 | 0.8479 |
| | SVM | 73.20 | 238.22 | 109.92 | 357.71 | 0.8629 | 86.51 | 33.31 | 118.53 | 45.64 | 0.8676 | 61.99 | 11.78 | 77.96 | 14.81 | 0.9725 |
| | ANN | 52.09 | 169.51 | 100.99 | 328.64 | 0.8570 | 93.92 | 36.16 | 132.68 | 51.09 | 0.8704 | 36.03 | 6.85 | 57.90 | 11.00 | 0.9836 |
| | CNN | 61.30 | 199.49 | 125.54 | 408.56 | 0.8709 | 121.88 | 46.93 | 161.65 | 62.24 | 0.8562 | 45.57 | 8.66 | 68.86 | 13.08 | 0.9776 |
| | LSTM | 51.87 | 168.78 | 102.06 | 332.12 | 0.8273 | 92.47 | 35.61 | 130.72 | 50.33 | 0.8385 | 38.61 | 7.34 | 63.99 | 12.16 | 0.9796 |
| | CNN-ANN | 46.07 | 149.92 | 96.86 | 315.22 | 0.8551 | 92.53 | 35.63 | 130.88 | 50.40 | 0.8582 | 33.75 | 6.41 | 57.04 | 10.84 | 0.9833 |
| | ANN-LSTM | 48.96 | 159.33 | 99.62 | 324.20 | 0.8593 | 94.71 | 36.47 | 132.79 | 51.13 | 0.8573 | 34.20 | 6.50 | 56.99 | 10.83 | 0.9832 |
| | CNN-LSTM | 44.56 | 145.02 | 97.16 | 316.18 | 0.8478 | 90.96 | 35.02 | 130.03 | 50.07 | 0.8598 | 33.17 | 6.30 | 56.28 | 10.69 | 0.9838 |
| Moore | Persistence model | 51.93 | 247.92 | 104.12 | 497.11 | 0.5797 | 121.14 | 51.79 | 158.18 | 67.62 | 0.7011 | 136.39 | 25.74 | 155.56 | 29.36 | 0.8542 |
| | SVM | 66.39 | 317.00 | 100.82 | 481.36 | 0.8291 | 82.52 | 35.28 | 112.61 | 48.14 | 0.8756 | 55.95 | 10.56 | 69.64 | 13.15 | 0.9766 |
| | ANN | 49.70 | 237.27 | 92.19 | 440.17 | 0.8429 | 85.00 | 36.34 | 120.82 | 51.65 | 0.8777 | 35.48 | 6.70 | 54.38 | 10.26 | 0.9837 |
| | CNN | 48.06 | 229.45 | 118.96 | 567.99 | 0.8418 | 111.57 | 47.70 | 159.01 | 67.98 | 0.8627 | 42.86 | 8.09 | 63.62 | 12.01 | 0.9782 |
| | LSTM | 42.51 | 202.98 | 92.93 | 443.71 | 0.8112 | 83.45 | 35.68 | 121.73 | 52.04 | 0.8664 | 33.50 | 6.32 | 57.44 | 10.84 | 0.9816 |
| | CNN-ANN | 34.49 | 164.66 | 85.33 | 407.39 | 0.8397 | 81.57 | 34.87 | 120.60 | 51.56 | 0.8737 | 31.68 | 5.98 | 52.20 | 9.85 | 0.9848 |
| | ANN-LSTM | 34.98 | 167.01 | 87.24 | 416.53 | 0.8362 | 83.91 | 35.87 | 122.07 | 52.19 | 0.8728 | 30.80 | 5.81 | 51.33 | 9.69 | 0.9851 |
| | CNN-LSTM | 34.45 | 164.48 | 88.02 | 420.25 | 0.8401 | 80.28 | 34.32 | 119.19 | 50.95 | 0.8757 | 30.50 | 5.76 | 50.95 | 9.62 | 0.9854 |
| Lamb | Persistence model | 51.60 | 187.64 | 100.14 | 364.18 | 0.6727 | 131.31 | 54.64 | 172.49 | 71.78 | 0.7003 | 139.97 | 26.10 | 159.30 | 29.71 | 0.8507 |
| | SVM | 70.06 | 254.78 | 106.22 | 386.28 | 0.8974 | 89.63 | 37.30 | 124.78 | 51.93 | 0.8762 | 55.59 | 10.37 | 70.02 | 13.06 | 0.9780 |
| | ANN | 49.01 | 178.23 | 100.04 | 363.84 | 0.8959 | 91.85 | 38.22 | 133.22 | 55.44 | 0.8705 | 31.76 | 5.92 | 50.85 | 9.48 | 0.9861 |
| | CNN | 55.63 | 202.32 | 140.48 | 510.91 | 0.8712 | 124.64 | 51.87 | 178.34 | 74.22 | 0.8423 | 41.00 | 7.65 | 60.87 | 11.35 | 0.9806 |
| | LSTM | 46.01 | 167.34 | 97.64 | 355.11 | 0.8844 | 90.99 | 37.86 | 134.98 | 56.17 | 0.8619 | 31.35 | 5.85 | 55.79 | 10.40 | 0.9831 |
| | CNN-ANN | 42.12 | 153.17 | 100.64 | 365.99 | 0.8895 | 89.82 | 37.38 | 134.39 | 55.93 | 0.8727 | 29.40 | 5.48 | 47.93 | 8.94 | 0.9875 |
| | ANN-LSTM | 44.63 | 162.31 | 102.76 | 373.71 | 0.9020 | 91.69 | 38.16 | 135.67 | 56.46 | 0.8728 | 28.61 | 5.34 | 46.54 | 8.68 | 0.9882 |
| | CNN-LSTM | 40.37 | 146.80 | 97.99 | 356.38 | 0.8929 | 88.82 | 36.96 | 133.83 | 55.69 | 0.8729 | 28.99 | 5.41 | 48.79 | 9.10 | 0.9872 |

**Fig. 10.** The number of times each model obtains the best performance metric values in terms of three sky conditions.

6. Conclusion

This study proposes a hybrid CNN-LSTM model with spatio-temporal correlations to improve the accuracy of short-term solar radiation prediction for supporting the optimum dispatch and management of power systems with high penetrations of PV power generation. The proposed model adopts a CNN to extract spatial features based on meteorological parameters and an LSTM network to extract temporal features based on historical GHI time series data, and effectively combines the temporal and spatial correlations of the data to obtain accurate GHI predictions 1 h in advance. The prediction performance and generalization ability of the proposed hybrid CNN-LSTM model are rigorously evaluated by analyzing its GHI prediction results in a whole year, different seasons and different sky conditions when applied to three datasets composed of spatiotemporal data collected from 34 locations spread across three different climate zones in Texas, USA. Meanwhile, the prediction performance of the CNN-LSTM model is compared with the performances obtained using the persistence model, SVM, ANN, CNN, LSTM, CNN-ANN, and ANN-LSTM models based on five evaluation metrics. The prediction results indicate that the proposed model typically provides the best annual and seasonal prediction performances of all models considered at the five target sites of the three datasets. The MAE values of CNN-LSTM at Dallas, San Jacinto, Zapata, Moore and Lamb on the whole year dataset are 41.88 W/m², 52.00 W/m², 43.66 W/m², 37.26 W/m² and 37.20 W/m², respectively. The percentile improvements at five target sites are 3.10%, 4.22%, 1.93%, 2.66% and 1.77% compared with CNN-ANN and 4.80%, 4.08%, 4.21%, 1.95% and 1.72% compared with ANN-LSTM, demonstrating the superiority of combining spatial and temporal correlations by means of the CNN-LSTM model. Meanwhile, the seasonal prediction results demonstrate that the seasonal distribution of prediction errors changes with respect to climate, and that the proposed CNN-LSTM model provides prediction results that are more greatly improved relative to the results of the other models considered during seasons when the prediction errors are relatively large. In addition, the proposed model has more improvement in cloudy and cloudless sky conditions, and a slight advance in partly cloudy sky condition according to the prediction results. The proposed hybrid model is hereby demonstrated to be a good choice for short-term GHI prediction, especially in cloudy and cloudless sky conditions. Meanwhile, the model needs massive data and has many parameters, so the training time is long. Therefore, storage and computing devices (such as GPU) are needed. In future research, the proposed model will be considered for long-term solar radiation prediction. Furthermore, other spatiotemporal correlation models are also worthy of further study.

CRedit authorship contribution statement

Haixiang Zang: Conceptualization, Methodology, Software. **Ling Liu:** Data curation, Software, Writing - original draft. **Li Sun:** Software, Writing - review & editing. **Lilin Cheng:** Writing - review & editing. **Zhinong Wei:** Writing - review & editing. **Guoqiang Sun:** Writing - review & editing.

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