SHORT-TERM PREDICTION OF REGIONAL ENERGY CONSUMPTION BY METAHEURISTIC OPTIMIZED DEEP LEARNING MODELS

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Abstract - Modern civilization is heavily dependent on energy, which burdens the energy sector. Therefore, a highly accurate energy consumption forecast is essential to provide valuable information for efficient energy distribution and storage. This study proposed a hybrid deep learning model, called I-CNN-JS, by incorporating a jellyfish search (JS) algorithm into an ImageNet-winning convolutional neural network (I-CNN) to predict week-ahead energy consumption. First, numerical data were encoded into grayscale images for input of the proposed model, showcasing the novelty of using image data for analysis. Second, a newly developed metaheuristic optimization algorithm, JS, was used to improving model accuracy. Results showed that the proposed method outperformed conventional numerical input methods. The optimized model yielded a mean absolute percentage error improvement of 0.5% compared to the default models, indicating that JS is a promising method for achieving the optimal hyperparameters. Sensitivity analysis further evaluated the impact of image pixel orientation on performance model.

Key words - short-term prediction; energy consumption; deep learning; convolutional neural network; metaheuristic optimization; machine learning; time-series deep learning

1. Introduction

The energy sector plays a vital role in the global economy, directly affecting industries, infrastructure, and social life. Ensuring a stable power supply helps minimize negative impacts on production and business while supporting the promotion of industrialization, modernization, and sustainable development. Forecasting energy consumption is one of the core factors in the effective management of the energy system, especially in the context of increasing scale and volatility in energy consumption [1].

However, with the increasing integration of renewable energy sources into the grid, the instability of the energy supply has become a challenge. The completely unpredictable nature of sources such as wind and solar, combined with the ever-changing demand, requires accurate forecasting tools to support system operators in decision-making. Therefore, forecasting energy consumption has become a vital task to optimize energy distribution, ensuring economic efficiency and sustainability of the energy system [2].

Traditional methods such as linear regression, time-based statistical models, or simple machine learning (ML) techniques have been widely used for many years to forecast energy consumption [3-5]. However, with the development of technology and the abundance of data, these methods are gradually becoming limited when faced with complex and highly nonlinear energy models [6]. Deep learning (DL) has emerged as a potential solution due to its ability to learn and model complex relationships in data. DL can exploit information from large, multidimensional datasets to forecast energy consumption more accurately [7].

One of the most widely used DL models is the convolutional neural network (CNN), thanks to its ability to capture spatiotemporal relationships as well as time series features [8]. However, implementing DL models for energy consumption forecasting also faces significant challenges, the most important of which is the parameter optimization process. DL models often require configuring parameters such as the number of layers, the number of nodes in each layer, and other hyperparameters, which directly affect the accuracy and performance of the model. Optimizing these parameters is often done by trial and error methods or simple optimization algorithms, but they do not always guarantee optimal performance for the model.

To improve this optimization, hyperparameter optimization algorithms have been applied to optimize hyperparameters and enhance the performance of deep learning models. These optimization algorithms are designed to search large parameter spaces, avoiding falling and local minima, a common problem in traditional optimization methods, while providing more flexible and efficient model tuning.

Although DL models have been applied in various fields, such as image processing, natural language processing, and medicine, their application in the field of short-term energy consumption forecasting is still limited and underexploited. Therefore, this study aims to bridge this gap by proposing a method that combines I-CNN models and metaheuristic optimization algorithms for regional energy consumption forecasting.

Specifically, this study will focus on:

1) Proposing a hybrid DL model based on I-CNN and JS algorithm to predict energy consumption.

2) Developing an automated process to convert numerical data into images as input for I-CNN.

3) Conducting sensitivity analysis to examine the effect of image pixel orientation on model accuracy.

2. Related works

2.1. Convolutional neural network

Convolutional neural networks (CNNs) are a type of artificial neural network specifically designed to process

data with a grid structure, such as images and videos. CNNs are widely used in computer vision, such as object recognition, image classification, face recognition, and video analysis. Unlike traditional models that require manual feature extraction, CNNs automatically learn features from raw data, especially spatial features, through the structure of filters.

The basic architecture of CNN typically consists of an input layer that receives an input image, and several hidden layers that include three different layers: a convolutional layer, a pooling layer, a fully-connected layer, and an output layer that produces the final output. Figure 1 displays a simple CNN architecture. CNN becomes more and more complicated as it progresses from the convolutional layer to the FC layer. Thanks to such an arrangement, CNN can first recognize simpler patterns (lines, curves) and then more complicated features (faces, objects) of an image before fully recognizing the pattern and extracting the useful features.

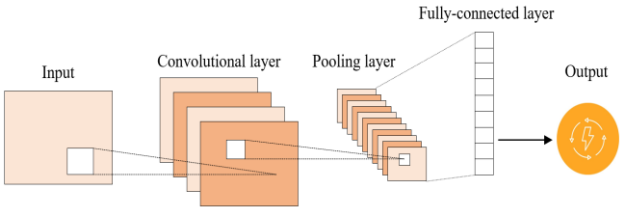

Figure 1. *The architecture of a CNN*

The convolutional layer is one of the main and most characteristic components of a CNN, which helps extract features from input data, especially images. The convolutional layer uses one or more filters (also known as kernels). These filters are small matrices whose values are learned during training. The filter is passed through the entire input image, calculating the convolution between the filter and the corresponding regions of the image, and creating a feature map.

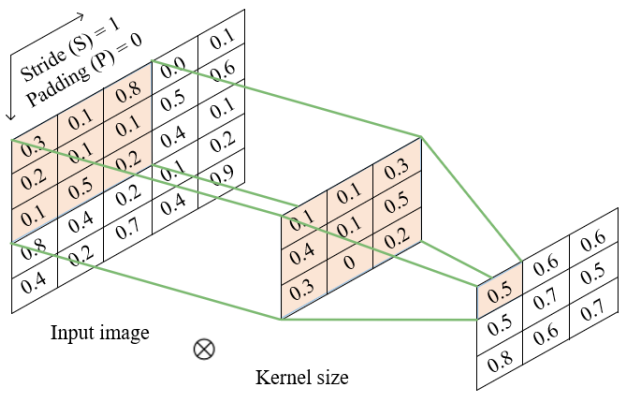

Figure 2. *Convolution operation of the convolution layer*

The convolution operation (Figure 2) multiplies each element of the filter by the corresponding part of the image, then sums it up and outputs a new value. This calculation continues as the filter moves through the entire image. The result of this process is a feature map that is smaller or equal to the original image, depending on parameters such as stride, and padding. The convolution operation can be defined as follows:

$$C_i = b_i + \sum_{j=1}^{d_i} I_j * F_{ij}\,,\ i = 1 \dots d_c \quad (1)$$

where, C_i is the output of convolutional layer or feature map of size $(c_w\ x\ c_h)$ in which $(c_w\ x\ c_h) = ((v_w - r_w - 2p)/s + 1)x((v_h - r_h - 2p)/s + 1)$ $(v_w, v_h$are the width and height of input volume, r_w, r_h are the width and height of receptive field size, p is the amount of zero padding used on the border, s is the stride with which they are applied), B_i is the bias, d_i is the depth of input, I_j is the input image, F_{ij} is the filter, and d_c is the depth of convolutional layer.

After convolution, the values in the feature map are usually passed through an activation function such as ReLU to nonlinearize, retain important features, and ignore negative values that are not meaningful to the model. The general formula of the activation function can be defined as follows:

$$Y_i = f(C_i) \quad (2)$$

where, Y_i is the output of the convolutional layer after applying the activation function and f is the activation function.

Pooling layer in CNN is a downsampling layer used to reduce the size of feature maps without losing too much important information. Pooling reduces the number of parameters and computations in the network, while increasing the resistance to changes in the location of features in the input data, making the model more robust to local changes in the image. The dimensions of the output obtained from the pooling layer are as follows:

$$(c_w - f_w + 1)/s\ x\ (c_h - f_h + 1)/s\ x\ c_n \quad (3)$$

where, c_n is the number of channels in the feature map and $f_w\ x\ f_h$ is the width and height of the filter.

Average pooling and max pooling are two typical pooling approaches. Max pooling is the most common type in CNN networks, which selects the largest value in each small region of the feature map. Instead of selecting the largest value, average pooling averages the values in the small regions. This is less commonly used than max pooling but still has applications in some cases. Figure 3 presents the illustration of max pooling and average pooling.

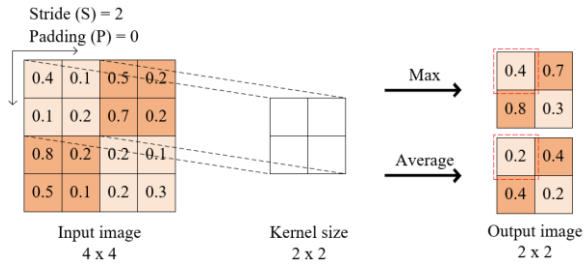

Figure 3. *Max pooling and average pooling*

A fully-connected (FC) layer is a layer in which each neuron is connected to all the neurons in the previous layer. It is the final component of CNN and is often used to perform tasks such as classification or prediction. After previous layers, such as convolutional and pooling layers, have extracted local features from the data, the FC layer aggregates and processes all of this information, allowing the network to learn more complex features from the entire data. In classification models, the FC layer is typically at

the end of the network and has as many neurons as there are labels to classify. In prediction tasks, the FC layer can predict continuous values, such as in regression problems. Figure 4 presents the structure of the FC layer.

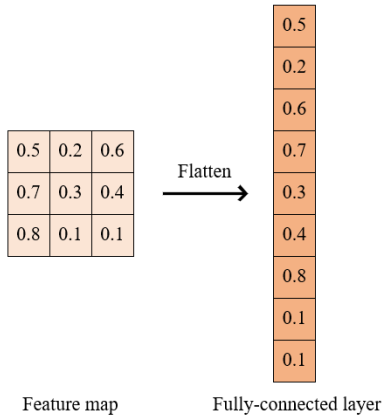

Figure 4. *Structure of a fully-connected layer*

2.2. ImageNet-winning convolutional neural network

The ImageNet Large Scale Visual Recognition Challenge (ILSVRC) is one of the most prestigious competitions in the field of computer vision, especially in object recognition in images. The winning CNN models in this competition have driven significant advances in computer vision technology. Several popular CNN architectures have been developed that differ in their approach and have significantly improved not only the accuracy but also the efficiency of the model on various tasks compared to their predecessors. Table 1 shows the I-CNN architectures used in this study.

Table 1. *Overview of I-CNN structures used in this study*

Attribute	Parameters (million)	Size (MB)
VGG19	143.7	549
ResNet50V2	25.6	98
Inceptionv3	23.9	92
MobileNetV2	3.5	14
DenseNet201	20.2	80
NASNetLarge	88.9	343
EfficientNetB0	5.3	29
ConvNeXtTiny	-	28.6

2.3. Jellyfish Search Algorithm

The JS algorithm is a metaheuristic optimization algorithm inspired by the migration and hunting behavior of jellyfish in the ocean, proposed by Chou et al. in 2020 [9]. The algorithm simulates the two main movements of jellyfish: random movements as they drift with the ocean currents and directional movements as they swim in search of food sources. Combining the exploration and exploitation of the search space, JS optimizes complex problems by balancing between exploring new regions and exploiting potential solutions, avoiding getting stuck in local extrema.

JS has been successfully applied to various optimization problems, from continuous space optimization to discrete optimization, and the results show that JS can achieve higher efficiency and faster convergence than traditional algorithms. In addition, the algorithm does not require many complex parameters. The flowchart and pseudocode of the JS algorithm are shown in Figures 5 and 6 respectively.

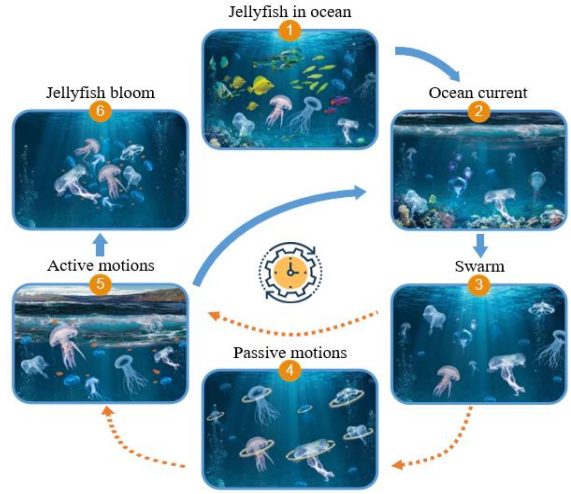

Figure 5. *Jellyfish behavior in the ocean*

```
BEGIN
    /*Input*/
    Define objective function f(X) | X=(x1, x2,...,Xd)^T
    Set search space: upper bound (Ub) and lower bound (Lb)
    Set population size (pop_size) and maximum iteration (max_iter)
    /*Initialization phase*/
    Generate the initial population of jellyfish Xi (i=1,2,...,pop_size) using a logistic chaotic map
    Calculate the quantity of food at each location Xi determined by f(Xi)
    Select jellyfish with the best location (X*) from the initial population
    /*Iteration start*/
    Set current iteration: t=1
    WHILE t ≤ max_iter
        FOR i=1: pop_size
            /*Time control-based 3 strategic motions */
            Calculate time control value c(t) using Eq. (18)
            IF c(t) ≥ 0.5: /*Jellyfish follows the ocean current*/
                Determine ocean current using Eq. (19)
                Update the new location of the selected jellyfish after it has moved using Eq. (20)
            ELSE /*Jellyfish moves inside a swarm*/
                IF rand(0,1) > (1-c(t)): /*Jellyfish follows passive motions*/
                    Update the new location of the selected jellyfish after it has moved using Eq. (21)
                ELSE /*Jellyfish follows active motions*/
                    Determine the direction of jellyfish using Eq. (22)
                    Update the new location of the selected jellyfish after it has moved using Eq. (23)
                END IF
            END IF
            Check boundary conditions and re-update the new location of jellyfish
            Calculate the quantity of food at the new location of jellyfish
            Update the best location of jellyfish
        END FOR i
        Update iteration number: t=t+1
    END WHILE /*Iteration end*/
    /*Output*/
    Output the final best results
END
```

Figure 6. *Pseudocode of the jellyfish search algorithm*

3. Proposed I-CNN-JS algorithm

3.1. Image conversion process

This study proposes a numerical-to-image data conversion method that allows the use of image processing and computer vision techniques to implement I-CNN models. Each time step is represented as a pixel in the image, enabling the model to capture spatial relationships between different time steps, correlations, and dependencies to identify geographically close regions and detect similar patterns in energy consumption, which are difficult to discern from raw digital data alone.

The image conversion process is detailed in Figure 7.

Initially, n attributes of each observation are used to generate a $n \times 1$ grayscale image. These initial images are processed using a sliding window technique with a window size of k to generate a $n+1 \times k$ grayscale image. First, min-max normalization is performed to scale the numerical data to values between 0 and 1. Then, the normalized data is multiplied by 255 and encoded into images with grayscale values between 0 and 255. Finally, each image is labeled with the $k + m^{th}$ energy consumption data.

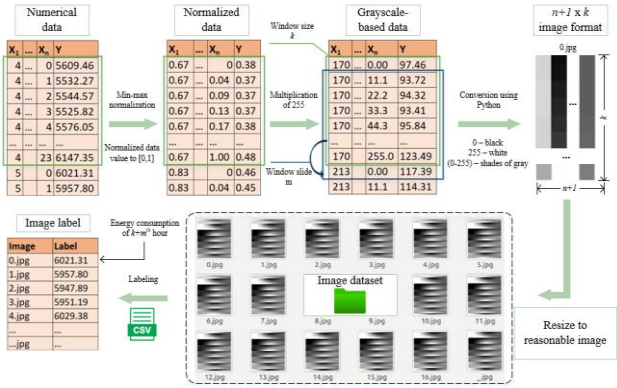

Figure 7. *The conversion of numerical data into grayscale images*

3.2. I-CNN-JS algorithm

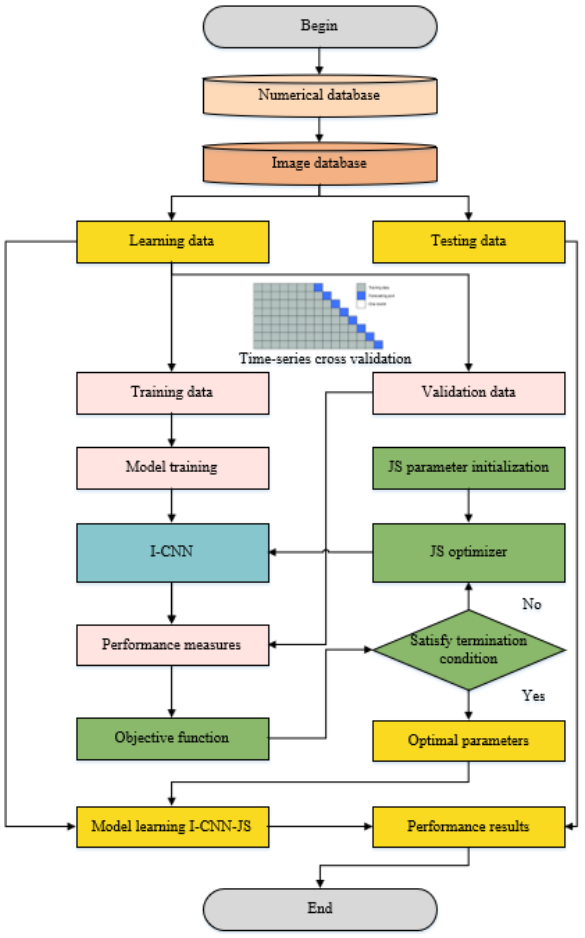

Figure 8. *The proposed optimized hybrid model*

The proposed I-CNN-JS algorithm, which combines the I-CNN architecture with the JS algorithm, not only aims to leverage the power of the I-CNN architectures in predicting energy consumption but also can find the global optimal solution to improve prediction accuracy. The process of the I-CNN-JS algorithm is depicted in Figure 8.

4. Result analysis

4.1. Dataset and parameter setting

This study collected five-year hourly energy consumption data from 2019 to 2023 from a power company by using the Data Miner tool on the PJM website (https://www.pjm.com/). This dataset includes 43,824 data points after the kNN imputation method was used to handle missing data during the data collection.

Table 2 presents the attributes of the energy consumption dataset used in this study. The time index was decomposed into time-series characteristics X1-X7 such as hour, month, quarter, year, day of the week, day of the month, and day of the year which were used to predict energy consumption Y.

Table 2. *Attributes of the dataset*

Attribute	Description
Time Index	Time data are recorded
Month	Month (1, 2, …, 12)
Quarter	Quarter (1, 2, …, 4)
Year	Year (2019, 2020, …, 2023)
Hour	Hours (0, 1, …, 23)
Day of week	Day (0, 1, …, 6)
Day of month	Day (0, 1, …, 31)
Day of year	Day (0, 1, …, 366)
Energy consumption	Energy consumption (MWh)

4.2. Validation and performance evaluation

The dataset was divided into 80% for learning (from 2018 to 2022) and 20% for testing (2023). The learning dataset was then divided into 85% and 15% for training and validation, respectively. This study uses the time-series cross-validation method, which divides the data in time order, ensuring that future data points are not used to predict past data to preserve the sequentiality of the data [10].

Five widely used regression metrics including the mean absolute error (MAE), root mean square error (RMSE), mean absolute percentage error (MAPE), training time, and synthesis index (SI) were used to evaluate and validate model performance. Table 3 presents the equation of these performance metrics.

Table 3. *Performance measures*

Performance measures	Equation
MAE	$\frac{1}{n}\sum_{i=1}^{n}\lvert y_i - \hat{y}_i\rvert$
RMSE	$\sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}$
MAPE	$\frac{1}{n}\sum_{i=1}^{n}\left\lvert\frac{y_i-\hat{y}_i}{y_i}\right\rvert$
SI	$\frac{1}{m}\sum_{i=1}^{m}\left(\frac{P_i-P_{(min,i)}}{P_{(max,i)}-P_{(min,i)}}\right)$

where, n is the number of predictions, y_i the predicted value; $\hat{y}_i$ is the actual value, m is the number of performance metrics, P_i is the value of the performance metric, $P_{(max,i)}$ is the maximum value of performance metric, and $P_{(min,i)}$ is the minimum value of performance

metric. Their lower values indicate better performance.

4.3. Model establishment

A typical CNN structure normally includes a softmax activation function at the end of the network for classification tasks. However, predicting energy consumption is a regression task. Therefore, the CNN models in this study were restructured by replacing the softmax activation function in the final layer with a linear activation, which allows the network to output continuous values rather than probabilities.

While CNN, LSTM, and GRU models were deployed using the Keras library in Python, ML models were constructed in Scikit-learn and XGBoost in Python. Table 4 presents the performance results of predictive models for week-ahead energy consumption.

Table 4. *Performance result of models for week-ahead energy consumption*

Model	MAE (kWh)	RMSE (kWh)	MAPE (%)	SI	t (h)
VGG19	388.4	421.6	8.1	(8)	1.52
ResNet50V2	367.6	387.1	7.5	(5)	1.23
Inceptionv3	388.4	413.1	7.9	(7)	1.22
MobileNetV2	372.8	393.6	7.6	(4)	1.02
DenseNet201	365.0	383.2	7.4	(3)	1.19
NASNetLarge	371.5	397.5	7.7	(6)	1.48
EfficientNetB0	363.7	368.9	7.3	(2)	1.00
ConvNeXtTiny	352.1	355.2	7.1	(1)	1.00
ANN	633.2	774.0	11.2	(13)	0.08
RF	622.8	762.5	10.9	(12)	0.09
SVR	645.8	787.6	11.4	(14)	0.08
XGBoost	568.2	686.9	10.3	(11)	0.08
LSTM	569.2	691.6	10.2	(10)	0.16
GRU	564.3	680.8	9.9	(9)	0.15

Note: kWh: kilowatt hours

The results revealed that ConvNeXtTiny, XGBoost, and GRU were the best-performing models in their categories in predicting week-ahead energy consumption, with MAPE values of 7.1%, 10.3%, and 9.9%, respectively. Notably, all CNN models provided more accurate predictions than the rest with the MAPE range from 7.1% to 8.1%, occupying the top 8 out of 14 models according to the SI index, in which ConvNeXtTiny is the best model. This impressive result demonstrated that the proposed model outperforms methods using numerical data.

The running time shows that the CNN models in this study take significantly longer than other numerical models. For example, the CNN model takes more than one hour to predict energy consumption, while the numerical models only take about 0.8 to 0.9 hour for the ML models and 0.15 to 0.16 hour for the time-series DL models.

Although CNN models provide better prediction results, users should choose the model based on their goals, usage context, and computational resources. For example, CNN models should be used in cases where accurate predictions are required for research and measurement purposes, where high accuracy is the top factor and longer computation times are accepted. In contrast, numerical models such as GRU are more suitable for real-time predictions, where the balance between accuracy and speed is important.

4.4. Optimization

A validation of the power of optimization algorithms, namely Jellyfish Search, and two well-known metaheuristic algorithms, Teaching-Learning-Based Optimization (TLBO) and Symbiotic Organisms Search (SOS), was performed before incorporating one of them into the best model for parameter optimization. Ten benchmark functions were selected to validate the effectiveness of these algorithms, namely Step, Trid10, Zakharov, Foxholes, Michalewicz2, Shubert, Ackley, Langermann2, and Fletcher Powell10. Hit rate, the ratio between the number of times the algorithm produces the optimal result and the number of times the independent optimization is performed, and the running time were used to compare the effectiveness of the algorithms.

The results in Table 5 show that JS outperforms SOS and TLBO in both hit rate and computation time. The hit rate of JS is 100%, which is 31.02% and 27.88% higher than SOS and TLBO. As for running time, JS only needs 11.02 seconds to find the optimal values of the benchmark functions, while the figures for SOS and TLBO are 63.69 and 62.96, respectively. Therefore, JS was then selected as the best optimization algorithm incorporated into the ConvNeXtTiny model.

Table 5. *Comparison results of benchmark functions in the optimization algorithms*

Criteria	JS	SOS	TLBO
Hit rate (%)	100	68.98	72.12
Running time (sec)	11.02	63.69	62.96

Table 6 shows the results of the model performance before and after optimization. The results demonstrate that JS is effective in improving the accuracy of the model, with MAPE improving by 0.5% compared to the original model. Table 14 shows the parameters after optimization.

Table 6. *Comparison results of model performance before and after optimization*

Model	MAE (kWh)	RMSE (kWh)	MAPE (%)
I-CNN (ConvNeXtTiny)	352.1	355.2	7.1
I-CNN (ConvNeXtTiny) - JS	334.2	336.2	6.6

4.5. Sensitivity analysis of image pixel order

Another numerical experiment was conducted based on the ConvNeXtTiny model to investigate the influence of image orientation on prediction accuracy. Two types of image orientations, including the original pixel array (randomly arranged) and the pixel array arranged according to the correlation between input attributes and energy consumption were adopted in this study. Specifically, the image data was reformatted in three ways: arranging the pixels randomly, arranging them in ascending order, and descending order based on the correlation value.

Table 6 presents the results of the sensitivity analysis of image orientation on the prediction model accuracy. It can

be seen that all evaluation criteria related to the arrangement in descending order and ascending order of image pixels give slightly worse results (0.3% difference in MAPE) compared to when using the originally arranged images on the same model. Therefore, the analysis results show that the arrangement of pixels in correlation order during the conversion of data to image form does not significantly affect the performance of the prediction model.

Table 6. *Sensitivity analysis of image orientation*

Criteria	Image orientation		
	Random	**Descending order**	**Ascending order**
MAPE (%)	6.62	6.68	6.72
RMSE (%)	336.22	338.32	340.01
MAE (kWh)	334.23	335.87	336.29

5. Conclusion

This study proposed a hybrid DL model called I-CNN-JS to predict regional energy consumption. The model can leverage the automatic feature extraction of CNN and provide more accurate prediction by using a JS optimizer to find the optimal parameters. Numerical data converted into grayscale image data were input into the I-CNN models.to utilize the available I-CNN models. The proposed model outperformed the ML and time-series DL models that used numerical data regarding accuracy. The results of the optimization process also show the effectiveness of using JS to optimize parameters and improve model accuracy. Users need to consider the goals and computational capabilities to choose the appropriate model because although the proposed model provides higher accuracy, it also consumes more resources and computational time.

The size of input images significantly impacts CNN models' performance and training time. If the images are too small, they may lack sufficient detail and features, leading to lower accuracy and weaker generalization. On the other hand, very large images can increase model complexity, require more computational power, and may cause overfitting, especially when working with large datasets. In this study, the image size was chosen manually through trial and error. Additionally, the model only used date index and hourly energy consumption-without considering other factors like weather or human behavior, which could influence energy consumption. As a result, the models may not fully capture the complexity of energy usage patterns.

Future studies could explore developing an automated method for selecting the optimal image size to improve both efficiency and performance. Additionally, incorporating data on environmental and human-related factors may further enhance model accuracy and learning. Future research should also extend the investigation to other regions or countries, employ alternative prediction techniques such as mid- and long-term forecasting, and examine various demand levels, from building to national scales, to validate the effectiveness and generalizability of the proposed models.

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