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The Optimization of Distributed Photovoltaic Comprehensive Efficiency Based on the Construction of Regional Integrated Energy Management System in China

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Abstract: In the context of energy crisis, environmental pollution, and energy abandoning in the large-scale centralized clean energy generation, distributed energy has become an inevitable trend in the development of China's energy system. Distributed photovoltaic boasts great potential for development in China due to resource advantages and policy support. However, we need improve the efficiency of photovoltaic generation, which is restricted by technology and dislocation of supply and demand. With a view to optimizing the efficiency of distributed photovoltaic, based on the concept of comprehensive efficiency, this paper discusses the influencing factors and chooses the optimization direction according to system dynamics (SD). The optimizing content is further clarified on the basis of energy management system. From the perspective of technology, this paper puts forward optimization methods from resource side, energy conversion and demand side, and the simulation results of applying the three methods verify the feasibility of the method. Comprehensive efficiency would be improved as the result of regional integrated energy management system and policy mechanisms. The conclusions of this paper will provide theoretical basis and optimized reference for the improvement of distributed photovoltaic comprehensive utilization in China.

Keywords: integrated energy management system; distributed photovoltaic; comprehensive efficiency; system dynamics (SD); optimized path; policy mechanism

1. Introduction

China is rich in resource and population, and its energy consumption is dominated by fossil energy such as coal as the result of the structure of primary energy and power generation technology [1]. In 2015, raw coal accounted for 72.1% of the production of primary energy and coal accounted for 64% of the consumption structure of primary energy. Thermal power generation took 73% of the total electricity generation, which means that the production and consumption of energy is dominated by coal and the power generation structure is directed by thermal power generation. However, according to the forecast by the International Energy Agency (IEA), as of 2015, the world's proven coal reserves can be exploited for 108 years and that of China can be developed for 29 years. China is facing a great crisis due to the non-renewable energy including coal and other fossil energy. In addition, the energy supply pressure caused by non-renewable fossil fuels, overuse and excessive emissions of fossil fuels has led to increasingly serious environmental pollution [2]. The statistics from National Energy Administration (NEA) shows that 85% of carbon dioxide, 74% of sulfur dioxide, 60% of hydroxide and 70% of dust in atmospheric pollution are caused by coal, and, according to the International Centre and the Climate Research (CICERO), the cumulative emissions of carbon dioxide by China in 2016 will exceed that of the United States, surpassing the U.S. and ranking the first in the world. Faced with dual pressure of the requirement of international community and the current situation of domestic environment, it is necessary for China to change the energy consumption structure and seek new ways to develop the clean and efficient energy.

However, due to the influence of the reverse distribution between resource reserves and power demand, the phenomenon of energy abandoning in large-scale centralized clean energy power generation can be found everywhere, and energy supply and demand are dislocated. According to the data from the NEA and the State Electricity Regulatory Commission (SERC), in 2015, the amount of domestic air abandoning was 33.9 billion kWh and water abandoning in Yunnan Province during the wet season was 330 million kWh, and the average rate of light abandoning in Gansu Province reached up to 31%. However, at the same time, relation between power supply and demand was tense in North China and East China and the largest power gap exceeded 700 million kilowatts. Against this background, distributed energy has become an important choice to develop the way of energy supply in the world considering its multiple economic and social benefits because of the characteristics of cost-effectiveness, safety, reliability, cleanness and environmental-friendliness [3].

In recent years, researches on distributed energy resources at home and abroad were mainly about site scheduling, policy coordination and so on. Qiong Wu et al. [4] utilized multi-objective optimization model to make sure the best location and capacity of the distributed energy system. M. M. Bashiri, E.D. Mehleria et al. [5,6] found that the constraint of loads, advanced technology of energy supply and storage were important factors influencing the operating efficiency of the distributed energy. Y.X. He et al. [7] pointed out that the government should promote the development of distributed energy by taking some measures such as carbon emission tax and resource tax. Solar energy is a kind of abundant clean energy in China and it is given top priority in terms of development and exploitation of renewable energy. Therefore, distributed photovoltaic plays an important role in the utilization of distributed energy under the background of China's natural resources [8]. Thus, it is of great importance to analyze distributed photovoltaic so as to understand the current situation of distributed energy in China.

However, whether it is general energy, renewable energy or distributed photovoltaic energy, the utilization situation was not ideal, as expected. Katharina Knoop et al. [9] pointed out that the overall energy efficiency of EU could be improved by at least 27% by 2030. It can be assumed that the global energy utilization efficiency can be further improved. Goran Grannić [10] insisted that the renewable energy has been widely used; however, the utilization efficiency should be improved. Thus, he put forward that the introduction of CO_2 emission tax is a powerful supportive policy. According to the results of the research, P. Thollander et al. [11] found that the average power of photovoltaic generation is one fifth of the installed power due to the volatility of the solar illumination. Thus, F. Asghar et al. [12] proposed that defects of distributed photovoltaic such as randomness and intermittence can be compensated by scientific integrated energy management system and upgraded energy utilization technology. Efficiency of photovoltaic generation will be further discussed in this paper on the basis of these researches.

In Section 1, the advantages of distributed energy are discussed in terms of the status of energy supply and demand in China, environmental pollution and the issues of large-scale centralized clean energy development. The existing research results of distributed energy and distributed photovoltaic at home and abroad are also summarize. In Section 2, the current situation and potential of the development of photovoltaic generation is discussed and the current situation of photovoltaic generation efficiency on the basis of characteristics of solar power generation and the operation of distributed photovoltaic is summarize. Furthermore, a series of problems that need to be solved in the process of development are put forward. In Section 3, under the guidance of SD, the key factors that exert an effect on comprehensive efficiency of distributed photovoltaic, laying the foundation for the choice of optimized path, are analyzed. Sections 4 and 5 are the critical parts of this paper, where the optimized paths are found by the distributed photovoltaic integrated energy management system, which will guarantee the promotion of comprehensive efficiency. In addition, this paper presents optimization methods from technical perspective for siting and sizing on the energy resource side, the dispatch optimization for energy conversion, the demand response on the energy demand side and optimization methods from policy perspective for price subsidies, operational regulation and industrial incentive. Part 6 is the conclusion. The research results of this paper will comprehensively optimize the overall efficiency of photovoltaic generation and then promote its high-efficient, economic and environmental development.

2. Analysis of Efficiency of Distributed Photovoltaic in China

2.1. The Trend Analysis of Distributed Photovoltaic

Distributed energy enjoys a development history of more than 20 years and distributed photovoltaic achieves great development under the support and guidance of relevant national policies in China. Since 2012, Chinese government has attached great importance to the development of distributed energy industry, which is represented by distributed photovoltaics. National Development and Reform Commission (NDRC), NEA, the State Grid Corporation of China (SGCC) and other departments take great efforts to clarify the orientation of development by introducing policies regarding distributed photovoltaic. As Table 1 shows, under the overall plan for distributed energy made by the State Council, Chinese government has made comprehensive arrangement in terms of the regional development and urban–rural planning for the distributed photovoltaic industry, and provided preferences and support in terms of electricity price subsidy, operational regulation and dispatch, etc.

Table 1. Related policies of distributed photovoltaic in China since 2012.

Policy Classification	Department	Name of Document	Year	Content
Integrated Planning	State Council	The Plan of Strategic Action for Energy Development (2014–2020)	2014	Regarding distributed energy as one of nine key areas of innovation—"Clarify the strategic direction and emphasis of energy technology innovation"
Priority Support	NDRC	The 13th Five-year plan for national economic and social development of the People's Republic of China: the energy sector	2016	Accelerate the development of distributed photovoltaic industry in the eastern and southern regions of China
	NEA	Opinions on the implementation of photovoltaic generation to alleviate poverty	2014	Expand distributed photovoltaic market by implementing distributed photovoltaic and agricultural photovoltaic poverty alleviation projects
Electricity Price Subsidies	NDRC	Notice about perfection on the benchmark price policies of onshore wind and photovoltaic generation	2015	Encourage all local governments to determine the owners and grid purchase price of relevant new energy projects by market-oriented approach such as bidding
	NDRC	Notice about promoting the healthy development of distributed photovoltaic industry by means of price lever	2013	Implement subsidy policies for overall photovoltaic generation, self-use of electricity will be free from various funds and surcharges
Operational Regulation	NEA	Interim Measures for operational regulation of photovoltaic generation	2013	Take charge of operating, trading and information disclosing for grid-connected photovoltaic power plant projects
	SGCC	Notice about work on distributed photovoltaic and network service	2012	According to the working principle "support, welcome, service", optimize and simplify the process of synchronize and improve service levels

Supported by national policies, distributed photovoltaic enjoys rapid development in China. Figure 1 shows that over the past decade, cumulative installed capacity of distributed photovoltaic in China increased about 6000 megawatt (MW), among which the annual growth rates exceed 100% from 2010 to 2012, laying a solid foundation for the stable development of China's distributed photovoltaic in the future.

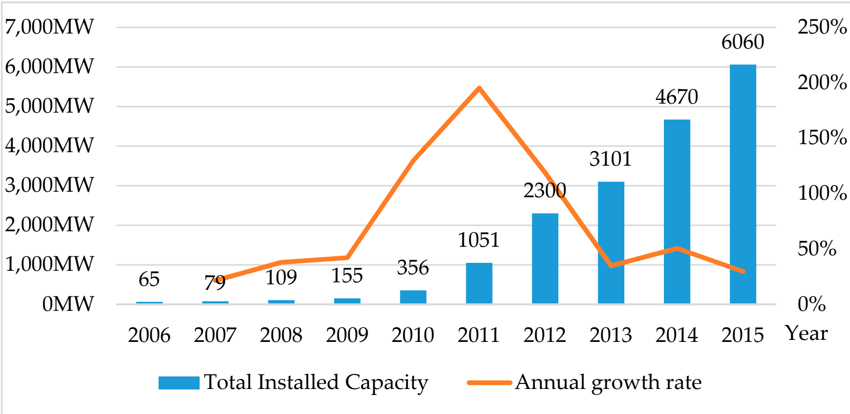

Figure 1. Installed capacity of distributed photovoltaic in China from 2006 to 2015 (official statistics from NEA (National Energy Administration)).

Although the annual growth rate of cumulative installed capacity has dropped slightly, with the powerful support of national policies, the expansion of application market, and the powerful stimulation of local subsidies, distributed photovoltaic still boasts great development potential and promotion prospects. The first batch of 18 distributed photovoltaic demonstration zones designated by NEA is listed in Table 2. By the end of 2015, almost all of the demonstration zones have basically achieved the targeted installed capacity, and the rate of self-use reached a record of more than 70%, which have obvious advantages in efficiency compared with the centralized photovoltaic power plant. However, the demonstration zones locate in developed regions including North China, East China, and South China; the planning directions of distributed photovoltaic in the future are expanding the project scale and extending geographical location to the west, with the aim of achieving the steady progress in the construction of distributed photovoltaic.

Table 2. The demonstration zones of distributed photovoltaic in China (official statistics from NEA).

The Name of the Demonstration Zone	Cumulative Installed Capacity in 2015 (MW)	Self-Use Rate
Haidian District, Beijing Zhongguancun Haidian Park	178	90%
Beijing Shunyi Development Zone	200	70%
Shanghai Songjiang Industrial Zone	50	90%
Tianjin Wuqing Development Area	100	80%
Hebei Gaobeidian Development Zone	150	80%
Hebei Baoding Yingli New Technology Development Zone	60	100%
Jiangsu Wuxi High-Tech Industrial Development Zone	50	100%
Jiangsu Nantong High-Tech Industrial Development Zone	150	90%
Shaoxing waterfront beach industrial agglomeration area, Zhejiang	150	70%
Hangzhou Tonglu Economic Development zone, Zhejiang	50	70%
High-Tech Industrial Development Zone, Hefei, Anhui	100	80%
High-Tech Industrial Development Zone, Xinyu, Jiangxi	72	90%
High-Tech Industrial Development Zone, Taian, Shandong	50	90%
High-Tech Industrial Development Zone, Zibo, Shangdong	50	90%
San Shui Industrial Park, Foshan, Guangdong	130	85%
Pearl Industrial Park, Conghua, Guangdong	83	80%
Shenzhen Qianhai modern service industrial Cooperation Zone of Shenzhen and Hong Kong	50	90%
Ningbo Hangzhou Bay Area	150	80%

2.2. The Efficiency Analysis of Distributed Photovoltaic

Although the distributed photovoltaic has achieved remarkable results and enjoys great prospects for development, polysilicon components has a photoelectric conversion efficiency of around 18%–19%, and this problem of energy conversion technology is the key constraint to improve the efficiency. In 2015, the annual output of photovoltaic modules in China exceeded 43 GW, and the newly installed capacity accounted for only one third of the annual capacity of photovoltaic modules. Photovoltaic capacity revealed a low utilization rate: the average utilization hours of photovoltaic generation throughout the year was 1133 h in 2015, whereas the amount of abandoned photoelectricity reached 4 billion kWh. Problems in the application of solar energy caused by the randomness of weather must be solved. Thus, it is essential to improve the production, installed capacity and utilization of photovoltaic generation.

The characteristic of self-sufficiency makes distributed photovoltaic have the advantage of efficiency compared to centralized PV power plant. However, the 2015 data show that even though the installed capacity of distributed photovoltaic completed 70% of the annual target, the overall operating rate of the project was only 40%, and problems in efficiency of the whole photovoltaic generation have also appeared in distributed photovoltaic.

Judging from the current situation of photovoltaic generation efficiency, we should optimize energy conversion and storage by technical methods, promote the application of component technology on the basis of policy mechanism, and guarantee balanced capacity and overall operation of distributed photovoltaic. Then, we can promote large-scale development of distributed photovoltaic and further optimize utilization efficiency to provide better service for customers.

3. The Introduction of Comprehensive Efficiency of Photovoltaic Generation and Analysis of Its Influencing Factors from the Perspective of SD

3.1. The Introduction of Distributed Photovoltaic Comprehensive Efficiency

The distributed photovoltaic system includes three core parts: energy supply, energy conversion and energy demand. Among them, the implementation of key links such as solar energy utilization, site planning, operation and dispatching, and users' demand analysis for cold, heat and electricity plays a vital role in the improvement of system efficiency. As a regional power system, in addition to improving energy efficiency on the basis of meeting the energy demand, distributed photovoltaic also takes the economic and environmental benefits into account. Comprehensive efficiency of distributed photovoltaic can be optimized and sustainable development becomes possible as long as meeting the requirements of energy-saving and emission reduction under the leading principle of cost-effectiveness.

Based on the analysis of the current situation of distributed photovoltaic, referring to the crucial parts of energy supply, energy conversion and energy demand, and considering the influence of internal and external environmental factors, such as energy, economy, technology and environment, this paper proposes that the comprehensive efficiency of distributed photovoltaic should include the rate of grid-connected power generation, the rate of capacity utilization, the rate of cost–benefit, the rate of energy-saving and emission reduction and the rate of users' satisfaction.

3.2. The Applicability Analysis of Distributed Photovoltaic Comprehensive Efficiency from the Perspective of SD

By revealing and analyzing the causal relationship between internal system components, system dynamics (SD) explores the main factors affecting the performance of the system, and thus provides evidence on improving targeted system operational performances [13,14].

The comprehensive efficiency of distributed photovoltaic is a complex analysis object with multiple factors such as energy, economy and environment. Analyzing from the perspective of SD, system science can be divided into various subsystems, which reveal positive and negative causal relationship and impact of the system elements on distributed photovoltaic. Thus, the key factors influencing the comprehensive efficiency improvement can be found, which provides the important reference for further optimization. Therefore, it is appropriate to analyze comprehensive efficiency of distributed photovoltaic by using SD. It is essential to analyze the influence factors of distributed photovoltaic based on SD to grasp the internal and external environment of distributed energy, identify the key factors and clear optimal direction, and then promote its comprehensive efficiency.

3.3. The Analysis of Distributed Photovoltaic Comprehensive Efficiency Based on SD

3.3.1. Cause-and-Effect Diagram

The comprehensive efficiency of distributed photovoltaic relates to the rate of grid-connected power generation, the rate of capacity utilization, the rate of cost–benefit, the rate of energy-saving and emission reduction and the rate of users' satisfaction. These factors interact with each other to form a cause-and-effect diagram, which reflects the relationships among the elements (Figure 2).

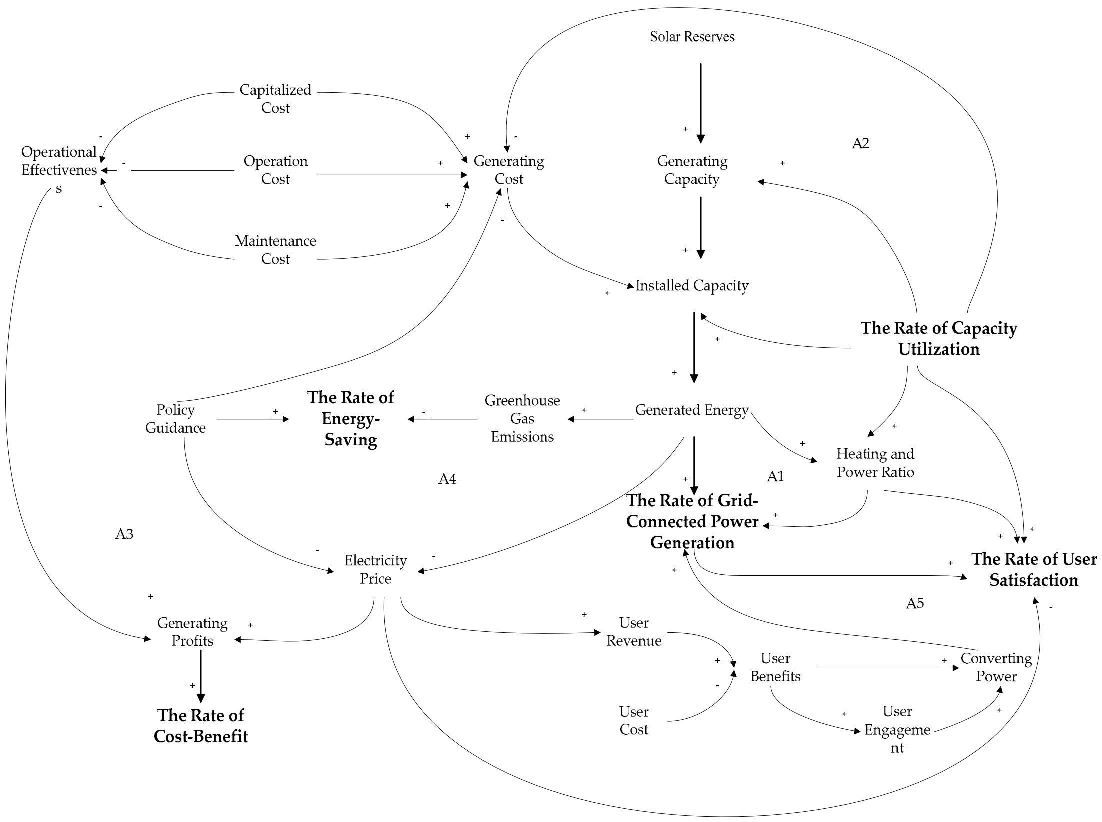

Figure 2. The cause-and-effect diagram of comprehensive efficiency.

The system is composed of five sub-modules that interact with each other and respond to each other: A1 is the energy factor module, A2 is the technical factor module, A3 is the economic factor module, A4 is the environmental factor module and A5 is the market factor module.

3.3.2. The Analysis of Sub-Modules

(1) The Energy Factor Module (A1)

The energy factor module mainly includes the process from solar energy supply to the distributed photovoltaic installation and generation and it shares casual relationship with the optimization of cooling and heating electricity ratio and user's transferred electricity. This module efficiency is measured by the rate of grid-connected generation (B_1):

$$B_1 = \frac{L}{S_C} \tag{1}$$

$$S_C = I \times t \times (1 - w) \tag{2}$$

where L is the active load, S_C is the capacity of grid-connected power generation, I is the installed capacity, t is the average full load hours, and w is the net loss.

(2) The Technical Factor Module (A2)

The technical factor module is mainly related to the application of solar energy reserve forecasting, the determinants of distributed photovoltaic location, CCHP and other technologies. Technology progress and application will be directly reflected in the growth of distributed photovoltaic and efficiency. This module should be measured by the rate of capacity utilization (B_2):

$$B_2 = \frac{S_E}{I} \tag{3}$$

where S_E is the amount of generated electricity and I is the installed capacity.

(3) The Economic Factor Module (A3)

The economic factor module includes the input and output factors. The input refers to the initial investment cost, running cost and unit start-stop cost of the distributed photovoltaic, and the power generation profit is formed by electricity price in the market. This module should be measured by the rate of cost–benefit (B_3):

$$B_3 = \frac{P_E}{C_E} \tag{4}$$

where P_E is the profit of power generation, and C_E is the cost of power generation.

(4) The Environmental Factor Module (A4)

The environmental factor module includes the impacts of photovoltaic generation on the environment, the amount of generated electricity, the support of policy, etc. This module is based on the rate of energy-saving and emission reduction (B_4). As the distributed photovoltaic basically produces no pollutant emissions, the rate of energy-saving and emission reduction is measured by the CO_2 from the photovoltaic generation of the same scale and level of 1 kWh thermal power generation.

$$B_4 = S_E \times (v + z + x) \tag{5}$$

where S_E is the amount of generated electricity; and v, z and x represent the carbon dioxide, sulfur dioxide, and hydroxide emission coefficient of 1 kWh thermal power generation respectively.

(5) The Market Factor Module (A5)

The market factor module is mainly affected by the price level, users' participation, user transferred electricity and other factors. This module is measured by the rate of user satisfaction (B_5):

$$B_5 = B_R + B_P \tag{6}$$

$$B_R = \frac{S_R}{S_C} \tag{7}$$

$$B_P = \frac{R_U}{C_U} \tag{8}$$

where B_R is the rate of demand satisfaction, B_P is the rate of users' return, S_R is the users' electricity demand, S_C is the grid-connected power generation, R_U is the users' return, and C_U is the users' cost.

Thus, the essential measures to improve comprehensive efficiency of distributed photovoltaic are: on the basis of securing profits of generation enterprises and promoting users' satisfaction, pay much more attention to the positive effects of the technical application on the amount of electricity and load, and give sufficient consideration on environmental benefits under the guidance of national policies in the process of large-scale development.

4. The Optimal Path of Comprehensive Efficiency of Distributed Photovoltaic Based on Regional Integrated Energy Management System

4.1. The Path Selection for Comprehensive Efficiency of Distributed Photovoltaic

4.1.1. The Selection of Optimal Direction Based on SD

Based on the five influencing factors of the comprehensive efficiency of distributed photovoltaic, the results of efficiency measured equations of all factor modules show (Figure 3) that the improvement of grid-connected efficiency and production efficiency require the optimization of distributed photovoltaic energy resources. The distributed generation capacity will be enhanced on the basis of full utilization of solar energy resources and reasonable planning. The improvement of energy conversion will lead to the promotion of the rate of production utilization, the rate of cost–benefit and the rate of energy-saving and emission reduction, only then can distributed photovoltaic take the technical, economic and environmental benefits into account. As the main market service object of distributed photovoltaic, the rate of users' satisfaction cannot be separated from the demand side. Therefore, this paper carries on research from three aspects, resource side, energy conversion and demand side, aiming at improving the comprehensive efficiency of distributed photovoltaic in the whole process.

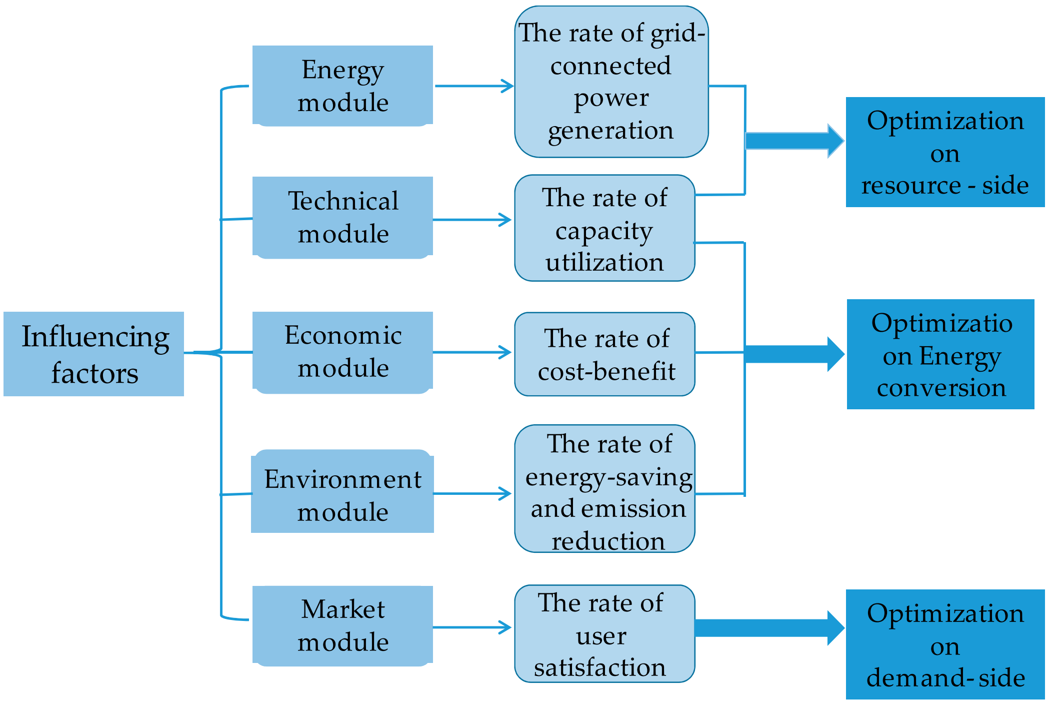

Figure 3. The corresponding relationship between the comprehensive efficiency of distributed photovoltaic and the optimization direction.

4.1.2. Optimal Content Based on Regional Integrated Energy Management System

Integrated energy management system takes electricity demand, energy supply, energy conversion and storage into account and integrates infrastructure of renewable energy sources [15,16]. Energy management system improves the availability and security of the system itself with optimized utilization efficiency of renewable energy sources and solutions to electricity defects, and strives to maximize efficiency and optimize environmental costs [17,18]. Energy management systems play an active role in energy investment, use and maintenance of equipment, energy transportation and other stages. The effective method to deal with problems of distributed photovoltaic is to improve the utilization efficiency of energy on the basis of rational layout and optimized facility allocation and management function in an economical and environmental way. Therefore, the application of energy management system plays a critical part in optimizing comprehensive efficiency of distributed photovoltaic.

Based on the applicability analysis of the energy management system, combining with the distributed photovoltaic efficiency optimization directions selected above, this paper proposes a regional integrated energy management system (Figure 4), and constructs an intelligent business management system from resource side, energy conversion and demand side, which demonstrates the whole process of distributed photovoltaic.

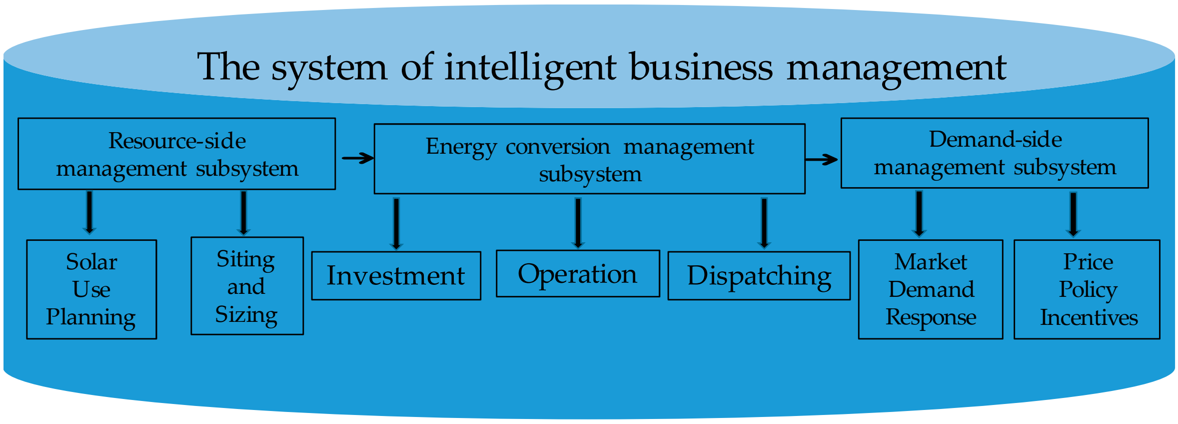

Figure 4. Intelligent business management system of distributed photovoltaic.

As the core of the integrated energy management system, the system of intelligent management is composed of the resource-side management subsystem, energy conversion management subsystem and demand-side management subsystem and it is responsible for the balance of energy supply and demand and optimization of dispatch. The main content of resource-side management is the planning and utilization of solar energy and the siting and sizing of distributed photovoltaic. Investment construction, production operation and grid-connected dispatch constitute the energy conversion management subsystem, which plays an important role in the transformation of regional distributed energy system from energy to electricity. The demand-side management subsystem accomplishes the efficient objective of sales-oriented production on the base of market demands and incentives of price policy.

Based on the analysis above, this paper selected three directions named siting and sizing, operation dispatching and demand response from resource side, energy conversion and demand side, respectively. Thus, we can improve the comprehensive efficiency of the whole distributed photovoltaic system with the aim of taking the economic and environmental benefits into account, improving energy utilization efficiency and meeting users' requirement.

4.2. The Implementation Methods of Optimization Path of Distributed Photovoltaic Comprehensive Efficiency

4.2.1. Introduction to the Methods

(1) The Promotion Path of Resource Use Efficiency Based on the Optimization of Siting and Sizing

Due to the great influence of the location and capacity on the absorption and utilization of solar energy, the technology of siting and sizing of distributed photovoltaic plays an important role in its operation and development [19]. Under dual restrictions of cost and technology, optimizing dynamic multi-objective and finding the best position, which is lowest-cost power generation, will enhance the efficiency of light use and give full play to distributed photovoltaic's advantages of economy, technology and environment [20].

Siting and sizing for distributed photovoltaic is a nonlinear, multi-objective, multi-dimensional and multi-constrained optimization problem. On the basis of existing research results, this paper constructed the multi-objective optimization model by taking the lowest running costs and carbon emissions as objectives, taking the node voltage, branch power and power conservation as constraints and considering the economic and environmental efficiency of distributed photovoltaic.

(i) The Objective Function

$$\Delta C = \Delta C_{OP} + \Delta C_{CO_2} \tag{9}$$

$$\Delta C_{OP} = \Delta C_{LOSS} + \Delta C_{P} \tag{10}$$

where ΔC_{LOSS} represents the changes of network loss cost after distributed photovoltaic accessing to network, and ΔC_P represents the changes of purchase cost after distributed photovoltaic accessing to network.

$$\Delta C_{CO_2} = -C_{PUN} E \left(\sum_{i=1}^{DP} \tau_{DP,i} P_{DG,i} \right) \tag{11}$$

where C_{PUN} represents carbon emissions penalty, 9.75 Yuan/t; and $E(\sum_{i=1}^{DP} \tau_{DP,i} P_{DG,i})$ represents equivalent reduction of CO_2 emissions after the distributed photovoltaic accessing to network.

(ii) The Constraint Condition

(a) The Branch Power Constraint

$$S_{ij} \leq S_{ij,max} \tag{12}$$

where S_{ij} represents the branch power; *i* and *j* represent the first and last branch node, respectively; and $S_{ij,max}$ represents the upper limit of branch power.

(b) The Node Voltage Constraint

$$U_{i,min} \leq U_i \leq U_{i,max} \tag{13}$$

where U_i represents voltage amplitude of the node i, and $U_{i,min}$ and $U_{i,max}$ represent the upper and lower limit of the voltage node respectively.

(c) Distributed Photovoltaic Capacity Constraint

$$P_{NE,i} \leq P_{NE,i,max} \tag{14}$$

where $P_{NE,i}$ represents the active output of the *i*-node, and $P_{NE,i,max}$ represents the maximum capacity of i-node which can access to distributed photovoltaic, measured in MW.

From the perspective of resource-side, the optimization path of siting and sizing proposed in this paper can determine the best location and capacity of distributed photovoltaic plant by technical means, which can ensure safe operation, taking economic and environmental benefits into account, and improve the utilization efficiency of solar energy.

(2) The Promotion Path of Resource Conversion Efficiency Based on the Optimization of Power Generation Dispatching

Solar energy has the characteristics of richness and environmental friendliness, so distributed photovoltaic can maximize resource value of solar energy in its application. However, solar randomness and volatility pose a serious challenge to the stability of a distributed photovoltaic system. Therefore, we should seriously take cost control and energy-saving and emission reduction into consideration and improve the energy conversion efficiency by optimizing generation dispatching [21,22].

Two-stage dispatching optimization model of distributed photovoltaic is proposed in this paper by taking into account the following factors: energy, economy and environment. The model divides the dispatching program into two stages: day-ahead dispatching and real-time dispatching. The day-ahead dispatching is responsible for generation scheduling. The real-time dispatching corrects the operation mode in the next interval and the day-ahead makes output plan based on forecast results. The entire dispatching process is presented in Figure 5.

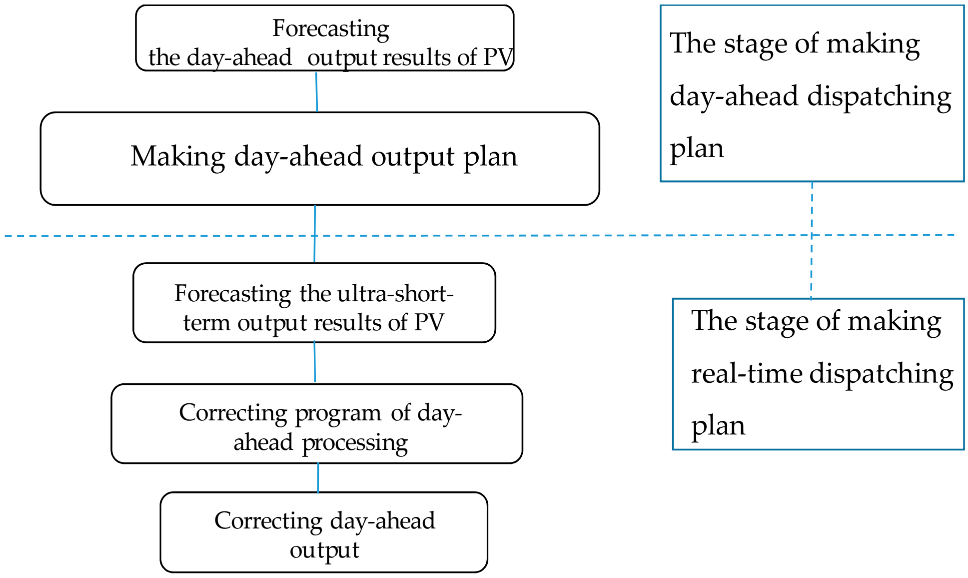

Figure 5. The dispatching flowchart of distributed photovoltaic.

Optimization of two-stage dispatching will reduce the effect of uncertainty of solar energy effectively and reduce the distributed photovoltaic's needs of operational reserve, thus it will optimize conversion efficiency of distributed photovoltaic in terms of economy and environmental protection.

(3) The Promotion Path of Demand-side Utilization Efficiency Based on the Optimization of Demand Response

Demand response refers to the behavior of electricity users for changing the existing electricity consumption patterns according to market price signals or incentive mechanism [23]. An important prerequisite for the implementation of demand response is whether electricity users respond to the plans of power use and measures of demand response. Users will reduce electricity consumption during peak. Transferring the electricity tariff periods to a lower point and decreasing electricity costs aim to bring economic benefits for electricity users [24]. This paper selects two response measures from demand-side: time-of-use electricity price and economic demand response based on incentive. Load model was built under the principle of maximizing benefits, so the overall operational level of distributed photovoltaic should be optimized and promoted from the demand-side.

(i) Demand Response Based on Time-of-use Electricity Price

The expression of self-elasticity coefficient and cross-elasticity coefficient are as follows:

$$E_{ij} = \frac{\frac{\Delta d(t_i)}{d_0}}{\frac{\Delta p(t_i)}{p_o}} \tag{15}$$

The amount load changes caused by day-ahead price error as users expected is expressed as follows:

$$\Delta d_i = \sum_{j=1}^{24} E_{ij} \times \left(\frac{\Delta p_j}{p_0}\right) \times d_0 \tag{16}$$

where Δd_i represents the load change of time i; E_{ij} represents the coefficient of elasticity, and, when $i = j$ its value represents the self-elasticity coefficient, whereas, when $i \neq j$, the value represents the cross-elasticity coefficient; and Δp_j represents the error value which is the users' desired price at point j.

Therefore, the amount of 24-h load change is expressed as follows:

$$\Delta \mathrm{d} = \mathrm{E} \times \left(\frac{\Delta p}{p_0}\right) \times d_0 \quad (17)$$

where Δd represents the vector of 24-h load variation; E represents the elastic matrix; and Δp represents price error vector.

(ii) The Economic Demand Response Based on Incentive

Economic demand response refers to the fact that the power company compensates the users who actively participate in load reduction as an incentive. Due to the uncertainty of the load reduction amount of distributed photovoltaic, demand response can be used to forecast the number of pre-agreed reduced load and stipulate disincentive measures of failing to respond, thus the electricity price can be controlled and maintained at the normal level.

Optimal system of demand response for distributed photovoltaic from the perspective of demand-side was built in this paper. It can be used to quantify users' responses to the electricity price and incentives. Power load curve can be stabilized by analyzing and controlling the changes of electricity demand. Therefore, the problem of supply instability of distributed photovoltaic can be solved and then demand-side utilization efficiency and users' satisfaction will be improved.

4.2.2. The Example Simulation

(1) The Process of Simulation

This paper performed simulations using a typical example of IEEE33-node distribution network wiring. Suppose the operation time of the project is 50 years, the maximum annual load loss is 4500 h, the maximum utilization time is 1800 h, and the range of maximum capacity of each node is 50–150 kW. The electricity price of power distribution is 0.7 Yuan/kWh, and the operation cost is 0.72 Yuan/kWh. Photovoltaic power generation is 10,000 Yuan/kW, which is equivalent to the annual construction costs 200 Yuan per kW. Over the same period, coal-fired power plant emits 950 g CO_2 when it generates one kilowatt electricity energy.

To optimize the siting and sizing, applying Equations (9)–(14), and using the algorithm of Particle Swarm Optimization (PSO), let 40 particles get iterated for 1000 times, this paper obtained the results of siting and sizing shown in Figure 6. As Figure 6 shows, applying 60 kW, 100 kW, 90 kW, 100 kW, 120 kW, and 100 kW capacity of photovoltaic equipment in 12, 14, 18, 25, 30, and 32 nodes, respectively, is the best location and optimal capacity of distributed photovoltaic when taking economic and environmental performances into account.

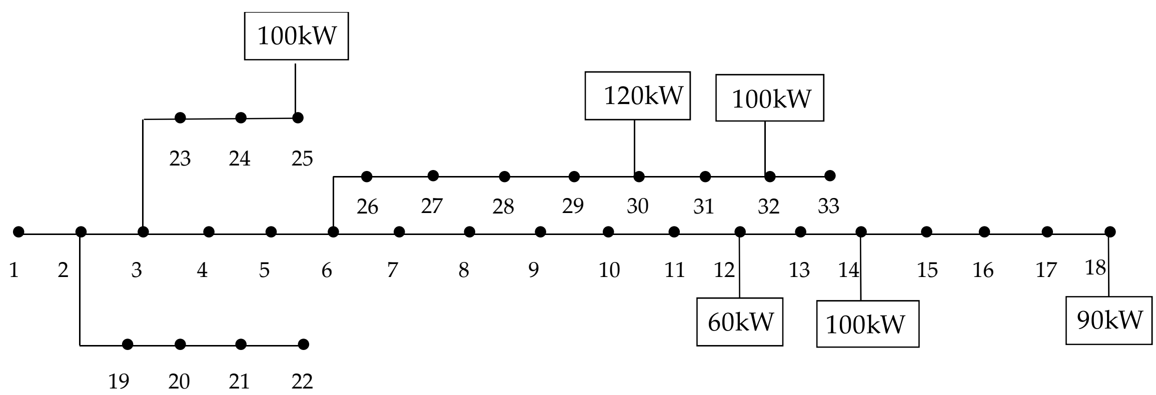

Figure 6. The study results of sitting and sizing.

To optimize the generation dispatching, the load at other times of day was adjusted on the basis of the total load of the reference case. The 24-h load and price forecast based on the photovoltaic power generation price in China are shown in Figure 7.

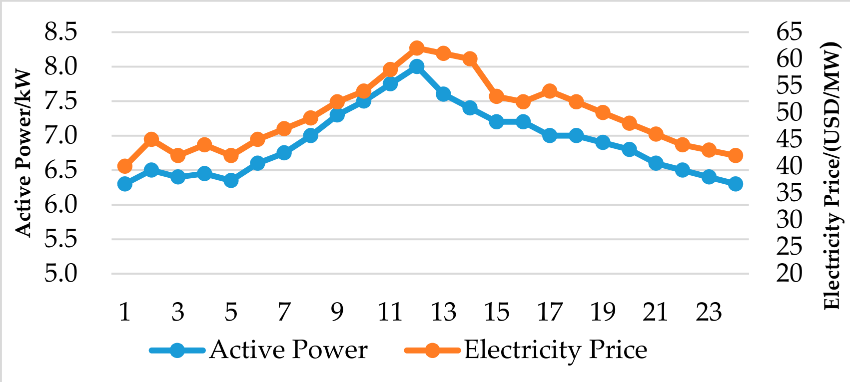

Figure 7. The predicted trends of load and price.

The ultra-short term photovoltaic output can be obtained by analyzing the flow chart in Figure 5 and the data of reference case, and the results are as follows.

The figure of photovoltaic active power forecast shows the power trend of photovoltaic devices within 24 h. As can be seen in Figure 8, the distributed photovoltaic system has output during 5:00 a.m.–20:00 p.m. and the output between 9:00 a.m. and 14:00 p.m. was above 100 kW which was the peak period. Arranging the output of photovoltaic power generation on the basis of forecast will reduce the influence of uncertain factors on the level and capacity of system generation, which provides effective support for revising the previous generation output and making the plan of day-ahead output dispatching.

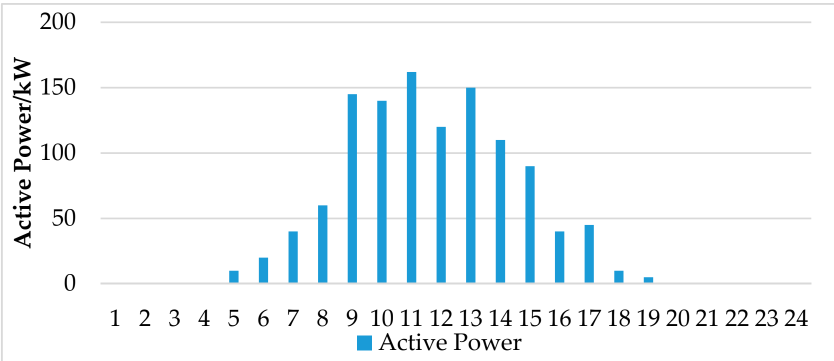

Figure 8. The predicted trend of active power.

To optimize the demand response, it is assumed that the distributed photovoltaic users in the case are residential users, and the load characteristics of the residential users and the price fluctuation of time-of-use (TOU) are shown in Tables 3 and 4.

Table 3. The load characteristics of resident user.

Self-Elasticity Coefficient E(*i*)	Cross-Elasticity Coefficient E(*i*,*j*)		
	Peak-Flat	Peak-Valley	Flat-Valley
−0.40	0.04	0.06	0.04

Table 4. TOU periods division and price fluctuations of resident user.

Time Period	Period Division	Price Fluctuation
Peak	17:30–(Next day) 00:00	Up 30%
Flat	06:30–17:30	No change
Valley	00:00–06:30	Down 30%

Changes of total load before and after the implementation of TOU price policy can be obtained by analyzing the existing data and Equations (15)–(17). Figure 9 shows the results.

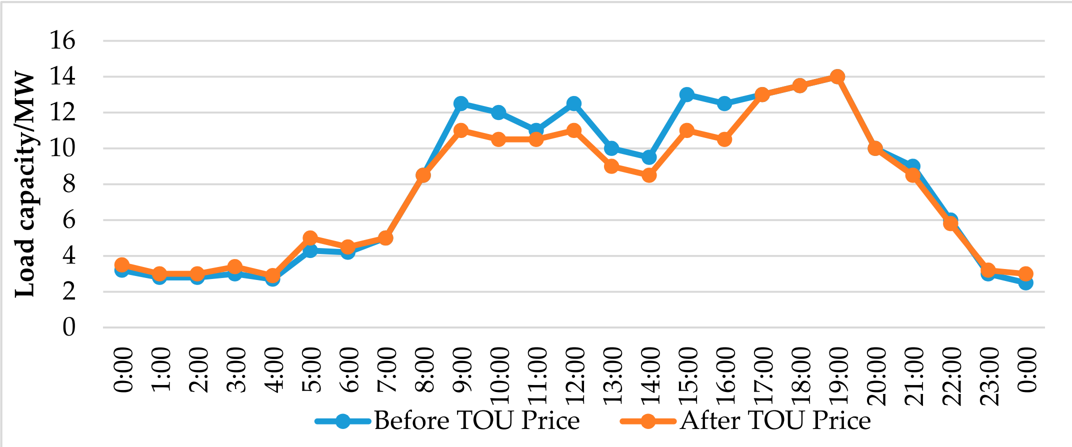

Figure 9. The load trends before and after the implementation of TOU price.

It can be seen in Figure 9 that the load peak period is cut down obviously after the residential users participating in the campaign of demand response, and the total load curve is smoother. Referring to the changes of the load in peak or valley period, residential users can reasonably arrange electricity plans, and power companies will take incentives or punitive measures to promote rational use of photovoltaic power generation and guarantee the stable price on the basis of satisfying users' demand.

(2) The Conclusions of Simulation

In this paper, the IEEE33-node distribution network wiring is selected as the research object. This paper did simulation experiments by using the methods of sitting and sizing, generation dispatching and demand response. The simulation results show that the optimization paths proposed in Section 4.2.1 can be used to select the best location and determine the optimized capacity of photovoltaic generation. Moreover, it will enhance the ability of energy absorption of the distributed photovoltaic generation by forecasting the output of photovoltaic units. The relationship between photovoltaic generation and users' demand can be coordinated by analyzing the effects of TOU on demand response or applying price incentive measures. The optimization methods proposed in this paper from the supply side, energy conversion and demand side provide technical support for improving the comprehensive efficiency of distributed photovoltaic.

4.3. The Realization Guarantee of Optimal Path Based on the Regional Integrated Energy Management System

As the core of the regional integrated energy management system, the intelligent management system makes it possible that siting and sizing of resource-side can be optimized, the operation and dispatch in the energy conversion can be optimized and demand-response of demand-side can be optimized. However, the promotion of distributed photovoltaic comprehensive efficiency relies on the peripheral support from regional integrated energy management system.

As shown in Figure 10, big data analysis system and comprehensive efficiency analysis, together with intelligent business management system constitute the regional integrated energy management system. The intelligent business management system constitutes the core link making resource analysis as the previous preparation, the process control and evaluative feedback as the guarantee and the comprehensive efficiency can be optimized by the final analysis system, which is on the basis of performance of energy utilization, economic efficiency and environmental protection.

Among them, data collection and processing, transmission storage, analysis and integrated utilization are operated in big data analysis system on the basis of analyzing the data of natural resources, planning operation, and users' demand. The system summarizes statistically the geographic information, the real-time and historical data from functional side and demand side of distributed photovoltaic hence it lays a good foundation for the further operation of distributed energy system. Besides, monitoring and protection system ensures the security and steady operation of the whole system through early warming, contingency plans and troubleshooting for system fault. On the basis of performance assessment, the consequence of quality supervision and the feedback, performance evaluation system evaluates the operational results roundly and provides some references for optimizing the comprehensive performance of regional integrated energy management system. The comprehensive efficiency analysis system of the highest level analyzes and appraises comprehensive efficiency of distributed photovoltaic systematically on the basis of analysis of solar energy utilization, cost–benefit and energy-saving and emission reduction. The regional integrated energy management system ensures the promotion of comprehensive efficiency of distributed photovoltaic.

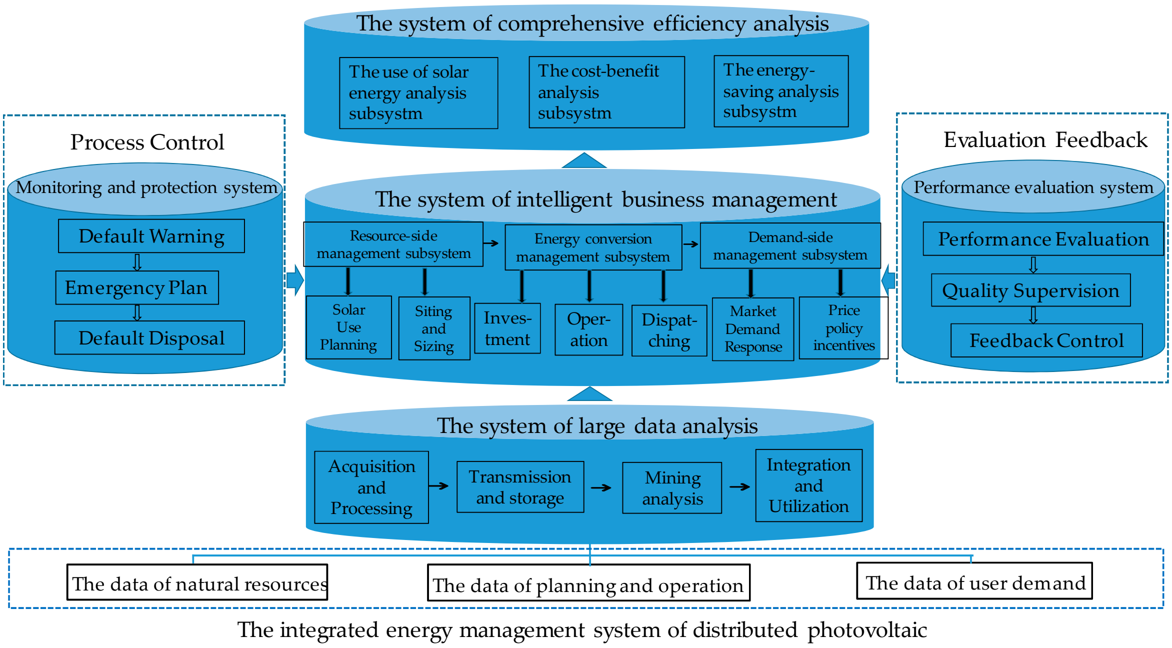

Figure 10. The regional integrated energy management system of distributed photovoltaic.

5. The Policy Recommendations for the Optimization of Comprehensive Efficiency of Distributed Photovoltaic

In recent years, Chinese government introduced many policies and measures related to distributed photovoltaic, so distributed photovoltaic has been actively promoted with powerful support. However, China's cumulative installed capacity of distributed photovoltaic in 2015 accounted for only 14.03% of the whole photovoltaic generation system. China lags far behind those developed countries in terms of the development speed and scale of distributed photovoltaic. In addition to technical factors, imperfect policies for distributed photovoltaic have seriously hindered the scale-development and the improvement of comprehensive efficiency. Thus, taking related policies as the breakthrough point, we should make targeted optimization by combining the future trends and existing safeguard measures, which makes great sense to facilitate the further development of distributed photovoltaic [25]. Recommendations are proposed in this paper for the optimization of distributed photovoltaic policies from three aspects: industrial incentives, price subsidies, and operational supervision.

5.1. The Policy Suggestions of Industrial Incentives

The development of distributed photovoltaic can bring positive external effects for energy, environment and other aspects. However, overvalued investments and operating costs hinder its large-scale application, so it is necessary for government to assist distributed photovoltaic industries to overcome negative external effects in economic terms by introducing the policies of industrial incentives for distributed photovoltaic [26,27].

For security policies, the government should pay much attention to the cultivation of distributed photovoltaic professionals and continue to provide more financial support for the distributed photovoltaic industry on the basis of optimizing the existing industrial policy. As for promoting policies, it is a great deal for government to strengthen unity on the planning and implementation of distributed photovoltaic, taking measures of serving loan, exempting tax to encourage the research and innovation of distributed photovoltaic industry, solving the problem of low rate of photoelectric conversion by promoting the technical progress of photovoltaic modules. For coordination policies, the admittance mechanism of distributed photovoltaic should be improved under the guidance of win-win cooperation to promote coordinated development of grid and centralized energy.

5.2. The Policy Suggestions of Price Subsidy

5.2.1. Price Mechanism

Forming price based on the market mechanism is the direction of China's reform on electricity system and it plays an important role in of the steady development of electricity in the future. Thus, price mechanism has become the priority of implementing policy mechanism in China. Distributed energy tariff policy experience of developed countries such as America and Japan show that a virtuous circle of market-oriented resource allocation and supply–demand affecting price can promote the development of high-efficient and low-carbon distributed photovoltaic [28,29].

When verifying the electricity price of distributed photovoltaic, we should improve differential pricing policies by considering light conditions, load situations, situation of construction and other factors in different regions. Market-oriented electricity price mechanism should be established on the basis of economic development, market demand and planning objectives in different regions and thus make electricity price adjustment flexible. Then we can effectively protect the reasonable profits of distributed photovoltaic and improve the generation efficiency as well as achieve sustainable development.

5.2.2. Subsidy Mechanism

In the early stage of the development of distributed photovoltaic, Chinese government introduced policies of financial subsidies or preferential loans for demonstrated projects and then initial investment costs were reduced [30]. Nowadays, as the development of distributed photovoltaic enters into a new phase of market-oriented operation, Chinese government should adjust the subsidies and incentives, and gradually coordinate supportive policies with market adjustment to facilitate the development of distributed photovoltaic industry.

In terms of the form of subsidies, it is supposed to follow the principle that top priority should be given to subsidies of feed-in tariff and subsidies for installed equipment should be subsidiary. Thus, we can guarantee orderly development of distributed photovoltaic. The time period and the amount of subsidies for feed-in tariff should be maintained within a certain range. Adhering to the principle of gradually declining until the abolition, we should support the current operation of distributed photovoltaic industry and we should take measures such as tax breaking, incentive purchasing to reduce deceptive behavior due to the high subsidies then we can make sure that the development of distributed photovoltaic to be flexible and unprejudiced.

5.3. The Policy Suggestions of Operation Supervision

The market players of distributed photovoltaic during the operational phase mainly involves government departments, suppliers, investors, operation and maintenance companies, power companies, users, and so on [31]. In order to improve operational efficiency and regulatory standards, the government should formulate relevant policies to encourage technological innovation of distributed photovoltaic with the focus on the key issues of photovoltaic devices, solar energy absorption, and grid-connected access and adopt financial policies to support photovoltaic companies to enter the field of distributed photovoltaic, forming a value chain which possesses competitive strength and growth prospects. China should communicate and cooperate with developed countries actively with the purpose of absorbing advanced technology and business model and then promote the upgrade of capacity utilization rate and energy-saving and emission reduction rate.

As for regulation, China should be alert to the issues of regional industry overcapacity and structural imbalances of distributed photovoltaic caused by its rapid development. Precautions should be taken to strengthen the regulation of excess capacity and the backlog of inventory, as well as to increase confidence of investors. Chinese government should attach importance to the implementation of the pre-approval and post-production of distributed photovoltaic demonstration projects; improve the transparency of planning, access, and transactions; and aim at forming a multilayer regulatory system, which involves government, non-governmental organization (NGO) and companies. Therefore, China would further promote healthy and standard development of distributed photovoltaic.

6. Conclusions

Based on the issues of energy crisis, environmental pollution and problems in the development of large-scale integrated energy in China, this paper focuses on the efficiency optimization of distributed photovoltaic. Under the guidance of the theory of system dynamics, integrated energy management system was established. This paper took efforts to research the optimal path for comprehensive efficiency of distributed photovoltaic from technical and policy perspectives, and draws the following conclusions:

(1) This paper proposed the concept of comprehensive efficiency of distributed photovoltaic after analyzing the current situation of distributed photovoltaic efficiency. According to the research and analysis using the theory of system dynamics, the comprehensive promotion of distributed photovoltaic relates to energy, technology, economy, environment and market, and depends on the factors of the rate of grid-connected power generation, the rate of capacity utilization, the rate of cost–benefit, the rate of energy-saving and emission reduction and the rate of users' satisfaction. Analyzing the comprehensive efficiency of distributed photovoltaic on the basis of five factors makes sense of understanding the whole direction of optimization.

(2) After analyzing the influencing factors of comprehensive efficiency, this paper clarified the direction of optimization from resource side, energy conversion and demand side, and established the core part of the regional integrated energy management system; that is, the system of intelligent business management. Then, the author proposed optimized path of the comprehensive efficiency of distributed photovoltaic from three various perspectives.

This paper proposes technological methods including siting and sizing optimization, operation dispatching optimization and demand response optimization from energy resource-side, energy conversion and energy demand-side. The results of simulations reveal that all of these methods can effectively improve energy conversion efficiency and utilization efficiency. The regional integrated energy management system built in this paper can ensure the optimization of the distributed photovoltaic comprehensive efficiency on the basis of scientific analysis and effective control. Based on the policy recommendations from the three aspects of industrial incentives, price subsidy, and operation supervision, this paper provides guidance and advice for high-efficient development of distributed photovoltaic.

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