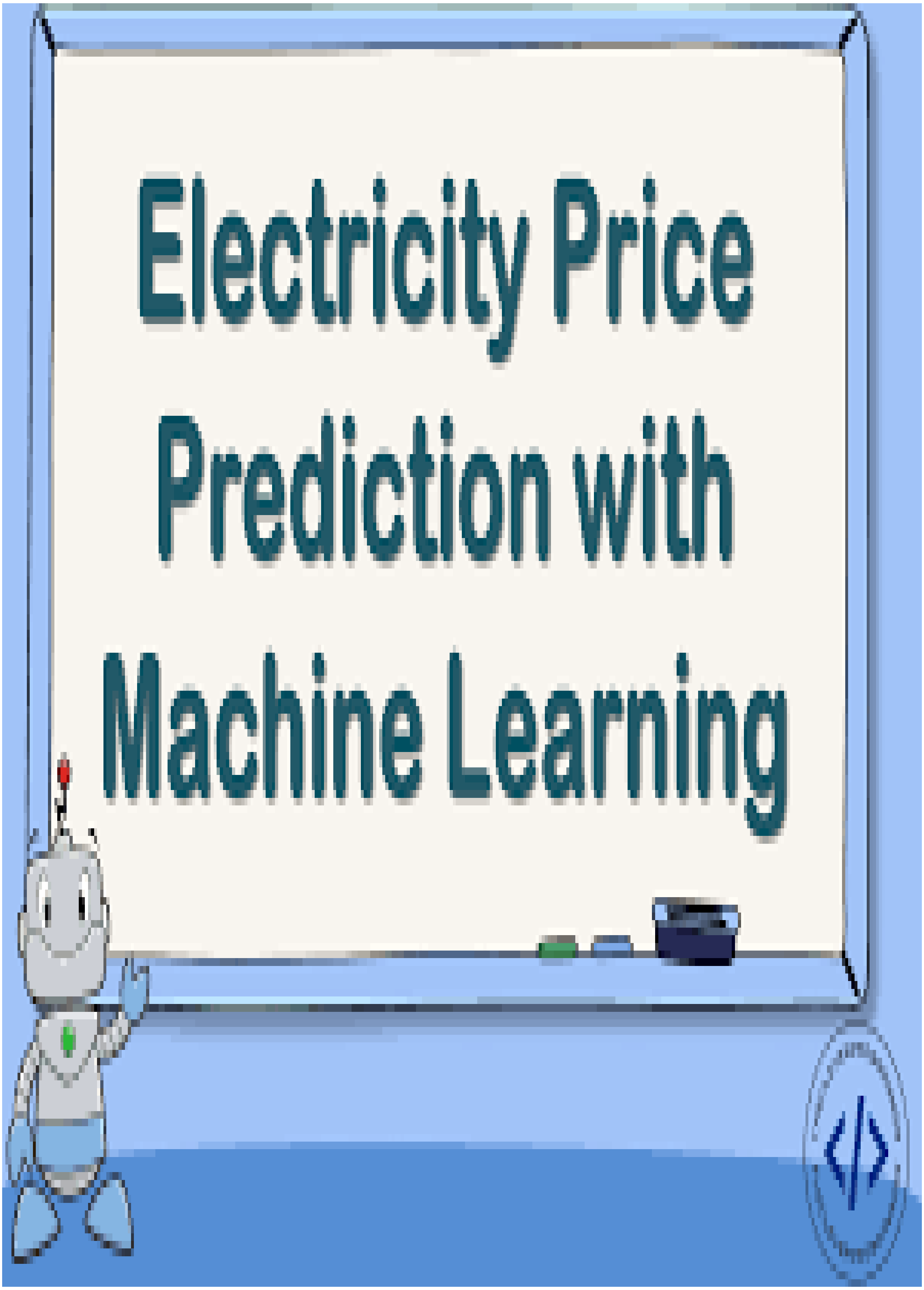
Electricity Price
Prediction with
Machine Learning

PREDICTING ELECTRICITY PRICE:

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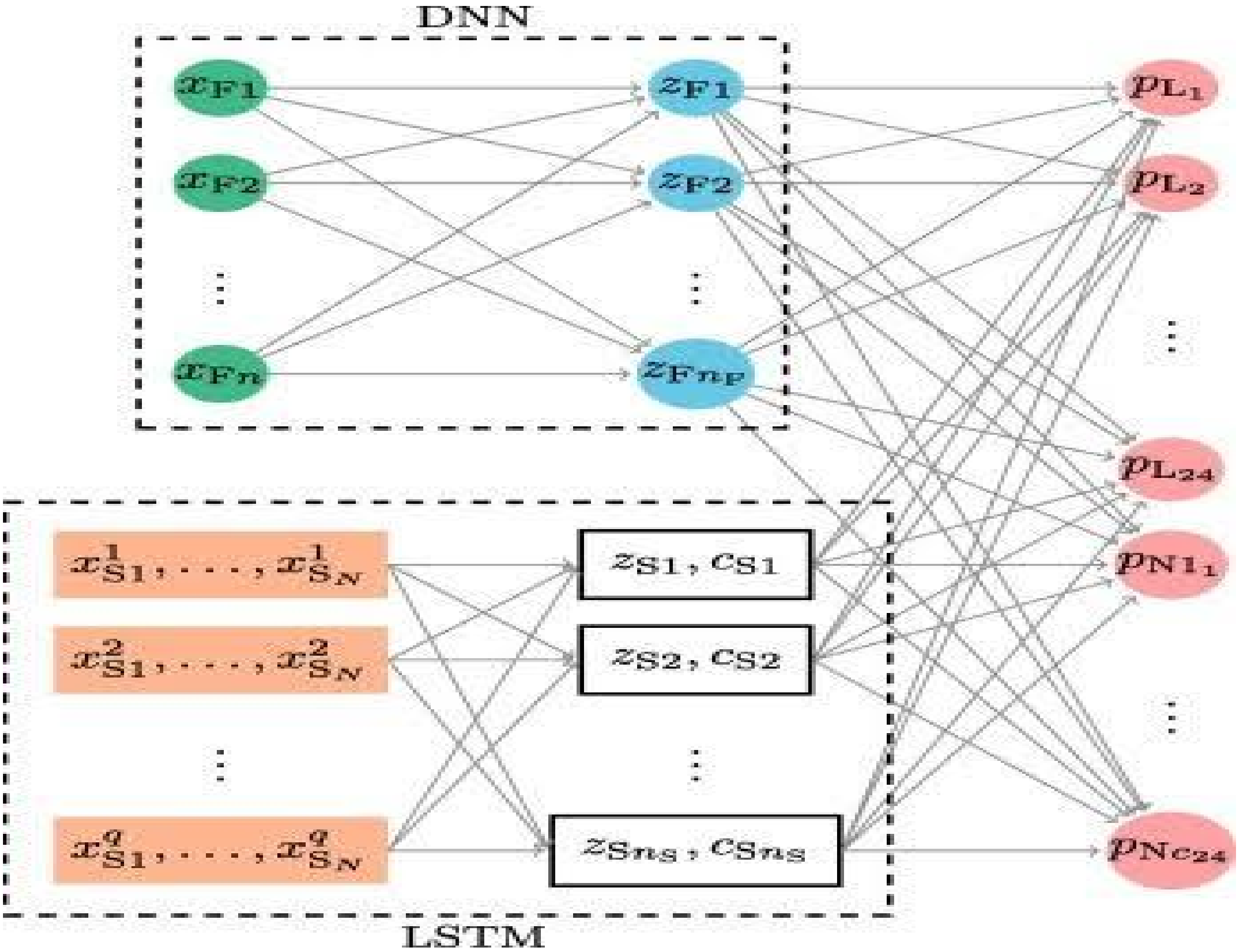
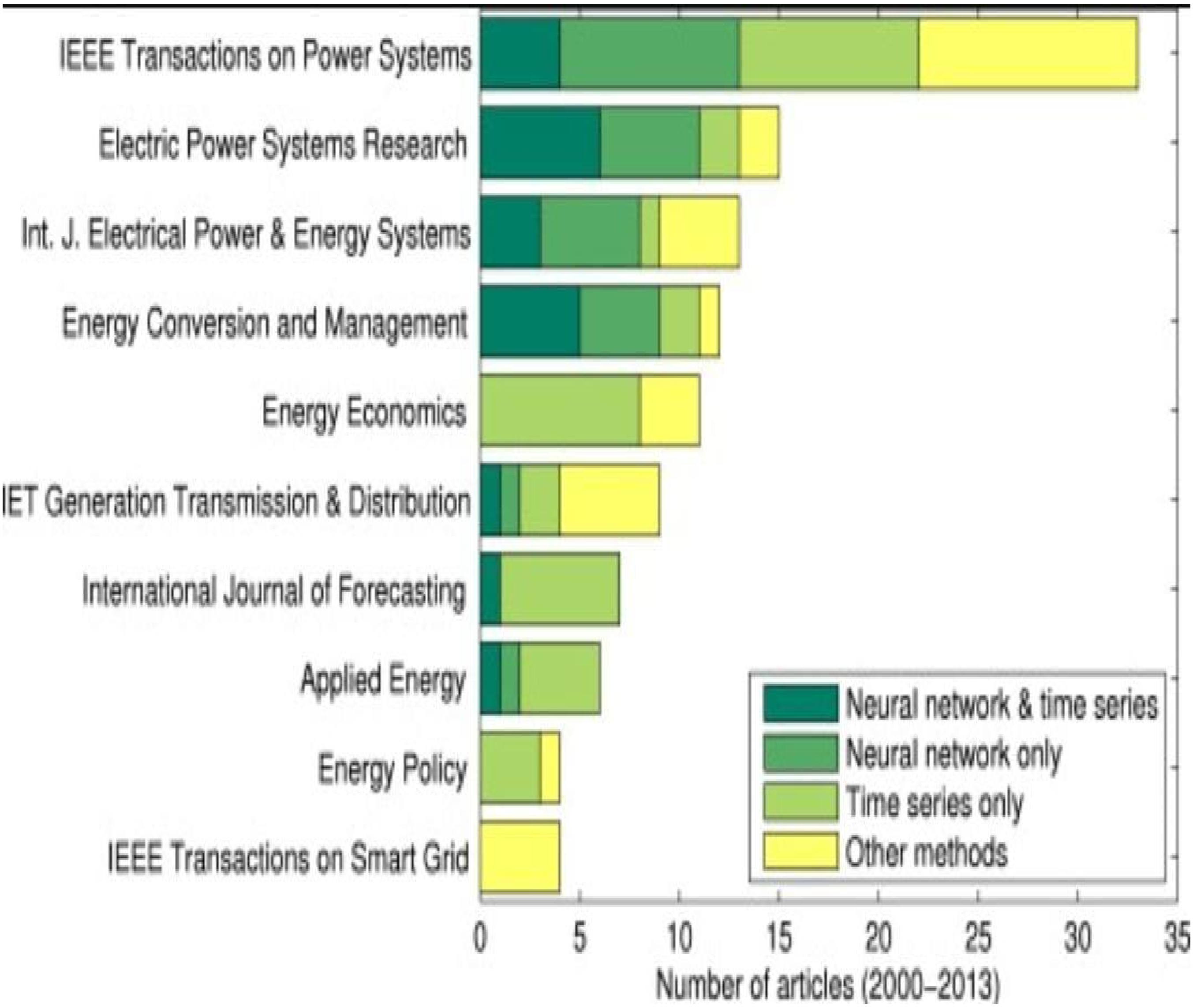
ABSTRACT:

Current electricity price forecasting models rely on only simple hybridizations of data preprocessing and optimization methods while ignoring the significance of adaptive data preprocessing and effective optimization and selection strategies to obtain optimal models that improve the forecasting performance. To solve these problems, this study develops an improved electricity price forecasting model that offers the advantages of adaptive data preprocessing, advanced optimization method, kernel-based model, and optimal model selection strategy. Specifically, the adaptive parameter-based variational mode decomposition technology is proposed to provide desirable data preprocessing results, and a leave-one-out optimization strategy based on the chaotic sine cosine algorithm is proposed and applied to develop optimal kernel-based extreme learning machine models. In addition, a newly proposed optimal model selection strategy is applied to determine the developed model that provides the most desirable forecasting result. Numerical results show that the developed model's performance metrics were best, and the average values of mean absolute error, root mean square error, mean absolute percentage error, index

of agreement, and Theil's inequality coefficient in four datasets are 0.5121, 0.7607, 0.5722%, 0.9997 and 0.0041, respectively, which imply that the developed model is a promising, applicable and effective electricity price forecasting technique in the real electricity market.





IEEE Transactions on Power Systems
Electric Power Systems Research
Int. J. Electrical Power & Energy Systems
Energy Conversion and Management
Energy Economics
IET Generation Transmission & Distribution
International Journal of Forecasting
Applied Energy
Energy Policy
IEEE Transactions on Smart Grid
Neural network & time series
Neural network only
Time series only
Other methods
0
5
10
15
20
25
30
35
Number of articles (2000–2013)

RATE COMPARISON

Consumer category	Existing	Approved
DOMESTIC SUPPLY		
Low tension (LT) domestic		
0-151 kWh/month	₹ 2.75	₹2.50
151-400 kWh/month	₹4.80	₹4.25
Above 400 kWh/month	₹5.20	₹4.65
High tension (HT) domestic	**₹4.80**	**₹4.30**
COMMERCIAL		
LT commercial		
0-150 kWh/month	₹5	₹4.50
151-400 kWh/month	₹5.30	₹4.70
Above 400 units	₹5.60	₹5
HT commercial	**₹5.30**	**₹4.70**
INDUSTRY		
Large industry	₹5	₹4.50
Medium industry	₹4.70	₹4.20
Small industry	₹4.80	₹4.30
Agriculture	**₹2.90**	**₹2.60**
PUBLIC LIGHTING		
Managed by MC	₹5.35	₹4.80
Advertisement, boards	₹7.10	₹6.40
Bulk supply	**₹4.90**	**₹4.40**
EV charging station	**₹4.00**	**₹3.60**

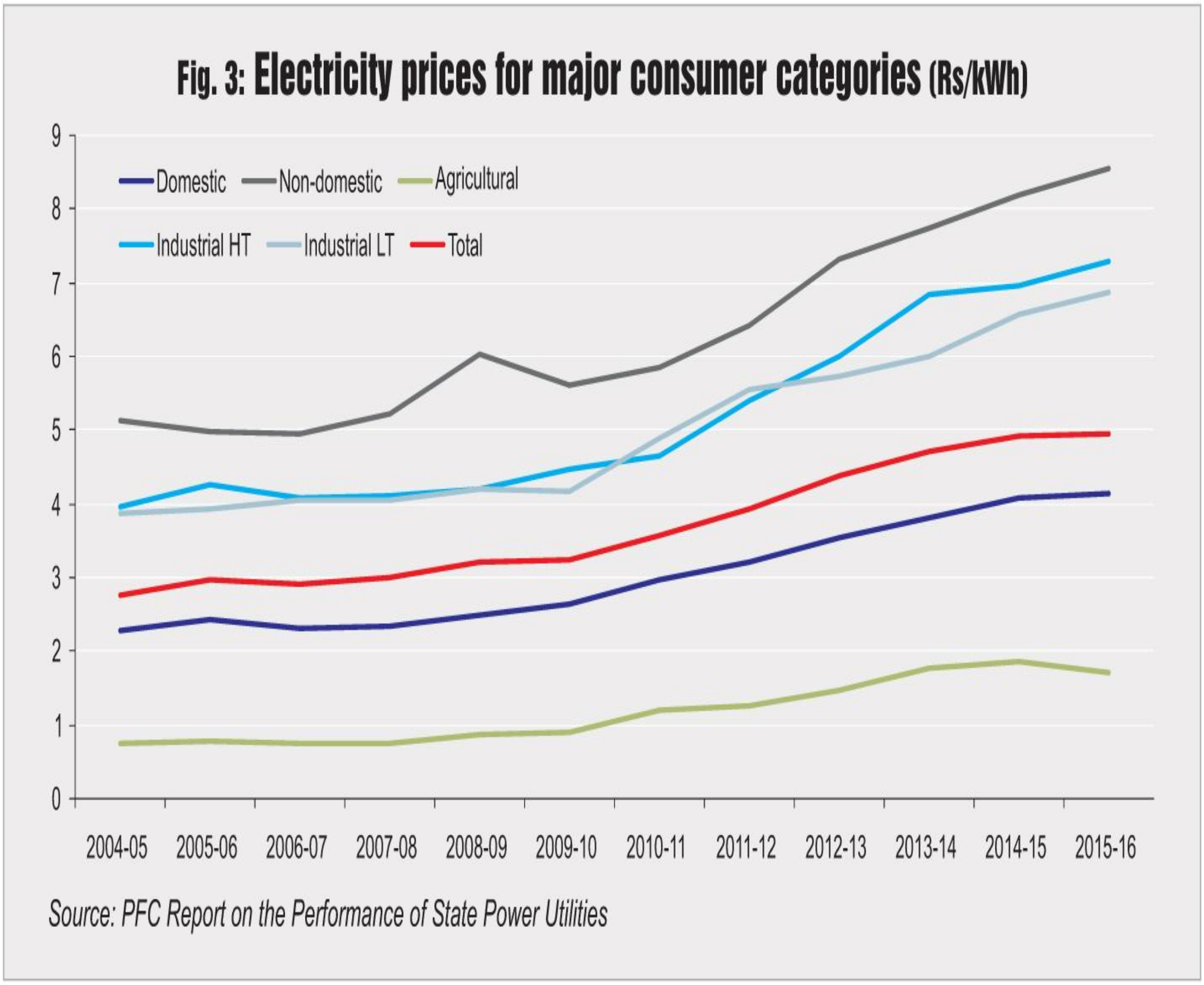
INTRODUCTION:

Forecasting theory and methods play crucial roles in promoting economic social development, offering significant economic and social benefits and reduced related costs [1]. In the last few decades, research and applications of forecasting models have received much attention in many research fields. The electrical power system, which is one of the most complex of all economic systems, includes the generation, transmission, scheduling and consumption of electrical energy, which plays an important role in every field of social production [2]. The dynamic changes that occur inside power systems influence the power supply quality and can even threaten the power system's safety and stability. Therefore, studies on electrical power systems are important both from theoretical and applied viewpoints and require further research due to their large sizes and growing influences. In recent years, numerous studies focused on electrical power systems have been conducted [3], such as power system planning [4], wind speed and power forecasting [[5], [6], [7], [8], [9], [10]], load forecasting [[11], [12], [13], [14], [15], [16]], and energy demand and price modeling [[17], [18], [19], [20]]. Note that research and application into forecasting theory and methods are of critical practical significance in power market management.

Furthermore, in the context of power market liberalization and deregulation policy, electricity prices have become a cornerstone by which market participants construct bidding strategies, procurement plans and make other decisions [19]. Market participants who can achieve effective electricity price forecasting can adjust their bidding strategies and change their production or consumption schedules to increase their profits. Therefore, electricity price forecasting is a widespread concern for all power market participants that can provide valuable information for risk management, planning and financial analysis [21].

In recent years, many forecasting models have been developed and employed to forecast electricity prices. Much research work and many trials have been undertaken from different perspectives to seek improved electricity price forecasting models that can be used in electrical power systems management and electricity markets. For example, the study in Wang et al. [22] was conducted from the perspectives of the data preprocessing algorithm, while the work in Zhang et al. [19] was carried out from the perspective of feature selection. A review of the related literature reveals that almost all models can be regarded as hybrid forecasting models. Most importantly, various studies have

shown that methods that hybridize different individual algorithms are the current state-of-the-art research direction [2]. For instance, Zhang et al. [23] proposed a hybrid electricity price forecasting model with linear and nonlinear prediction abilities for three real electricity markets. Cheng et al. [24] developed a novel hybrid model to improve the accuracy of electricity price forecasting and validated the model well using four different case studies from the European Power Exchange Spot. Zhang et al. [25] designed a novel adaptive hybrid model for short-term electricity price forecasting, which is verified on data from three real electricity markets. Given the highlighted limitations of individual forecasting models and the emerging development trend of hybrid forecasting methods in electricity price forecasting research, studies involving hybrid forecasting methods with the excellent characteristics of "learn from the strong to offset one's weaknesses" is carried out by capitalizing on the unique merits of different methods. Such approaches can provide new and innovative perspectives in electricity price forecasting research.

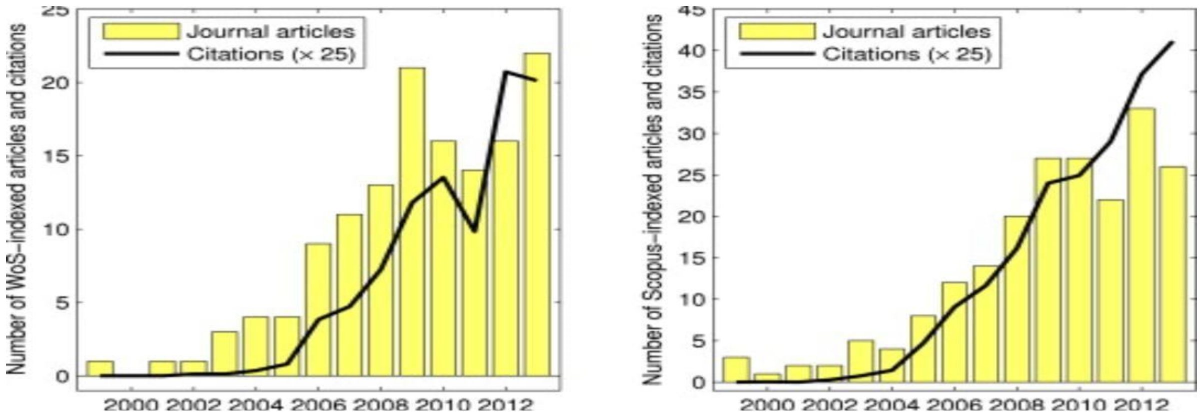


According to the related literature survey, it can be concluded that:

(a)

The selection strategy of the optimal model plays a vital role in the final forecasting performance in practical applications. This selection provides an important alternative for accurate electricity price forecasting and real applications in the management of electrical power systems and electricity markets.

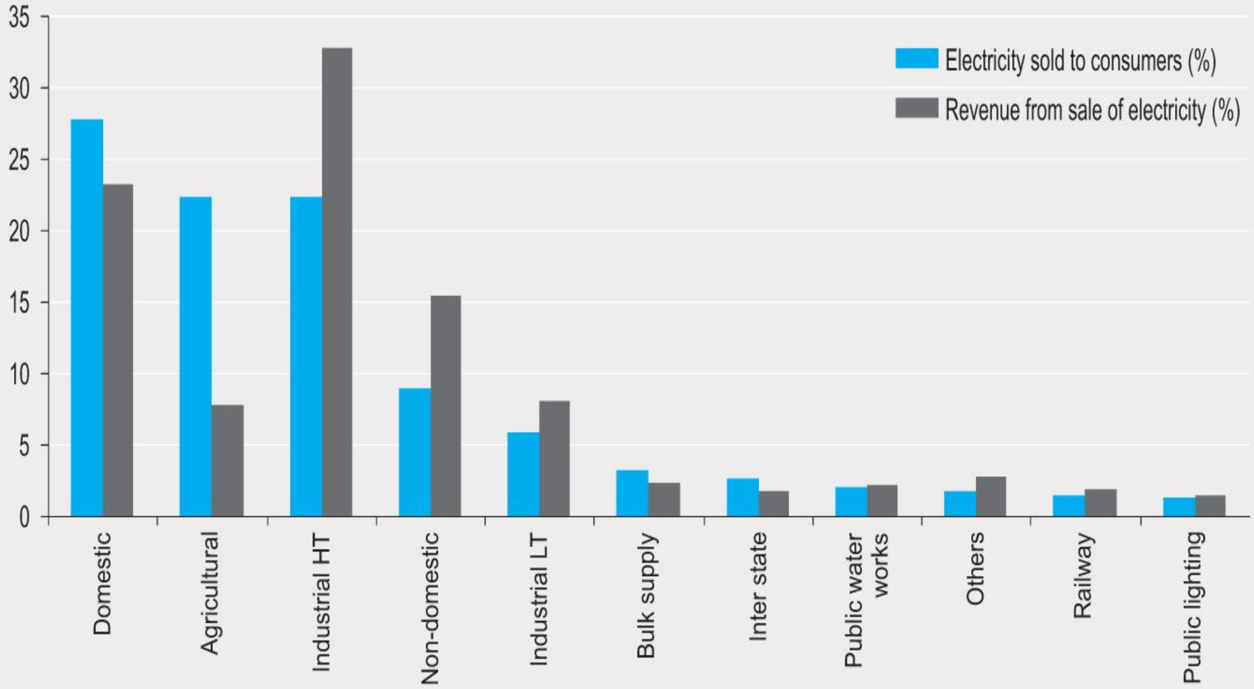
In particular, although many forecasting models have been developed to improve different perspectives, one remaining issue is how to determine the optimal model for electricity price forecasting in real applications, which is a question that is important to all power market participants.



(b)

It is shown that applying and improving data decomposition technology is promising for improving forecasting performance in general [[26], [27], [28]]. Recently, variational mode decomposition (VMD) technology has been successfully applied in many fields, including foreign exchange rate forecasting [29], energy price forecasting [30], and wind energy forecasting [[31], [32], [33]]. The VMD can enhance model's performance to some extent. However, the selection of decomposed numbers is both the premise and guarantee for the successes of VMD for effectively improving forecasting performances [34]. Specifically, empirical mode decomposition (EMD), is one of the most basic methods among all decomposition algorithms, which performs worse than some other algorithms, such as ensemble empirical mode decomposition (EEMD), complete ensemble empirical mode decomposition (CEEMD) and VMD. However, EMD has a substantial advantage in that no predefined parameters are needed for data decomposition.

Fig. 2: Electricity sold to consumers and revenue from sales in 2015-16 (%)



Source: PFC Report on the Performance of State Power Utilities, 2015-16

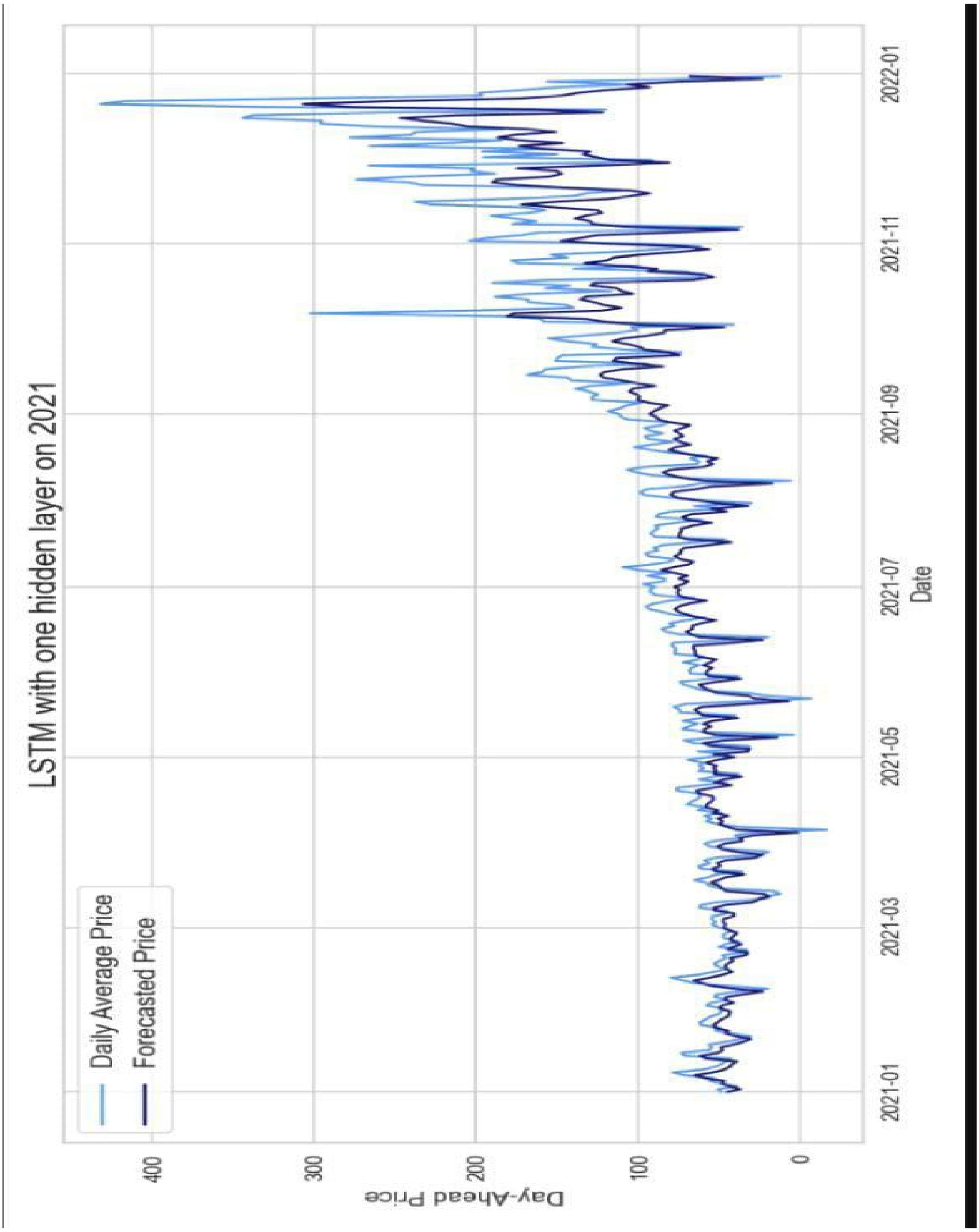
POWER CONSUMERS

Category	Number
Domestic	2,01,809
Commercial	27,418
Large supply	98
Medium supply	1,270
Small supply	1,336
Bulk supply	560
Agriculture	123
Public lighting	1,484
Temporary supply	398
Total	**2,34,497**

(c)

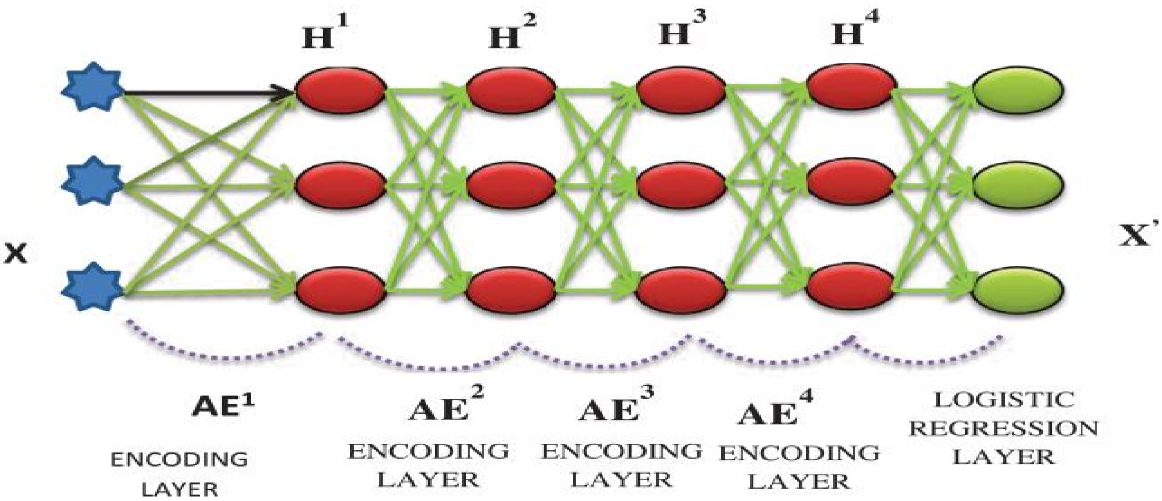
The selection of basic predictors for forecasting electricity prices directly influences the performance of electricity price forecasting methods; thus, basic predictor selection is a key factor and functions as the cornerstone of electricity price forecasting. Traditional statistical models, such as autoregressive integrated moving average (ARIMA) [35,36] and generalized autoregressive conditional heteroskedasticity (GARCH) [37], have been widely applied in electricity price forecasting. Although such statistical methods are effective overall, they often fail to produce the expected results [38]. Specifically, the statistical methods are suitable for the relatively stable power market but offer limited advantages and exhibit poor abilities in unstable markets. As a result, in recent years, artificial neural

network (ANN) models have been widely applied to electricity price forecasting and have achieved some successes.



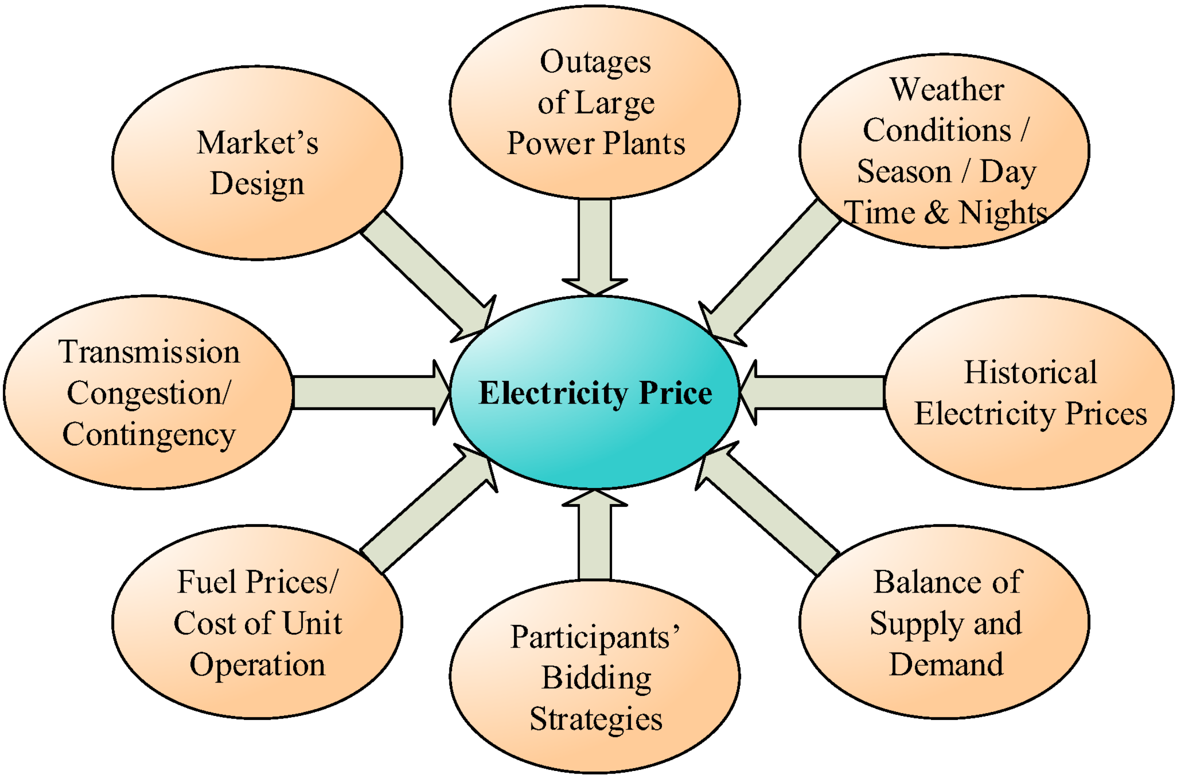
(d)

Some problems also remain due to the limitations of ANN models. These limitations mainly involve three aspects: 1) their inherent drawbacks, which include overfitting, lengthy execution times, becoming easily trapped in local minima, slow learning rate, large numbers of tunable parameters and rapid convergence [39]; 2) their time-varying nature, which occurs because the functional relationships that influence power prices change over time; thus, features extracted by an ANN model may become increasingly less relevant over time [40]; 3) their excessive subjectivity, because the parameters and structures of ANN models are usually based on experiments. All of these limitations tend to distort various aspects of the nonlinear relationships, resulting in poor forecasting performances.



(e)

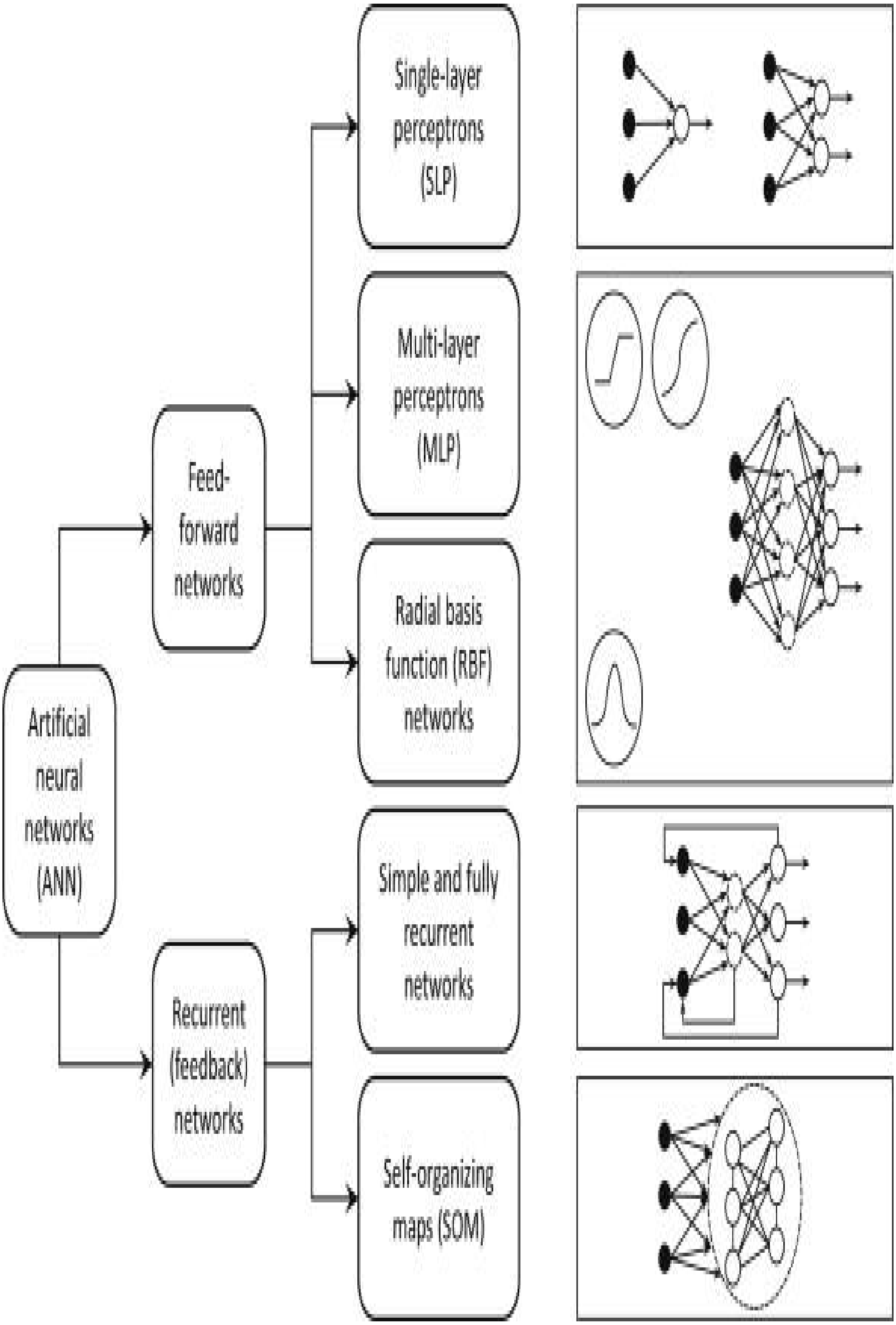
The extreme learning machine (ELM) was proposed to break down the barriers between biological learning mechanisms and traditional artificial learning [23]. Due to its outstanding performances in many forecasting fields, researchers have expended substantial research efforts in improving the ELM model, and various improved versions of the ELM have emerged in recent years. One typical representative is the kernel-based extreme learning machine (KELM) model, which employs a kernel function to map the training data into a high-dimensional space. Different from the original ELM model with random characteristics, the KELM model solves the random fluctuation issue of the original ELM because the KELM output is fixed if the appropriate penalty factors and kernel parameters are determined. The KELM model has both strong generalizability and stability; these advantages not only match the merits of the original ELM model but also overcome the limitations of ANN models [42]. To the best of our knowledge, however, few studies have employed KELM for electricity price forecasting despite its desirable forecasting performance. Meanwhile, as Li et al. [43] noted, the KELM model's generalizability and stability can be improved by selecting an optimal kernel parameter. Inspired by Hao et al. [44], Niu et al. [45] and Zhou et al. [46], artificial intelligence optimization algorithms can play crucial roles in determining optimal model parameters. Obviously, efforts should be made to develop an optimal KELM model whose strong generalization ability and stability are augmented by combining it with the advantages of an advanced artificial intelligence optimization algorithm.



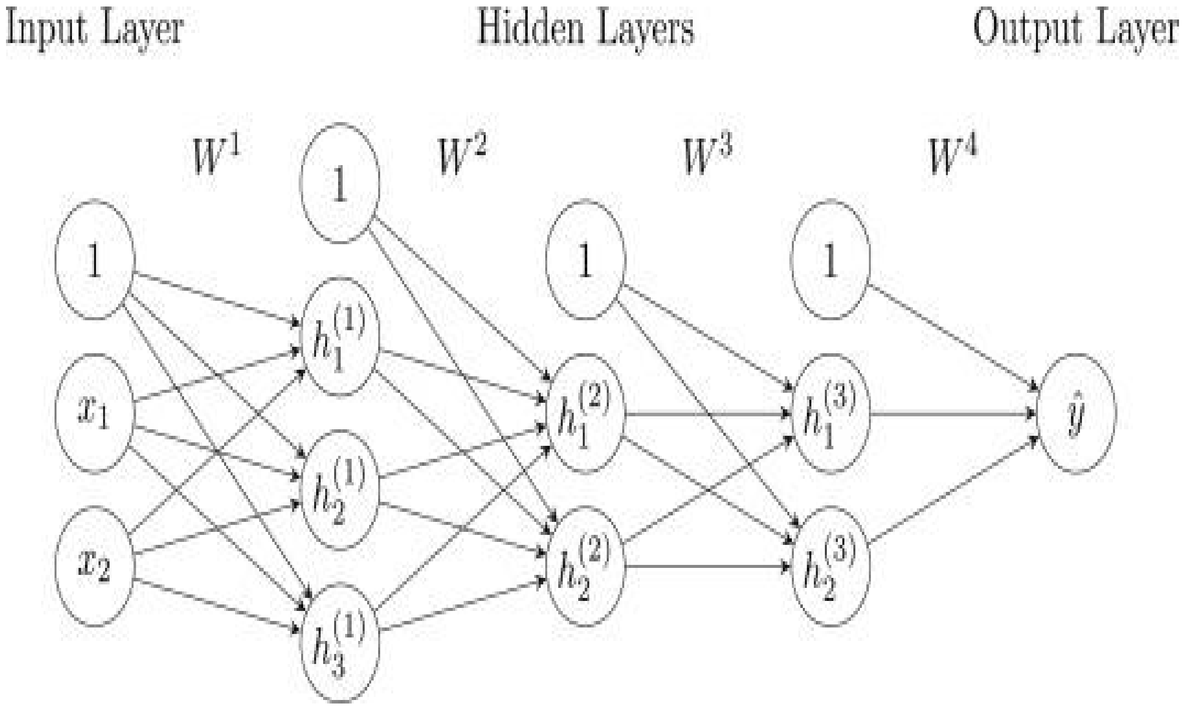
Based on the problems revealed in the existing methods and given the current situation that hybrid algorithms are acknowledged mainstream leaders, in this study, we develop an improved electricity price forecasting hybrid algorithm based on the newly proposed selection strategy to obtain the optimal model in this study, which exhibits significantly better forecasting power than other comparison models. The forecasting power of the developed hybrid algorithm is attributable to five

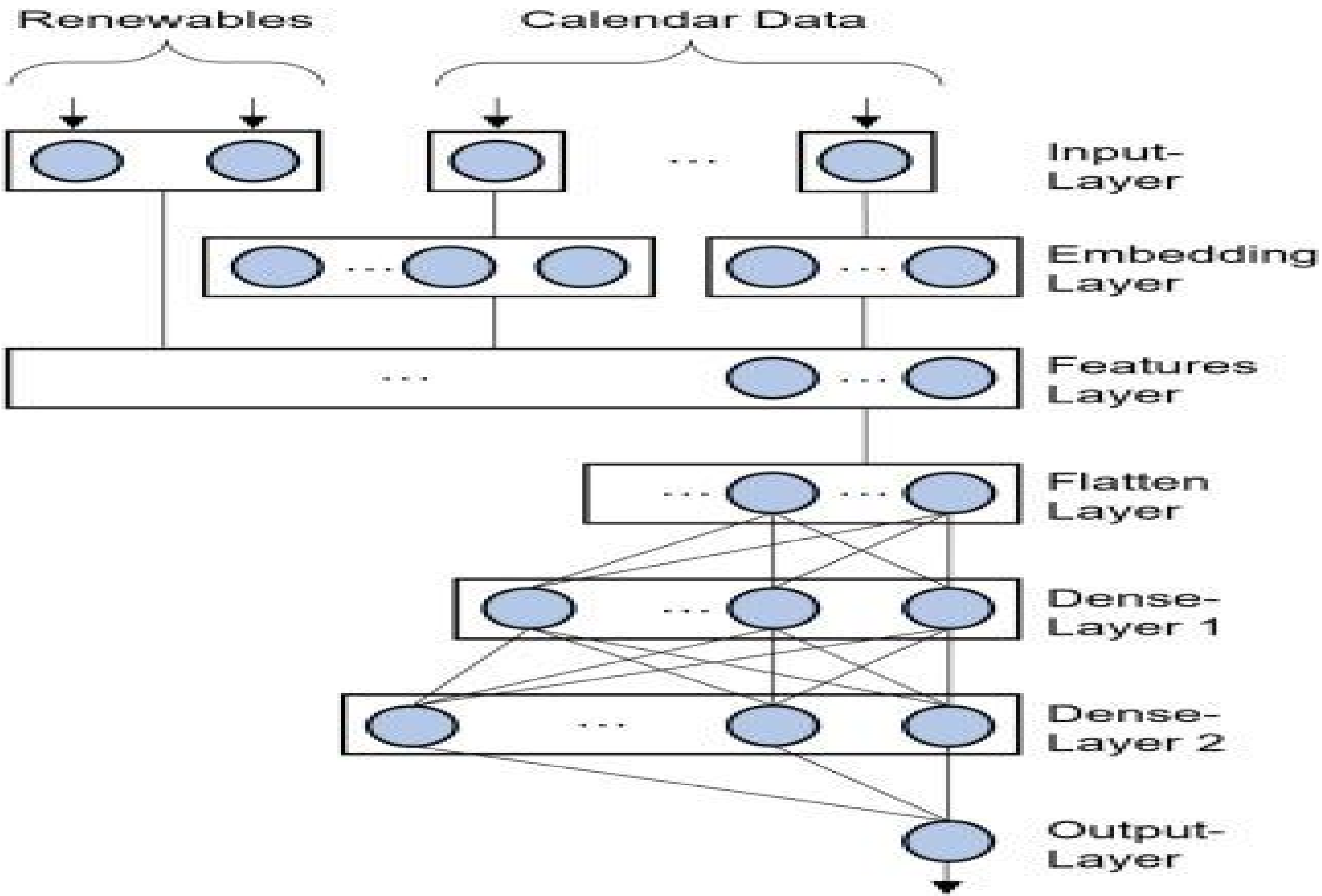
features. First, the KELM model possesses strong generalization ability and stability, which not only capitalizes on the merits of the original ELM model but also overcomes the limitations of ANN models. Second, the chaotic sine cosine algorithm (CSCA), one of our newly developed heuristic algorithms for solving optimization problems, is employed during the training process of the KELM model. Third, we develop the adaptive parameter-based variational mode decomposition (APVMD) method, which does not require many experiments and can automatically determine the decomposition number parameter. Fourth, we propose a leave-one-out optimization strategy based on CSCA and apply it to the task of developing an optimal KELM model that exhibits stronger generalization ability and stability. Fifth, a new strategy to select the optimal model is developed and applied to electricity price forecasting. This approach effectively generates a desirable forecasting model to enhance the final forecasting performance and provide more promising forecasting results for participants in electrical power systems and markets. The developed hybrid algorithm is applied in electricity price forecasting for real power markets. The experimental results reveal that the hybrid algorithm proposed in this study is substantially superior to various benchmark models, including kernel-based models, several popular forecasting models applied

in recent studies and some state-of-the-art models. The details about the developed model are presented in Section 3.

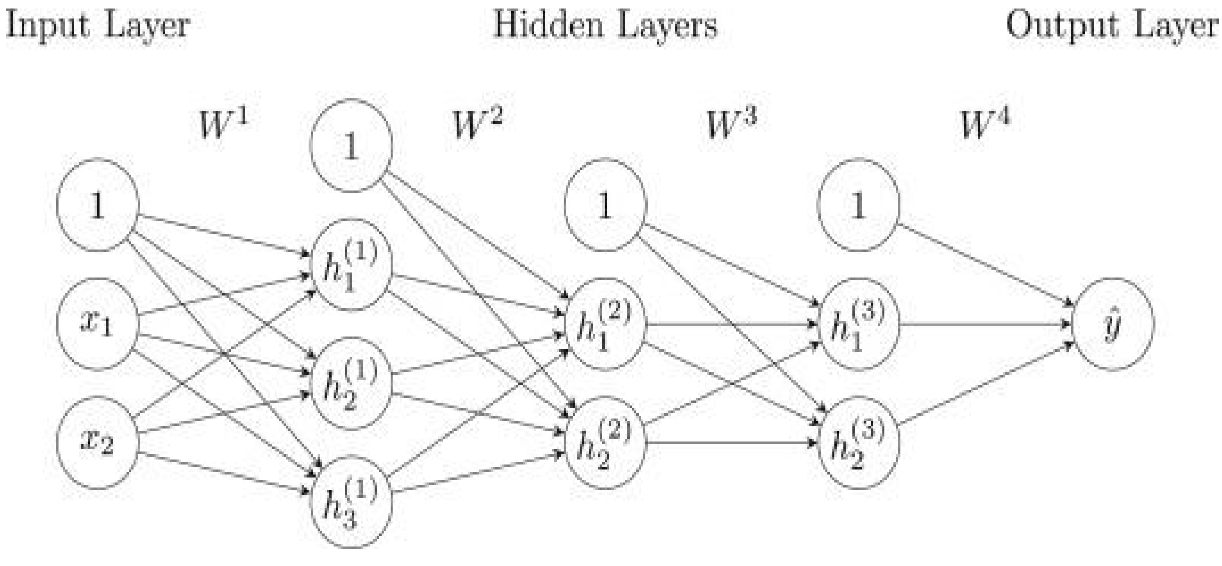


Compared with most previous studies in the field of electricity price forecasting, the main contribution of this paper is that we first attempt to select the optimal model for machine learning-based electricity price forecasting and subsequently develop an improved electricity price forecasting hybrid algorithm. The proposed algorithm compensates for the deficiencies in the existing research, primarily by considering three aspects that most previous electricity price forecasting studies have ignored but that can be considered as three primary contributions of the present study: the significance of optimal model selection strategy, adaptive data preprocessing, and a selection and optimization strategy for the basic predictors that can improve the model's performance. The detailed novelties and contributions of this study are explained as follows:



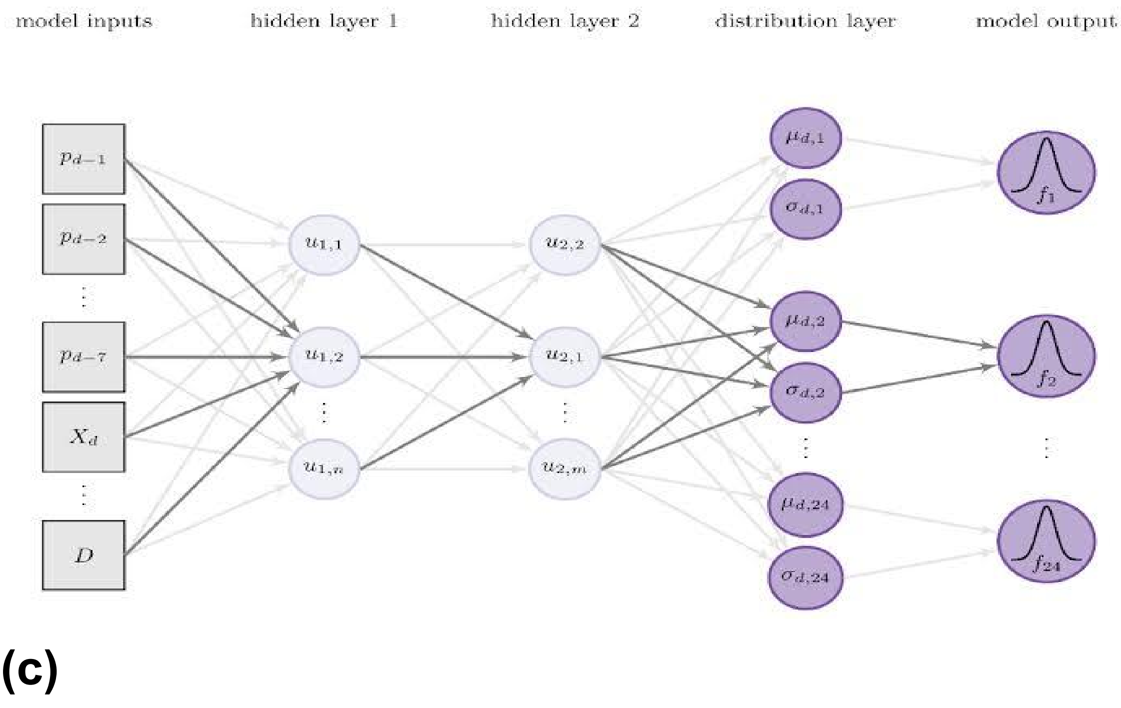

Renewables
Calendar Data
Input-
Layer
Embedding
Layer
Features
Layer
Flatten
Layer
Dense-
Layer 1
Dense-
Layer 2
Output-
Layer

(a)
In previous electricity price forecasting studies, the research and application of optimal model selection strategy are almost empty, so there are many merits problem need to depth study. To fill the research gap, this paper develops a new selection strategy for the optimal model that can effectively generate a desirable forecasting model that enhances the final forecasting performance and provides more promising forecasting results for participants in electrical power systems and markets. Empirical results provide solid evidence that the selection strategy of the optimal model is significant for obtaining more accurate electricity price forecasts and for use in real applications in power market management.



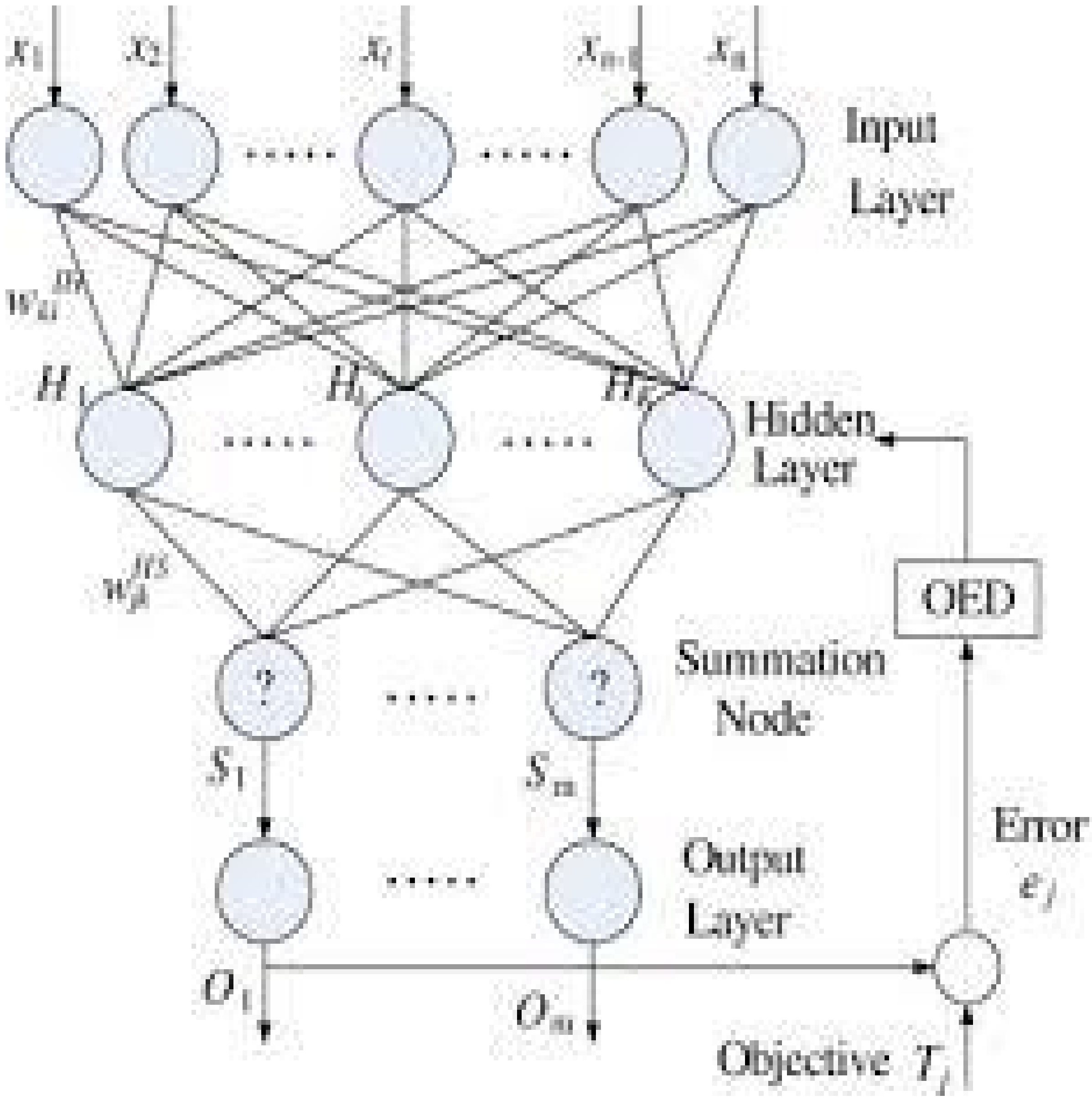
(b)
Previous forecasting models employed traditional individual decomposition methods to improve

forecasting performance, which have their own advantages and disadvantages. For example, the number of modes should be predefined in the VMD algorithm, while the EMD algorithm performs worse than other algorithms but has no predefined parameters. Inspired by Wang et al. [22], by combining the advantages of individual decomposition technology, we develop the APVMD method in this study. The benefit of APVMD is that it does not require many experiments to be able to automatically determine the decomposition number parameter and effectively generate desirable decomposition results.



(c)

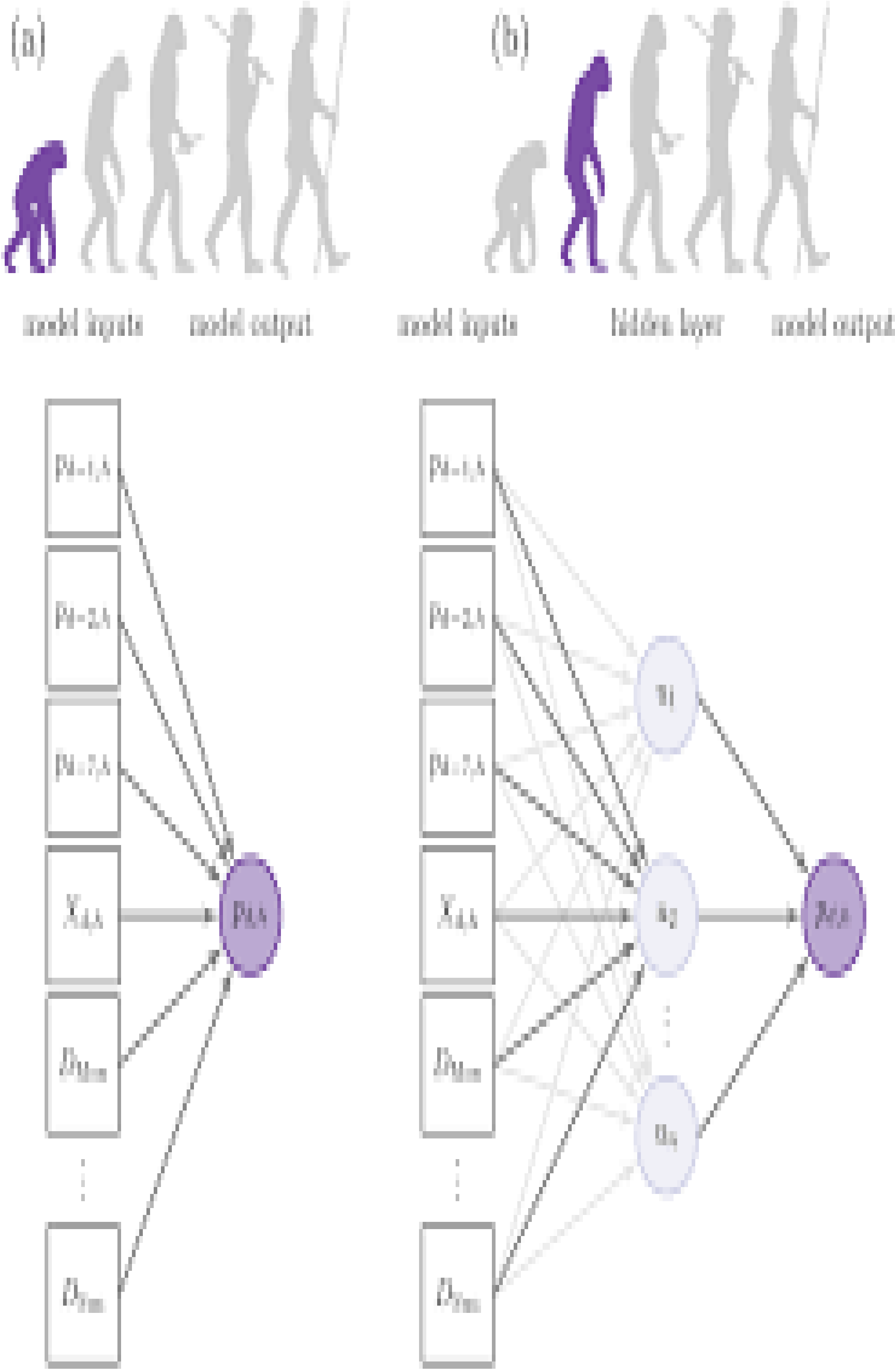
To the best of our knowledge, few studies have employed KELM in electricity price forecasting despite its capabilities. which not only match the merits of the original ELM model but also overcome the limitations of ANN models. Therefore, in this study, the optimal KELM model is developed to replace the traditional ANN models and original ELM model to realize more desirable forecasting results, which exhibits stronger generalization ability and stability. In particular, our recently proposed CSCA algorithm is employed during the training process of the KELM model. More importantly, the leave-one-out optimization strategy is developed and applied in the development of the optimal KELM model.



MACHINE LEARNING BASED ELECTRICITY PRICE PREDICTION MODEL BASED OK OPTSL MODEL BASED ON OPTIMAL MODEL SELECTION STRATEGY

EMPIRICAL ANALYSIS:

In this section, the developed improved electricity price forecasting hybrid algorithm is verified using data from two real electricity marketplace. The experimental data and the detailed empirical results and analysis are introduced in this section. All the experiments are performed in MATLAB R2015a on a computer equipped with a Windows 10 operating system, a 64-bit 2.60 GHz Intel Core i7-6700HQ CPU, and 8 GB of RAM.


(a)
(b)
model inputs
model output
model inputs
hidden layer
model output

CONCLUSION:

Energy market participants have always been nervous about the economic consequences of soaring electricity prices. Many forecasting models in the energy market focus on predicting normal price and load movements without dealing with extreme load or price situations in the market. In this paper, we combine EEMD and BiLSTM-AM to predict electricity loads and prices while capturing spikes and peak points. The EEMD algorithm decomposes the data to reduce the effect of noise. We then applied the BiLSTM-AM model to obtain the occurrence and normal fluctuation values of price and load peaks from the decomposed data. Using three data with different time horizons and different volatility patterns, we examine the predictive performance, efficiency, and consistency of the proposed model by forecasting the short to medium term. The proposed method is compared with night benchmark methods, including four machine learning models (SVR, ELM, GBRT, and BPNN), three deep learning models (LSTM, BiLSTM, and BiLSTM-AM), a classical ARIMA model, and a hybrid method (EMD-BiLSTM-AM). The results show that the proposed method outperforms other models in terms of prediction accuracy and spike capture ability, with EEMD reducing the mean absolute

percentage error (MAPE) by 53%, 54%, and 60%, respectively. Over the three forecast periods, the average MAPE and are 0.097 and 0.92, respectively. Furthermore, the analytical results of MCS and KSPA tests show that the EEMD-BiLSTM-AM model has the best predictive ability