

A forecasting model for power consumption of high energy-consuming industries based on system dynamics

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Abstract. It is of great significance to make accurate forecasting for the power consumption of high energy-consuming industries. A forecasting model for power consumption of high energy-consuming industries based on system dynamics is proposed in this paper. First, several factors that have influence on the development of high energy-consuming industries in recent years are carefully dissected. Next, by analysing the relationship between each factor and power consumption, the system dynamics flow diagram and equations are set up to reflect the relevant relationships among variables. In the end, the validity of the model is verified by forecasting the power consumption of electrolytic aluminium industry in Ningxia according to the proposed model.

1. Introduction

With the advance of industrialization and urbanization, high energy-consuming industries are of great importance in the development of secondary industry in China. High energy-consuming industries are the industries who have a relatively high proportion of primary energy or secondary energy consumption in the whole energy consumption, and a relatively high proportion of energy costs in value of output during the production. The six major high energy-consuming industries include steel, nonferrous metals, building materials, petrochemical, chemical and electric power [1,2].

High energy-consuming industries are closely related to the power consumption and its development is due to its high power consumption. On the one hand, the power consumption of high energy-consuming industries accounts for a large proportion in the total power consumption. On the other hand, its power consumption has a direct relationship with the achievement for energy conservation and consumption reduction. It is of great significance to forecast the power consumption of high energy-consuming industries accurately. Making accurate forecasting could provide data and build foundation for the forecasting of total society power consumption, and then offer guidance to the project and construction of power sources.

At present, there are plenty of solutions that have been proposed by experts and scholars around the world to forecast the power demand, which include grey prediction, trend extrapolation, time series, multi-model combined forecast and so on. For instance, algorithm of support vector machine is used to forecast electricity demand of high energy-consuming industries in reference [3], and the model is modified according to different conditions of economic development. In reference [4], a forecasting model is built based on ARMA, and then modified with industrial cycle index. In reference [5], neural network is used to make long-term forecasting of high energy-consuming industries while their heterogeneity and noise are taken into consideration. Dynamic relation between power consumption



and influence factors is discussed in reference [6], which is based on VECM model and co-integration relationship between macro-economic variables and industrial variables.

A forecasting model for power consumption of high energy-consuming industries which is based on system dynamics is built in this paper. First, several factors which have an impact on power consumption are analyzed, based on two macro dimensions of GDP and energy consumption per unit of GDP of high energy-consuming industries. Then, the weights of all influence factors are calculated by the analytic hierarchy process, and the system dynamics flow diagram and equations are set up to reflect the relevant relationships among variables. In the end, the power consumption of electrolytic aluminum industry in Ningxia during 2017 to 2020 is forecasted according to the proposed model.

2. Analysis for factors of high energy-consuming industries power consumption

The power consumption of high energy-consuming industries is equal to the product of GDP and energy consumption per unit of GDP. Recently, the structure optimization and industrial upgrading have a great effect on industrial power consumption because of economic development and structural transformation. Performances of this effect include the development of advanced large enterprises and the extinction of laggard small enterprises [7]. At the same time, the unit cost of products decreases constantly due to the development of technology, especially the maturation of energy conservation and consumption reduction technology.

The relations between influence factors and power consumption of high energy-consuming industries are shown in Figure 1.

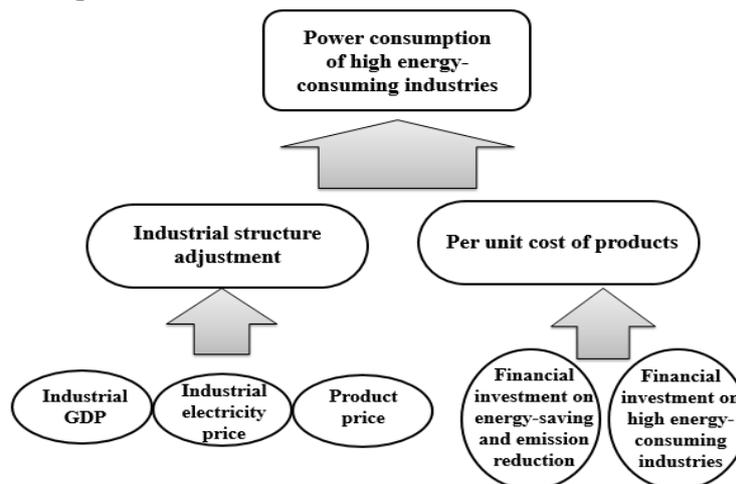


Figure 1. Influence factors of high energy-consuming industries power consumption.

2.1. GDP of high energy-consuming industries

GDP is the most important determinant of power consumption. There is a positive correlation between the variation of GDP and power consumption, and development of GDP reflects the improvement of production development and energy consumption level. With the constant optimization and upgrade of industrial structure, the proportion of high energy-consuming industries in societal GDP is also changing, and this leads to the change of power consumption.

2.2. Industrial electricity prices

Industrial tariff is carried out in high energy-consuming industries. Rise of electricity prices means the decrease of product profits, and production would be reduced by relevant enterprises as well. At present, the differential electricity price policy is adopted to restrain the excessive growth of high energy-consuming industries in some areas. It can lead the adjustment and transitions of high energy-

consuming industries by charging devices which have exceeding energy consumption for a higher electricity price.

2.3. *Product prices*

Product prices of high energy-consuming industries are influenced by relation between market supply and demand, policy, economic cycle, etc. Production is improved to acquire profits while product prices is rising. On the other hand, the phenomenon of oversupply would occur if the production has been improved to a certain extent, and due to which product prices would decrease. It implies that product prices interact with production.

2.4. *Government investment*

Currently, it is the trend of high energy-consuming industries development to transform the development mode, improve the efficiency of production and achieve green and low-carbon goals. With the energy conservation and emission reduction policy, high energy-consuming enterprises utilize energy conservation and consumption reduction technology to improve ratio of energy utilization, reduce energy consumption intensity, decrease cost and increase efficiency. In order to support high energy-consuming industries to adjust its energy utilization mode, government has been expanding financial investment on energy conservation and emission reduction policy constantly in recent years. Thus the unit cost of products decreases further. Forecasting model for power consumption of high energy-consuming industries

2.5. *Overview of system dynamics*

System dynamics model is proposed by Professor Forrester in 1958. It was used to analyse several business issues like production management and inventory at first [8]. It bases on the interdependent relation between system behaviour and internal mechanism, explores the causation which generates transformation forms, namely the system structure, through construction and manipulation of mathematic model [9]. Characteristics of nonlinear, high-order and multivariable possessed by system dynamics model provides a solution for long-term forecasting of power consumption, which has a more specific systematic and dynamic characteristics and cause-and-effect relation[10,11].

System dynamics is applied in many fields but it is hardly applied to long-term forecasting of power demand. In fact, system dynamics is rational to be applied to analyze the power demand forecasting problem because its characteristics of nonlinear, high-order and multi-feedback.

2.6. *Forecasting model based on system dynamics*

System dynamics schematic diagram of high energy-consuming industries power consumption can be drawn as shown in Figure 2 through analysis on influence factors on high energy-consuming industries power consumption. Relations between power consumption and each factors are described specifically in Figure 2.

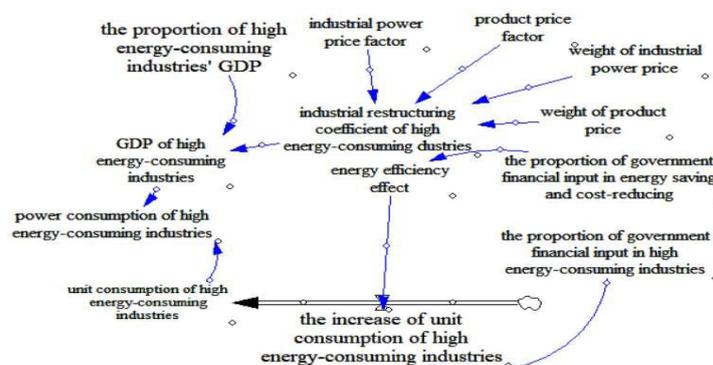


Figure 2. System dynamics schematic diagram of high energy-consuming industries power consumption.

Since the power consumption of high energy-consuming industries is equal to the product of GDP and energy consumption per unit of GDP, the relation below can be worked out:

$$W = G_g C \tag{1}$$

where C is unit cost of high energy-consuming industries, W is power consumption of high energy-consuming industries, and G_g is GDP of high energy-consuming industries. W and G_g are influenced by a series of related factors, and relations among them can be described as the expression below:

$$G_g = G_s \alpha_1 (1 + S) \tag{2}$$

where G_s is GDP of the whole province, α_1 is the percentage which GDP of high energy-consuming industries account for in province's GDP, S is structure adjustment index of high energy-consuming industries. This equation indicates that GDP of high energy-consuming industries would be influenced by industrial structure adjustment.

$$S = P_e \alpha_2 - P_c \alpha_3 \tag{3}$$

where P_e is industrial electricity price factor, α_2 is weight of influence from industrial electricity price, P_c is product price factor, α_3 is weight of influence from product price. Structure adjustment of high energy-consuming industries is mainly influenced by product price and electricity price.

$$\Delta C = C (D_g \alpha_4 - E) \tag{4}$$

where ΔC is increment of unit cost of high energy-consuming industries, D_g is proportion of financial investment that government allocate to high energy-consuming industries, α_4 is weight of influence from government investment on high energy-consuming industries, E is energy efficiency factor. E can be indicated as the followed equation:

$$E = D_j \alpha_5 \tag{5}$$

where D_j is financial investment on energy conservation and consumption reduction, α_5 is weight of influence from financial investment on energy conservation and consumption reduction.

3. Example analysis

3.1. Current situation of high energy-consuming industries in Ningxia

At present, power consumption of high energy-consuming industries in Ningxia has accounted for two-thirds of which of the whole autonomous region as shown in Figure 3. Under the situation, Ningxia has been in a state of industrial structure which relies on heavy industry and high energy-consuming industries for a long time. However, total level of resources utilization in Ningxia is still very low. In the meantime, as the important pivot in the Belt and Road Initiative strategy, Ningxia is facing the challenge for economic transition and industrial upgrading[12,13]. The target to attain a higher energy utilization level and being more sustainable cause higher demands on energy saving and consumption reduction work in Ningxia.

Forecasting of power consumption of high energy-consuming industries in Ningxia can support the industries to participate in power system operating. It can provide data basis to the forecasting of entire power consumption in Ningxia as well.

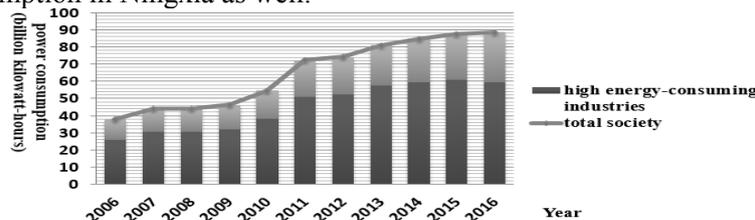


Figure 3. Power consumption of the whole society and high energy-consuming industrials in Ningxia.

Electrolytic aluminum industry is a typical main power consumer of high energy-consuming industries in Ningxia. Electricity demand of electrolytic aluminum industry accounts for nearly 26% of the whole industrial demand. Therefore, power consumption forecasting of electrolytic aluminum industry is taken for an example to test the forecasting model for power consumption of high energy-consuming industries which is based on system dynamics in this paper.

3.2. Weight determining

Analytic hierarchy process is determined to calculate weights of each factors. AHP refers to a system method for optimal decision with multiple targets and multiple solution, where a complex multi-objective decision is considered as a system at first, then a target is divided to several targets and then is decomposed into several multi-index levels, hierarchy single sorting (weight) and total sorting are calculated by fuzzy quantification of qualitative indexes in the end.

Nine-demarkation system is used to construct the matrix to compare the importance between each factor. The judgement matrix obtained is listed in Table 1:

Table 1. Indgement Matrix

	y_1	y_2	y_3	y_4
y_1	1	7	3	5
y_2	1/7	1	1/3	1/5
y_3	1/3	3	1	1/3
y_4	1/5	5	3	1

where y_1 represents product price of electrolytic aluminum industry, y_2 represents industrial electricity price, y_3 represents financial investment that government allocate to electrolytic aluminum industry, y_4 represents financial investment that government allocate to energy conservation and emission reduction.

Calculate the maximum eigenvalue and corresponding eigenvectors, and then weights of each factor can be obtained: weight of product price of electrolytic aluminum industry is 0.56, weight of industrial electricity price is 0.05, weight of financial investment on electrolytic aluminum industry is 0.18 and weight of financial investment on energy conservation and emission reduction is 0.26.

Consistency index $CR=0.0328$. All the weights are rational since the results have passed the consistency test.

3.3. Model solution

According to Ningxia Statistic Almanac and relevant historical data of electrolytic aluminum industry, the forecasting results can be obtained as follows.

Compare predictive values with historical values and calculate relative errors. System dynamics model can be applied in forecasting for power consumption of high energy-consuming industries if the errors are within an acceptable range. Table 2 has shown that the errors of forecasting model based on system dynamics keep below 6%, which means the forecasting method has a high precision and is fit for long-term forecasting for power demand of high energy-consuming industries. The power consumption of electrolytic aluminum industry in Ningxia during 2017 to 2020 can be forecasted by the model, which is shown in Figure 4 below.

Table 2. Comparison between forecasting value and actual value.

Year	Actual power consumption / (billion kW•h)	Forecasting power consumption / (billion kW•h)	Relative error
2006	8.162	80.13	-1.82%
2007	8.954	87.23	-2.58%
2008	9.122	89.80	-3.75%
2009	10.013	96.08	-4.04%
2010	12.952	123.12	-4.94%
2011	18.288	173.54	-5.11%
2012	21.001	202.57	-3.54%
2013	21.402	205.73	-3.87%
2014	19.748	207.11	4.88%
2015	16.870	174.10	3.20%
2016	14.885	155.65	4.57%

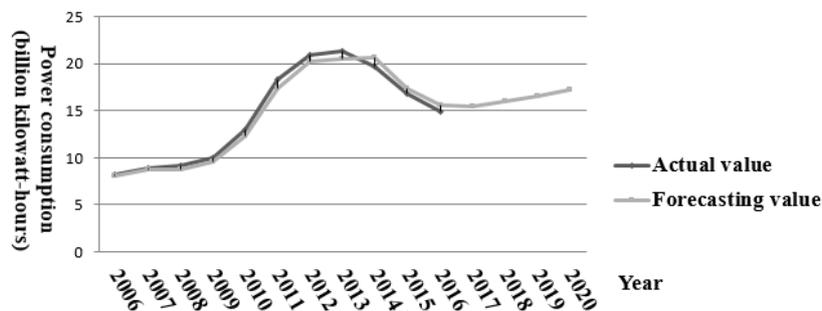


Figure 4. Actual and forecasting power consumption of electrolytic aluminium industry in Ningxia.

The specific data are shown in Table 3.

Table 3. Forecasting results of electrolytic aluminum industry power consumption during 2017 to 2020.

Year	2017	2018	2019	2020
Forecasting value (billion kW•h)	15.56	16.00	16.52	17.22

From the historical data, power consumption of electrolytic aluminum industry in Ningxia kept growing in a high speed before 2012. And then the rate of rise slows down, and the consumption has been in negative growth until 2014. The phenomenon can be explained from these three aspects:

(1) Preferential electricity price policy for high energy-consuming industries like electrolytic aluminum industry in Ningxia has been canceled since 2012. Since then, differential electricity price has been carried out in electrolytic aluminum industry, and price markup standard has been raised constantly. Thus, rapid development of high energy-consuming industries is restrained in electricity price policy.

(2) With the constant influence of global overcapacity since 2014, China economy has entered the new normal of economic development in a medium-high speed. Overcapacity has occurred because of oversupply in high energy-consuming industries. As a result, product price has been down, and operation rates of enterprises and rate of rise of power consumption have reduced.

(3) Thanks to the promotion by energy conservation and emission reduction policy, high energy-consuming industries in Ningxia has enhanced structure optimization and technology upgrading, updated key technology and equipment, improved industrial energy efficiency and level of resource

utilization. Meanwhile, more and more financial investment are allocated to high energy-consuming industries and played a conducting role. It has promoted enterprises to propel technology improvement of energy conservation and emission reduction and improve investment on circular economy.

Product price of electrolytic aluminum industry has risen since 2017, which brings a beneficial effect on production condition of relevant industries. According to the result, the trend of high energy-consuming industries market is largely smooth in the context of capacity reduction and structure adjustment, power consumption of electrolytic aluminum industry will keep stable in 2017 to 2020 instead of excessive growth.

4. Conclusions

(1) Power consumption of high energy-consuming industries is mainly influenced by the percentage which GDP of high energy-consuming industries account for in province's GDP, product price, industrial electricity price, proportion of financial investment that government allocate to high energy-consuming industries and financial investment on energy conservation and consumption reduction. Industrial GDP, product price and electricity price affect power consumption mainly by influence the structure adjustment of high energy-consuming industries while financial investment mainly changes energy consumption per unit of high energy-consuming industrial products.

(2) Forecasting model for power consumption can be built by analyzing relations between power consumption and factors of high energy-consuming industries which is based on system dynamics, and the model is of high accuracy.

(3) High energy-consuming industries will deal with the severer challenge in the future. It should improve industrial technology, take measures to promote energy conservation, emission reduction and circular economy, reduce the unit cost of products and make greater contribution to Green GDP in the area. At the same time, the country ought to strengthen guidance offered to product prices by macro-control means, control the power consumption of high energy-consuming industries by supply and demand in the market.

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