sustainability

MDPI

Article

# Research on the Changing Trends in Electricity Prices in Gansu Province Considering High Future Penetration of Sustainable Energy

**Rong Huang [1], Xiang Wang [2,*], Tian Liang [1], Jing Zhi [1], Yongsheng Jin [1], Jiaxin Qian [2] and Haibo Li [2]**

[1] State Grid Gansu Electric Power Research Institute, Lanzhou 730070, China; hr_1103@163.com (R.H.)
[2] Sichuan Energy Internet Research Institute, Tsinghua University, Chengdu 610213, China
* Correspondence: wangxiang@my.swjtu.edu.cn

**Abstract:** Carbon peaking and carbon neutrality goals have put forward new requirements for the development of sustainable energy. As an important part of the energy system, the power system plays an important role in achieving sustainable energy development. Future power systems will be sustainable, with a high proportion of renewable energy such as photovoltaic and wind power. With advancements in technology and the sustainable development of power systems, the construction costs of wind power, photovoltaics, and other renewable energy sources will continue to decline. At the same time, in order to cope with the uncertainty of renewable energy, more flexible resources need to be built. Under a high proportion of sustainable energy penetration, the utilization rate of flexible resources is low, which will lead to an increase in adjustment costs. Economic issues have an important impact on the development of new power systems, and power system construction will in turn affect social and economic development. Therefore, it is necessary to analyze changing trends in electricity prices in the process of power system sustainability from a quantitative perspective, so as to provide guidance for future planning. In view of the above problems, this paper takes Gansu Province as an example, predicts future power installation trends, by analyzing the power system form evolution, and uses production operation simulation technology to determine the power generation and consumption situation. On this basis, the costs of various power supplies and power grids are calculated, and trends in electricity prices in Gansu Province are forecast.

**Keywords:** carbon peak and carbon neutrality; sustainable power system; form evolution; cost estimation; trend of electricity price



**Citation:** Huang, R.; Wang, X.; Liang, T.; Zhi, J.; Jin, Y.; Qian, J.; Li, H. Research on the Changing Trends in Electricity Prices in Gansu Province Considering High Future Penetration of Sustainable Energy. *Sustainability* **2024**, *16*, 3340. https://doi.org/10.3390/su16083340

Received: 31 January 2024
Revised: 23 March 2024
Accepted: 3 April 2024
Published: 16 April 2024



## 1. Introduction

Against a background of "carbon peak and carbon neutrality", the proportion of installed renewable energy capacity and power generation will gradually increase. In this process, with the dual factors of technology maturity and scale effect, the cost-per-unit capacity of installed new energy will still have room to decline [1–3]. At the same time, under the extremely high proportion of renewable energy penetration, in order to ensure the realization of the goal of "carbon peak and carbon neutrality", it is also necessary to increase the proportion of new energy generation, which will inevitably lead to a decline in the utilization rate of installed new energy, so the power generation cost will rise in this respect. On the other hand, in order to cope with the volatility of new energy output, there will also be a large increase in energy storage, supporting thermal power units, and other flexibility to adjust resource investment. The utilization efficiency of such resources is generally low, and will also promote rising electricity prices [4–7]. Therefore, in the process of the evolution of the new power system, trends of change in electricity pricing are still uncertain.

At present, the price of renewable energy power generation has dropped significantly, and most of the newly built new energy-generating units can achieve more affordable internet access than traditional energy. As a result, the economy of renewable energy power generation has begun to be highlighted.

Many scholars have carried out related research on the changing trends of future electricity prices. In research on the wind power economy, the authors of [8] internalized external costs and benefits, comprehensively considering internal and external costs and benefits, and put forward a reasonable price calculation method for wind power online. The authors of [9,10] analyzed the economic benefits of new energy and proposed a calculation method of equivalent on-grid electricity pricing of new energy. The authors of [11] proposed a dynamic incentive mechanism for electricity transmission and distribution prices in view of the current situation of energy transition, the authors of [12] took green certificate and carbon trading prices into consideration in peak regulation strategies, and the authors of [13–15] carried out research on the cost recovery mechanism and market price design of extraction and storage. Based on externality theory, the authors of [16] studied the cost dispersal mechanism of grid-side energy storage, while the authors of [17] analyzed the technical economy of various types of energy storage absorbing new energy.

A comprehensive model has been developed to assess the spatiotemporal evolution of China's techno-economic grid PV potential from 2020 to 2060 [18], assuming continued cost decline in line with the trends of the last decade. An integrated approach was developed to analyze the grid parity of onshore wind power from a system cost perspective [19]. In addition, the levelized cost of PV was calculated, taking into account factors such as capacity factor, capital expenditure, annual plant operation and maintenance costs, discounts and interest rates, and economic life [20–23].

In a wind farm life cycle analysis, the impact of infrastructure construction was considered [24]. A large-scale levelized cost of electricity mapping of floating offshore wind power over the European Atlantic was proposed in [25] to quantitatively analyze different costs throughout the life cycle. An LSSA-BP neural network prediction model was established to accurately predict onshore wind power costs in [26]. The existing research methods for analyzing the levelized costs of offshore wind power and the challenges faced by large-scale development of offshore wind power are introduced in [27,28]. A techno-economic model is developed for wind energy cost analysis of a new Ferris wheel wind turbine in [29]. The model was used to conduct a technical and economic analysis of wind turbine site selection in low-wind-speed areas on the African continent, verifying its feasibility from an economic perspective.

In general, the current research on the cost and price of new energy and storage has mainly been focused on a single variable and has not taken into account the impact of future power system evolution on changes in electricity price. Taking Gansu Province as an example, this paper analyzes the evolution path of future power systems, comprehensively considers the cost of power generation and transmission and distribution links, and calculates trends of change in terminal electricity price in Gansu Province based on the simulation results of production operation, which provides a price basis for the construction of new power systems and a more ideal power market in the future.

## 2. Methodology

The price of electricity depends on the costs of production, transmission, regulation and storage. Therefore, when calculating the electricity price in this article, the grid side and the power supply side are considered separately. The cost calculation on the power supply side adopts the operating period method model, which considers the construction and operating costs of thermal power, wind power, photovoltaic power generation, hydropower, electrochemical energy storage and pumped hydropower, and, finally, calculates the average electricity price on the power supply side. On the grid side, a cost and benefit calculation model is used to allocate the construction, operation, and maintenance costs of grid-side transmission facilities, substation facilities, and distribution facilities. Based on Gansu's future load development trend and power supply construction planning, future power generation is calculated through production simulation, and then the electricity price change trend in Gansu Province is obtained.

## 3. Power Side Cost Calculation

### 3.1. Operating Period Model

Operating period cost analysis is an important theory to study the one plant one price problem, which is widely used in the price setting of conventional energy and renewable energy. The operating period model of the power system obtains the annual cost of the whole life cycle of the system through capital conversion and then calculates the kWh cost on the basis of ensuring a certain financial profit rate. The idea of operating period cost analysis is to calculate the equivalent annual cost of the net present value of each annual cash flow in the operating life of the project, which is exactly equal to the total static investment, for a given interest rate value. Then, divide by the estimated annual on-grid electricity, and find the unit electricity cost. The operating period model of typical power system cost analysis is as follows [30]:

$$\sum_{n=1}^{N} \frac{I_n(C, Q, S, \cdots) - O_n(V_n, \rho_n, T_n, \cdots)}{(1 + r_e)^n} = 0 \quad (1)$$

where $N$ represents the length of the project operation period; $I_n$ $(C, Q, S)$ is the total income obtained in the $n$-th year of the project, which is affected by the project reserve price $C$, annual power generation $Q$, residual asset value $S$ and other factors. $O_n$ ($V_n$, $\rho_n$, $T_n$) is the cash outflow obtained in the $n$-th year of the project, which is affected by factors such as fuel price $V_n$, loan repayment $\rho_n$, tax payment $T_n$, etc. $r_e$ is the expected internal rate of return on the funds used for the project.

If other factors are not considered, there is a definite relationship between the internal rate of return (IRR) of project capital $r_e$ and the project reserve price ($C$), which is called the kWh cost corresponding to IRR $r_e$. The operating period model is mainly used to calculate the power generation cost of various power sources.

### 3.2. Thermal Power Cost Calculation

Thermal power cost mainly includes thermal power unit environmental penalty cost and thermal power unit investment and operation cost [7,17]. Among them, the environmental penalty cost of thermal power is as follows:

$$F_{\mathrm{NEPT}t} = \sum_{t=1}^{T} \sum_{i=1}^{m} k_{\mathrm{CO_2}} k_{\mathrm{NO}_x} k_{\mathrm{SO_2}} k_i P_{\mathrm{T}it} \quad (2)$$

(2) The operating costs of thermal power units can be expressed as follows [17].

$$F_{\mathrm{TOP}t} = \sum_{i=1}^{m} P_{\mathrm{TOP}i.t} P_{\mathrm{T}it} \quad (3)$$

where $m$ is the number of thermal power units in the system; $k_{\mathrm{CO2}}$ is the carbon dioxide emission coefficient, $k_{\mathrm{NOx}}$ is the nitrogen oxide emission coefficient, $k_{\mathrm{SO2}}$ is the sulfur dioxide emission coefficient, $k_i$ is the coal consumption coefficient of the thermal power unit. $P_{\mathrm{TOP}i,t}$ is the electricity generation price of the $i$ thermal power unit within $t$ per unit period after excluding the environmental penalty cost; $P_{\mathrm{T}it}$ is the generating power of the corresponding unit in the corresponding time period.

It can be concluded that the electricity price of thermal power units in the time period $t$ is as follows:

$$V_{\mathrm{T}t} = F_{\mathrm{NEPT}t} + F_{\mathrm{TOP}t} \quad (4)$$

### 3.3. Wind Power Cost Calculation

Wind power generation does not require fuel, so the marginal cost is close to 0. The operation process does not pollute the environment, and its environmental cost is generally considered to be 0. The main costs of wind farms include construction costs, operation and maintenance costs, etc.

Wind power cost includes wind farm construction and operation cost $F_1$, negative efficiency operation penalty cost $F_2$ considering wind farm ultimate penetration power, and additional rotational reserve capacity compensation cost $F_3$ considering wind farm output forecast reliability. Wind power operation price can be represented by the following model [31,32].

$$V_{\mathrm{W}t} = F_1 + F_2 + F_3 \tag{5}$$

The specific expression of $F_1$, $F_2$, and $F_3$ is referred to in the literature [33], which will not be repeated in this paper due to space limitations.

### 3.4. Photovoltaic Cost Calculation

Similar to wind power, photovoltaic farm costs include the costs generated by the operation of the power station itself and the compensation costs of rotating standby capacity caused by the uncertainty of photovoltaic output.

Considering that photovoltaic does not consume fuel in the power generation process, by taking into account the investment, operation, and maintenance costs of photovoltaic, the average power generation cost of photovoltaic has an approximate linear relationship with its power generation during the whole life cycle. The mathematical model of photovoltaic cost is shown as follows [17,34]:

$$F_{\mathrm{pv}.t} = \sum_{i=1}^{x} P_{\mathrm{pv}.it} \cdot f_{\mathrm{p,cost}} \tag{6}$$

where $F_{\mathrm{pv}.t}$ is the total operating cost of photovoltaic power station in the unit period t studied; $P_{\mathrm{pv}.it}$ represents the planned power generation output of the $i$ photovoltaic power station during this period; $f_{\mathrm{p,cost}}$ refers to the cost and price of photovoltaic power generation in this period, and the specific value is related to the operation of photovoltaic power stations.

The uncertainty of PV output leads to the deviation between the actual output of PV connected to the grid and the forecast output of the power station, which will increase the system rotation reserve capacity and generate the corresponding cost. Photovoltaic rotation reserve capacity compensation cost can be expressed as follows [17,34]:

$$F_{\mathrm{PV}t} = \sum_{i=1}^{x} C_{\mathrm{PV}t}(1 - E_{\mathrm{PV}.it})P_{\mathrm{PVF}.it} \tag{7}$$

Among them, $F_{\mathrm{PV}t}$ represents the rotational reserve capacity cost generated by the system in response to the uncertainty of PV output prediction in a certain unit time period t; $C_{\mathrm{PV}t}$ is the reserve capacity price of the system during this period. $E_{\mathrm{PV},it}$ is the predicted output of the $i$ photovoltaic power station in this period; $x$ is the number of photovoltaic power stations, $P_{\mathrm{PVF},it}$ is the rated photovoltaic output.

Based on the above cost analysis, the cost of PV can be expressed as follows [17,34]:

$$V_{\mathrm{PV}t} = F_{\mathrm{pv}.t} + F_{\mathrm{PV}t} \tag{8}$$

### 3.5. Hydropower Cost Calculation

Hydropower costs are usually calculated using a two-part electricity price system, in which capacity electricity price includes investment costs, a certain proportion of fixed operation and maintenance costs, and a certain proportion of investment income, and electricity price includes the remaining fixed operation and maintenance costs, residual investment income, and all variable operation and maintenance costs. The hydropower costs can be as follows [35]:

$$V_{\text{water},t} = F_{\text{Cap}} + F_{\text{Elec}} \tag{9}$$

where $F_{\text{Cap}}$ is the hydropower capacity electricity price, $F_{\text{Elec}}$ is the electricity price of hydropower.

### *3.6. Cost Estimation of Electrochemical Energy Storage*

The cost of electrochemical energy storage mainly includes construction investment costs and operation and maintenance costs.

Electrochemical energy storage construction investment cost includes power cost and capacity cost in two parts. The life cycle construction investment cost of the energy storage system can be shown as follows [17]:

$$F_1 = F_{\text{P}} P_{\text{C}} + F_{\text{E}} E_{\text{C}} \tag{10}$$

where $F_{\text{P}}$ is the unit power cost of electrochemical energy storage, $F_{\text{E}}$ is the unit capacity cost of the battery, $P_{\text{C}}$ is the rated power of the energy storage and $E_{\text{C}}$ is the rated capacity of the energy storage system.

The operation and maintenance cost of an electrochemical energy storage system is determined by the scale of energy storage, which can be expressed as follows [17]:

$$F_2 = F_{\text{m}} P_{\text{C}} \tag{11}$$

where $F_{\text{m}}$ is the annual operation and maintenance cost per unit of energy storage capacity.

According to the working life of the energy storage system and the internal rate of return on investment, the cost is divided within the working life of the energy storage system. The annual operation and maintenance cost is superimposed. So the annual cost of energy storage is as follows [36,37]:

$$V_{\text{S}t} = \left(\frac{(1+r)^T r}{(1+r)^T - 1} F_1 + F_2\right) \tag{12}$$

where $r$ is the internal rate of return of the investment cost of the energy storage system, and $T$ is the life of the energy storage system.

### *3.7. Cost Calculation of Pumped Storage*

Starting from the whole life cycle and considering the cost expenditure generated during the operation of pumped storage units, the whole life cycle cost model of pumped storage can be obtained [37]:

$$C_{\text{LCC}} = C_{\text{I}} + C_{\text{O}} \tag{13}$$

Among them, $C_{\text{LCC}}$ is the life cycle cost, $C_{\text{I}}$ is the investment cost, and $C_{\text{O}}$ is the operation cost.

Converting the full life cycle cost to each year, the annual cost is as follows [38]:

$$V_{\text{LCC},t} = \frac{(1+r)^T r}{(1+r)^T - 1} C_{\text{LCC}} \tag{14}$$

In Formula (14), $r$ is the internal rate of return of the investment cost of extraction and $T$ is the life of extraction.

### 3.8. Power Side Cost Calculation

The comprehensive cost of power supply includes all types of power supply and energy storage costs, which can be expressed as follows:

$$V_{\mathrm{S}} = \frac{V_{\mathrm{T}t}Q_{\mathrm{T}t} + V_{\mathrm{G}t}Q_{\mathrm{G}t} + V_{\mathrm{W}t}Q_{\mathrm{W}t} + V_{\mathrm{PV}t}Q_{\mathrm{PV}t} + V_{\mathrm{Water},t}Q_{\mathrm{Water},t} + V_{\mathrm{S}t} + V_{\mathrm{LCC},t}}{Q_{\mathrm{T}t} + Q_{\mathrm{G}t} + Q_{\mathrm{W}t} + Q_{\mathrm{PV}t} + Q_{\mathrm{Water},t}} \tag{15}$$

Among them, $V_{\mathrm{T}t}$, $V_{\mathrm{G}t}$, $V_{\mathrm{W}t}$, $V_{\mathrm{PV}t}$, $V_{\mathrm{Water},t}$ are, respectively, the kWh cost of thermal power, gas power, wind power, photovoltaic power generation and hydropower; $V_{\mathrm{S}t}$, $V_{\mathrm{LCC},t}$ are the converted cost of energy storage and extraction storage. $Q_{\mathrm{T}t}$, $Q_{\mathrm{G}t}$, $Q_{\mathrm{W}t}$, $Q_{\mathrm{PV}t}$, $Q_{\mathrm{Water},t}$ are, respectively, thermal power, gas power, wind power, photovoltaic power generation and hydropower.

## 4. Cost Calculation of Power Grid Side

### 4.1. "Cost + Benefit" Calculation Model

At present, the approved principle of transmission and distribution cost in China is permitted cost plus reasonable income [30]. The average power transmission and distribution price of the grid side is calculated by the ratio of the total allowable income and the power transmission and distribution. The permitted total income includes the permitted cost, the permitted income, and the tax several parts; the permitted cost includes the base period cost and the new cost, the permitted income is the product of the effective assets and the weighted average cost of capital, and the tax includes the enterprise income tax, the urban construction tax, and the education surcharge. "Cost + benefit" mainly considers the impact of power grid transmission and distribution construction, operation and maintenance costs, electricity prices, taxes, new investment and power growth factors on the cost.

### 4.2. Grid-Side Cost Calculation Model

The cost of the power grid mainly includes two parts, construction cost and operation and maintenance cost, among which the construction cost includes three parts: construction cost converted to the current period, investment cost of the new power grid in the current period, and asset replacement cost in the current period. Therefore, the power grid cost can be expressed as follows [39]:

$$F_{\mathrm{Net},t} = F_{\mathrm{Pre},t} + F_{\mathrm{New},t} + F_{\mathrm{Rep},t} + F_{\mathrm{op},t} \tag{16}$$

where $F_{\mathrm{Net},t}$ is the total cost of the power grid, $F_{\mathrm{Pre},t}$ is the construction cost converted to the current period, $\mathrm{F}_{\mathrm{New,t}}$ is the new power grid investment, $F_{\mathrm{Rep},t}$ is the asset replacement, $F_{\mathrm{op},t}$ is the operation and maintenance cost.

The cost of electricity price on the grid side can be converted by the total amount of electricity transmitted:

$$V_{\mathrm{Net},t} = \frac{F_{\mathrm{Net},t}}{Q_{\mathrm{Tran},t}} \tag{17}$$

where $V_{\mathrm{Net},t}$ is the reflection of the cost of the grid in the price of electricity and $Q_{\mathrm{Tran},t}$ is the total electricity transmitted by the grid.

## 5. Morphological Evolution Analysis of New Power System

### 5.1. An Evolutionary Analysis Approach Based on Planning

According to the development goal of the new power system in the future, combined with the resource endowment, load forecasting, and development mode of the province, the resources of the load and storage side of the source network are coordinated planning. Provincial power grid planning is based on operation constraints and considers the requirements of power supply security and renewable energy consumption under source load uncertainty [33]. The planning model can be abstracted into the following forms:

$$\begin{cases} \min\left(\sum_{y=1}^{Y} C_{\mathrm{z}}(y, \boldsymbol{t})\right) \\ \quad \phi_{\mathrm{g}}(\boldsymbol{x}, \boldsymbol{u}) \le 0 \\ \quad \phi_{\mathrm{l}}(\boldsymbol{x}, \boldsymbol{u}) \le 0 \\ \text{s.t.} \quad \phi_{\mathrm{d}}(\boldsymbol{x}, \boldsymbol{u}) \le 0 \\ \quad \phi_{\mathrm{s}}(\boldsymbol{x}, \boldsymbol{u}) \le 0 \\ \quad F(\boldsymbol{x}, \boldsymbol{t}, \boldsymbol{u}) \le 0 \end{cases} \tag{18}$$

where $C_z$ ($y$, $\boldsymbol{t}$) is the total system cost in y years in the evolution cycle considering the influence of decision variables; $\phi_g$ ($x$, $\boldsymbol{u}$), $\phi_l$ ($\boldsymbol{x}$, $\boldsymbol{u}$), $\phi_d$ ($\boldsymbol{x}$, $\boldsymbol{u}$), $\phi_s$ ($\boldsymbol{x}$, $\boldsymbol{u}$), $F$ ($\boldsymbol{x}$, $\boldsymbol{t}$, $\boldsymbol{u}$) are the flexibility resources of each side of the source network and the operational constraints of the system with decision variables, respectively. $\boldsymbol{x}$ is the vector matrix of optimized output results in production operation simulation; $\boldsymbol{t}$ is the input parameter vector matrix of multi-type decision variables in planning simulation; $\boldsymbol{u}$ is the input parameter vector matrix in the production run simulation.

Under different development levels, the production simulation model with cooperative flexibility adjustment characteristics takes the future power supply security and new energy consumption as the optimization objectives. Due to the large number of binary variables in the operation constraints of thermal power and thermal power, a mixed integer nonlinear optimization problem is formed. The linear processing is carried out by defining the online capacity of thermal power and solar thermal power units of the whole network to reduce the model solving scale. By forming constraint sets for thermal power peak load capacity (flexible transformation) and minimum start-up mode requirement constraints, hydropower seasonal power and electricity constraints, grid mutual transmission limit constraints, demand-side response power constraints, energy storage power constraints, etc., the operating cost of various types of flexible resource investment is quantified. Optimize and solve the multi-category flexible resource investment capacity and operation output of the source network, and realize the integration planning and evolution analysis of the source–network–load–storage flexibility.

### *5.2. Load–Storage Collaborative Planning Model of Source Network*

In collaborative planning, the lowest total system cost $C_{\mathrm{sys}}$ is the goal, and the system assembly is the investment cost and system operation cost of the power generation side, the transmission and distribution system, and the energy storage system, namely [40]:

$$\begin{cases} \min C_{\mathrm{sys}} = C_{\mathrm{sys}}^{\mathrm{inv}} + C_{\mathrm{sys}}^{\mathrm{oper}} \\ \text{s.t.} \quad C_{\mathrm{sys}}^{\mathrm{inv}} = C_{\mathrm{gen}}^{\mathrm{inv}} + C_{\mathrm{line}}^{\mathrm{inv}} + C_{\mathrm{sto}}^{\mathrm{inv}} \\ \quad\quad C_{\mathrm{sys}}^{\mathrm{oper}} = C_{\mathrm{gen}}^{\mathrm{oper}} + C_{\mathrm{line}}^{\mathrm{oper}} + C_{\mathrm{sto}}^{\mathrm{oper}} + C_{\mathrm{load}}^{\mathrm{oper}} \end{cases} \tag{19}$$

where $C_{\mathrm{sys}}^{\mathrm{inv}}$ and $C_{\mathrm{sys}}^{\mathrm{oper}}$ are the total investment cost and total operating cost of the system, respectively; $C_{\mathrm{gen}}^{\mathrm{inv}}$ is the power supply investment cost, $C_{\mathrm{line}}^{\mathrm{inv}}$ is the power grid investment cost, $C_{\mathrm{sto}}^{\mathrm{inv}}$ is the energy storage side of the construction cost; $C_{\mathrm{gen}}^{\mathrm{oper}}$, $C_{\mathrm{line}}^{\mathrm{oper}}$, $C_{\mathrm{sto}}^{\mathrm{oper}}$ and $C_{\mathrm{load}}^{\mathrm{oper}}$ are, respectively, the operating costs of the power side, the transmission and distribution network, the energy storage system and the load side.

The investment cost of power supply, grid, and energy storage can be expressed as follows [40]:

$$\begin{cases} C_{\mathrm{gen}}^{\mathrm{inv}} = \sum_{i=1}^{N_{\mathrm{g}}} C_{\mathrm{g},i}^{\mathrm{inv}} G_i + \sum_{i=1}^{N_{\mathrm{h}}} C_{\mathrm{h},i}^{\mathrm{inv}} H_i + \sum_{i=1}^{N_{\mathrm{w}}} C_{\mathrm{w},i}^{\mathrm{inv}} W_i + \sum_{i=1}^{N_{\mathrm{p}}} C_{\mathrm{p},i}^{\mathrm{inv}} P_i \\ C_{\mathrm{line}}^{\mathrm{inv}} = \sum_{i=1}^{N_{\mathrm{l}}} C_{\mathrm{l},i}^{\mathrm{inv}} L_i \\ C_{\mathrm{sto}}^{\mathrm{inv}} = \sum_{i=1}^{N_{\mathrm{s}}} C_{\mathrm{s},i}^{\mathrm{inv}} S_i \end{cases} \tag{20}$$

where $C_{g,i}^{inv}$, $C_{h,i}^{inv}$, $C_{w,i}^{inv}$, $C_{p,i}^{inv}$, $C_{l,i}^{inv}$ and $C_{s,i}^{inv}$ correspond to the unit capacity construction costs of thermal power, hydropower, wind power, photovoltaic, power grid and energy storage, respectively. $N_g$, $N_h$, $N_w$, $N_h$, $N_l$ and $N_s$ are the number of corresponding items. $G_i$, $H_i$, $W_i$, $P_i$, $L_i$ and $S_i$ are the capacity to be built or the capacity demand of the corresponding project, respectively, and the decision variable of the optimization model.

The total operating cost of the system includes the power generation cost of all power sources, the flexible adjustment cost of thermal power, the operating loss cost of line and energy storage and the system load reduction cost, which can be expressed as follows [40,41]:

$$\begin{cases} C_{gen}^{oper} = \sum_{t=1}^{T} \sum_{i=1}^{N_g} (C_{g,i}^{ud} g_{i,t}^{ud} + C_{g,i} g_{i,t} + C_{h,i} h_{i,t} + C_{w,i} w_{i,t} + C_{p,i} p_{i,t}) \\ C_{line}^{oper} = \sum_{t=1}^{T} \sum_{i=1}^{N_l} C_{l,i} l_{i,t} \\ C_{sto}^{oper} = \sum_{t=1}^{T} \sum_{i=1}^{N_s} C_{s,i} s_{i,t} \\ C_{load}^{oper} = \sum_{t=1}^{T} \sum_{j=1}^{N_d} (C_{d,j}^{z} d_{j,t}^{z} + C_{d,j}^{f} d_{j,t}^{f} + C_{d,j}^{cut} d_{j,t}^{cut}) \end{cases} \tag{21}$$

where $T$ is the period divided by the optimization cycle and $N_d$ is the number of loads accessed; $C_{g,i}^{ud}$ is the unit start-up and shutdown cost of the $i$ thermal power unit; $C_{g,i}$, $C_{h,i}$, $C_{w,i}$, $C_{p,i}$, $C_{l,i}$ and $C_{s,i}$ correspond to the unit power generation cost of the $i$ thermal power, hydropower, wind power, photovoltaic, line and energy storage; $C_{d,j}^{z}$, $C_{d,j}^{f}$ and $C_{d,j}^{cut}$ are unit interruption, translation and load cutting costs of load I, respectively, and the above parameters are known quantities. $g_{i,t}^{ud}$ is the start-stop capacity of thermal power $i$ at time $t$; $g_{i,t}$, $h_{i,t}$, $w_{i,t}$, $p_{i,t}$, $l_{i,t}$ and $s_{i,t}$ are the output of the $I$ thermal power, hydropower, wind power, photovoltaic, line and energy storage at time $t$, respectively. $d_{j,t}^{z}$, $d_{j,t}^{f}$ and $d_{j,t}^{cut}$ are, respectively, the j-th interruptible load power, shiftable load power, and shear load at time t. The above parameters are optimization decision variables.

### *5.3. Production Run Simulation Model*

Constraints of the production and operation simulation model mainly consider the power supply and demand balance of the system, the total reserve constraints of the system in the whole region, the output operation characteristics constraints of conventional thermal power, hydropower, solar thermal, wind power, photovoltaic and other power sources, the transmission limit constraints of the interconnected grid, the load side response capacity and power constraints, and the charging and discharging power requirements of the energy storage system [40,41].

The regional power supply and demand balance constraint of the system is as follows [40,41]:

$$\begin{aligned} &\sum_{i \in \Omega_n^g} g_{i,t} + \sum_{i \in \Omega_n^h} h_{i,t} + \sum_{i \in \Omega_n^w} w_{i,t} + \sum_{i \in \Omega_n^p} p_{i,t} \\ &- \sum_{i \in \Omega_n^{ls}} l_{i,t} + \sum_{i \in \Omega_n^{lr}} l_{i,t} + \sum_{i \in \Omega_n^s} (s_{i,t}^{dis} - s_{i,t}^{cha}) = \\ &\sum_{i \in \Omega_n^d} (d_{j,t} - d_{j,t}^{cut}) + \sum_{i \in \Omega_n^{dz}} d_{j,t}^{z} - \sum_{i \in \Omega_n^{df}} d_{j,t}^{f} \end{aligned} \tag{22}$$

where $\Omega_n^g$, $\Omega_n^h$, $\Omega_n^w$, $\Omega_n^p$, $\Omega_n^s$, $\Omega_n^d$, $\Omega_n^{dz}$ and $\Omega_n^{df}$ are the collection composed of thermal power, hydropower, wind power, photovoltaic, energy storage, load, transferable load and interruptible load in the $n$-th region of the system, respectively. $\Omega_n^{lr}$, $\Omega_n^{ls}$ are, respectively, a collection of incoming and outgoing channels in the region; $s_{i,t}^{cha}$ and $s_{i,t}^{dis}$ are, respectively, the charging and discharging power of the first energy storage system at all times are decision variables.

When flexible load, grid mutual benefit capacity, energy storage and discharge capacity involved in demand-side response are included in the system standby capacity, the system standby constraint is expressed as follows [40,41]:

$$g_{i,t}^{\mathrm{r}} + h_{i,t}^{\mathrm{r}} + l_{i,t}^{\mathrm{r}} + s_{i,t}^{\mathrm{r}} \geq k(d_{j,t} - w_{i,t} - p_{i,t} - d_{j,t}^{\mathrm{zr}} - d_{j,t}^{\mathrm{fr}}) \tag{23}$$

where $g_{i,t}^{\mathrm{r}}$, $h_{i,t}^{\mathrm{r}}$, $l_{i,t}^{\mathrm{r}}$, $s_{i,t}^{\mathrm{r}}$, $d_{j,t}^{\mathrm{zr}}$ and $d_{j,t}^{\mathrm{zf}}$ are the standby capacity provided by the thermal power, hydropower, power transmission, energy storage, transferable load and interruptible load of power grid $i$ in a single region at the middle time, respectively. $k$ indicates the ratio of the system standby capacity to the net load capacity.

The operating characteristics of thermal power units are constrained as follows [40,41]:

$$\begin{cases} 0 \leq g_{i,t} \leq G_i \\ \lambda_{\mathrm{g},i} O_{\mathrm{g},i,t} \leq g_{i,t} \leq O_{\mathrm{g},i,t} \\ O_{\mathrm{g},i,t} = O_{\mathrm{g},i,t} + g_{i,t}^{\mathrm{on}} - g_{i,t}^{\mathrm{off}} \\ -\alpha_{\mathrm{g},i}^{\mathrm{dn}} G_i \leq g_{i,t} - g_{i,t-1} \leq -\alpha_{\mathrm{g},i}^{\mathrm{up}} G_i \\ \sum_{\tau=1}^{T_{\mathrm{on}}} g_{i,t-\tau}^{\mathrm{on}} \leq O_{\mathrm{g},i,t} \leq G_i - \sum_{\tau=1}^{T_{\mathrm{off}}} g_{i,t-\tau}^{\mathrm{off}} \end{cases} \tag{24}$$

where $\alpha_{\mathrm{g},i}^{\mathrm{dn}}$ and $\alpha_{\mathrm{g},i}^{\mathrm{up}}$ are, respectively, the climbing rate and the climbing rate of the i thermal power unit; $O_{\mathrm{g},i,t}$ is the total online capacity of the i thermal power unit at time t; $\lambda_{\mathrm{g},i}$ denotes the lower limit of output of the i thermal power unit; $g_{i,t}^{\mathrm{on}}$ and $g_{i,t}^{\mathrm{off}}$, respectively, refers to the unit capacity increase and decrease in the i thermal power unit at time t; $T_{\mathrm{on}}$, $T_{\mathrm{off}}$, respectively, indicates the shortest time interval between on and off.

Hydropower unit constraints are as follows [40,41]:

$$\begin{cases} 0 \leq h_{i,t} \leq \mu_i H_i \\ -\alpha_{\mathrm{h},i}^{\mathrm{dn}} H_i \leq h_{i,t} - h_{i,t-1} \leq \alpha_{\mathrm{h},i}^{\mathrm{up}} H_i \\ 0 \leq \sum_{t=1}^{N_{\mathrm{m}}} h_{i,t} \leq E_{\mathrm{h},i}^{\mathrm{m}} \end{cases} \tag{25}$$

where $\mu_i$ is the monthly maximum upregulation capacity coefficient of hydropower $i$; $H_i$ is the rated capacity of hydropower i in the target year; $N_{\mathrm{m}}$ is the monthly total time period; $E_{\mathrm{h},i}^{\mathrm{m}}$ is the monthly available power generation of hydropower $i$ affected by monthly incoming water; $\alpha_{\mathrm{h},i}^{\mathrm{dn}}$ and $\alpha_{\mathrm{h},i}^{\mathrm{up}}$ are the upward adjustment and downward adjustment speed of hydropower $i$.

The output constraints of wind power and photovoltaic are as follows:

$$\begin{cases} 0 \leq w_t \leq w_{\mathrm{w},t} W \\ 0 \leq p_t \leq w_{\mathrm{p},t} P \end{cases} \tag{26}$$

where $w_{\mathrm{w},t}$ and $w_{\mathrm{p},t}$ are, respectively, the normalized predicted power coefficient of the wind-solar electric field at time $t$, that is, the power generation capacity of the unnormalized electric field.

The section power flow constraint is as follows:

$$-L \leq l_t \leq L \tag{27}$$

where $l_t$ is the section power and $L$ is the section power limit.

Load-side response constraints are as follows [40,41]:

$$\begin{cases} -d_{j,t}^{\text{zmax}} \leq d_{j,t}^{\text{z}} \leq d_{j,t}^{\text{zmax}} \\ 0 \leq d_{j,t}^{\text{f}} \leq d_{j,t}^{\text{fmax}} \\ \left| d_{j,t}^{\text{z}} \right| = 0 \end{cases} \tag{28}$$

where $d_{j,t}^{\text{zmax}}$ and $d_{j,t}^{\text{fmax}}$ are the maximum power values of transferable load and interruptible load, respectively.

The charge and discharge constraints of the energy storage system are as follows [40,41]:

$$\begin{cases} 0 \leq s_{i,t}^{\text{dis}}, s_{i,t}^{\text{cha}} \leq S_i \\ E_{\text{s},i,t} - E_{\text{s},i,t-1} = \eta_{\text{s},i} s_{i,t}^{\text{cha}} - s_{i,t}^{\text{dis}} / \eta_{\text{s},i} \\ 0 \leq E_{\text{s},i,t} \leq T_{\text{s},i} S_i \end{cases} \tag{29}$$

where $S_i$ is the rated capacity of the $i$ th energy storage system in the target year; $\eta_{\text{s},i}$ is the charging and discharging efficiency of the corresponding energy storage; $E_{\text{s},i,t}$ is the state of charge at the energy storage time $t$; $T_{\text{s},i}$ is the continuous charging and discharging time of the energy storage.

## 6. Case Study—Gansu Province as an Example

Taking Gansu Province as an example, this paper predicts the future installed capacity of Gansu Province based on the form evolution model and the planning objectives and economic and social development trends of the new power system construction action plan of Gansu Province. The forecast of installed power capacity and construction cost of Gansu Province from 2030 to 2060 is shown in Tables 1 and 2.

**Table 1.** Forecast on the development of power source installed capacity in Gansu.

| Power Supply/Year | 2030 | 2040 | 2050 | 2060 |
|---|---|---|---|---|
| Coal power | 3854 | 4509 | 4509 | 4509 |
| Hydroelectric | 1050 | 1050 | 1050 | 1050 |
| Pump storage | 780 | 1300 | 1800 | 1800 |
| Stored energy | 1124 | 1732 | 5417 | 9510 |
| Wind power | 7624 | 9246 | 12,947 | 14,570 |
| Solar power | 6969 | 10,081 | 15,725 | 21,505 |
| Total | 21,401 | 27,918 | 41,448 | 52,944 |

Unit: million kilowatts.

**Table 2.** Construction cost of the sources.

| Power Supply/Year | 2030 | 2040 | 2050 | 2060 |
|---|---|---|---|---|
| Coal power | 3500 | 3500 | 3500 | 3500 |
| Hydroelectric | 15,000 | 20,000 | 25,000 | 30,000 |
| Pump storage | 6300 | 6500 | 6700 | 6900 |
| Stored energy | 7200 | 6000 | 5000 | 3000 |
| Wind power | 7000 | 6500 | 6000 | 5500 |
| Solar power | 4600 | 4000 | 3500 | 3000 |

Unit: CNY/kW.

As can be seen from the table, the installed capacity of coal power will peak in 2040, hydropower will reach the maximum installed capacity of 10.5 million kilowatts in 2030 due to the limitation of resource endowment, and pumped storage will be fully developed in 2050 with an installed capacity of 18 million kilowatts. The installed capacity of energy storage, photovoltaic, and wind power continues to grow, and by 2060, the proportion of new energy installed capacity will increase to 68.14%.

On this basis, the annual utilization time of various power supplies can be obtained through production operation simulation, as shown in Table 3.

**Table 3.** Annual utilization hours of power sources.

| Power Supply/Year | 2030 | 2040 | 2050 | 2060 |
|---|---|---|---|---|
| Coal power | 4543.30 | 4724.13 | 3693.58 | 3120.50 |
| hydroelectric | 3828.68 | 3865.23 | 3770.02 | 3704.58 |
| Energy storage (including extraction and storage) | 1873.16 | 1899.90 | 2417.67 | 2640.37 |
| Wind power | 1876.52 | 1824.69 | 1750.87 | 1693.91 |
| Solar power | 1484.84 | 1435.06 | 1383.34 | 1331.93 |

As can be seen from the table, in terms of annual utilization hours, with the increase in the proportion of new energy and energy storage, the start-up time of thermal power units is gradually compressed, the utilization time of energy storage is gradually increased, and the annual utilization hours of hydropower, wind power, and photovoltaic are slightly decreased.

On this basis, considering the changing trend of construction cost and operation cost of different types of power supply in the future, based on the electricity price calculation model, the corresponding changing trend of electricity price cost of different types of power supply and power grid in Gansu Province is given. The results are shown in Figures 1–6.

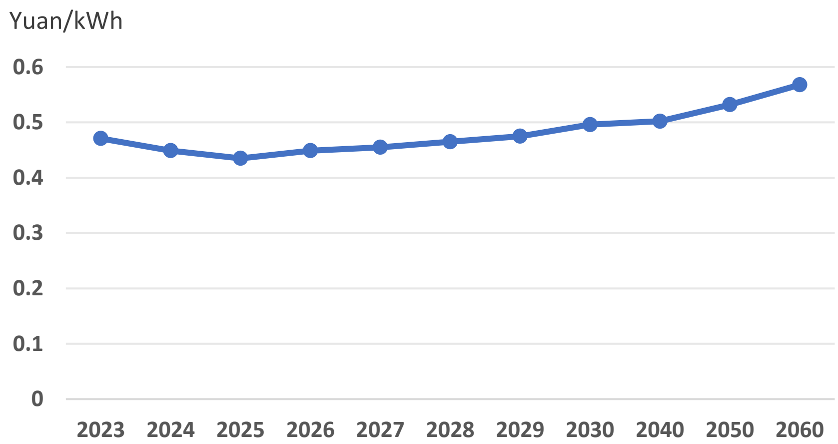


**Figure 1.** Trend of coal electricity costs in Gansu Province.

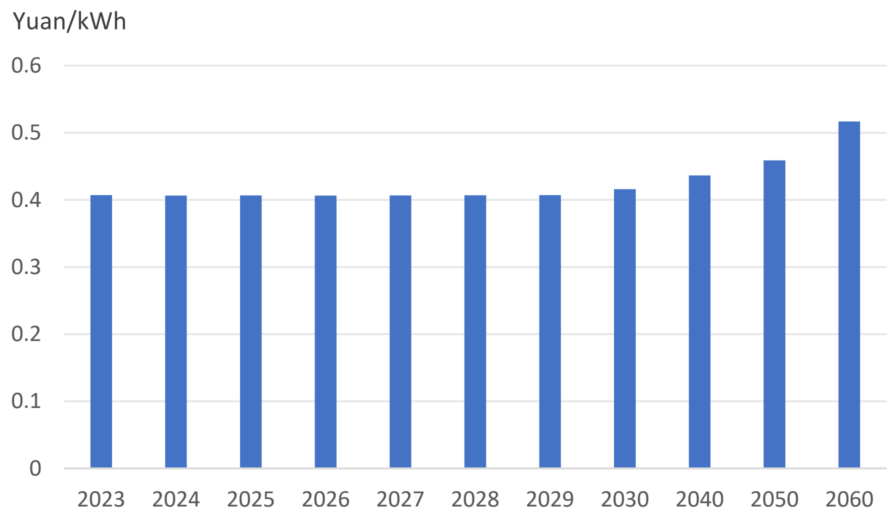


**Figure 2.** Trend of wind power costs in Gansu Province.

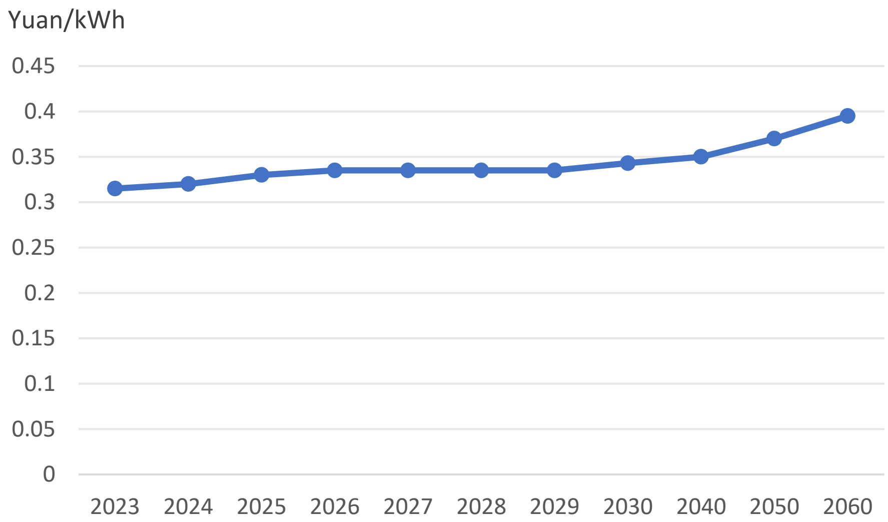


**Figure 3.** Trend of solar power costs in Gansu Province.

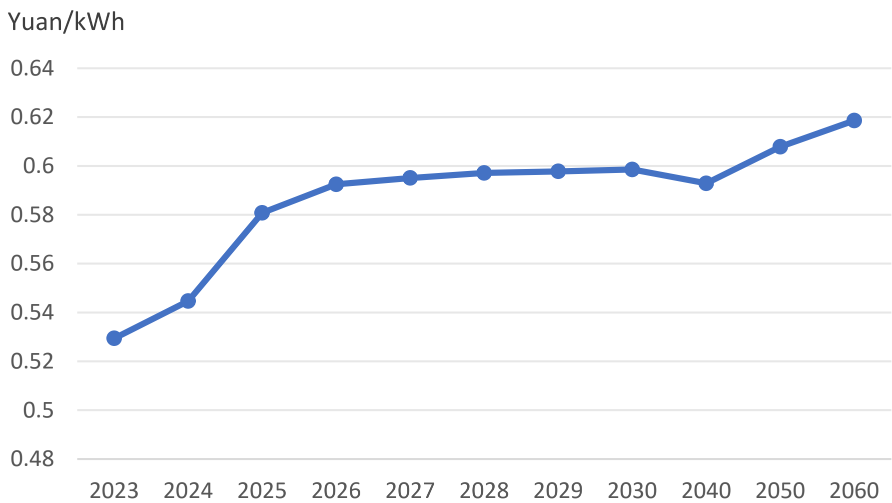


**Figure 4.** Trend of hydropower costs in Gansu Province.

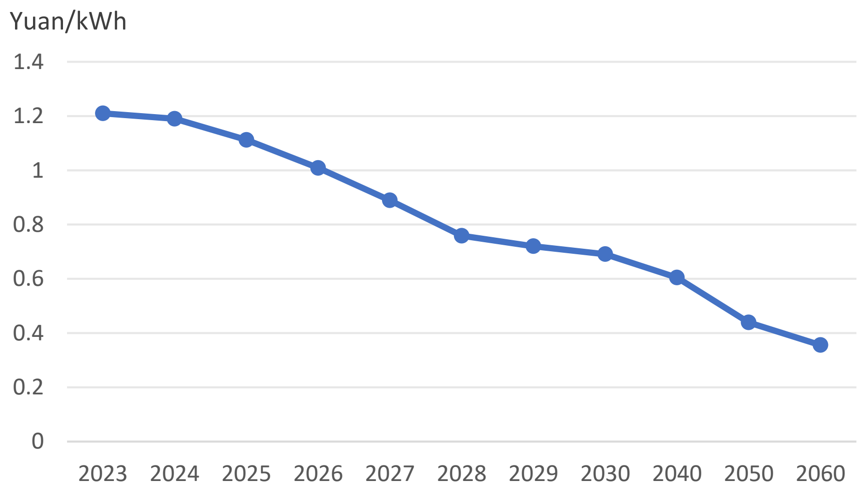


**Figure 5.** Trend of energy storage system costs in Gansu Province.

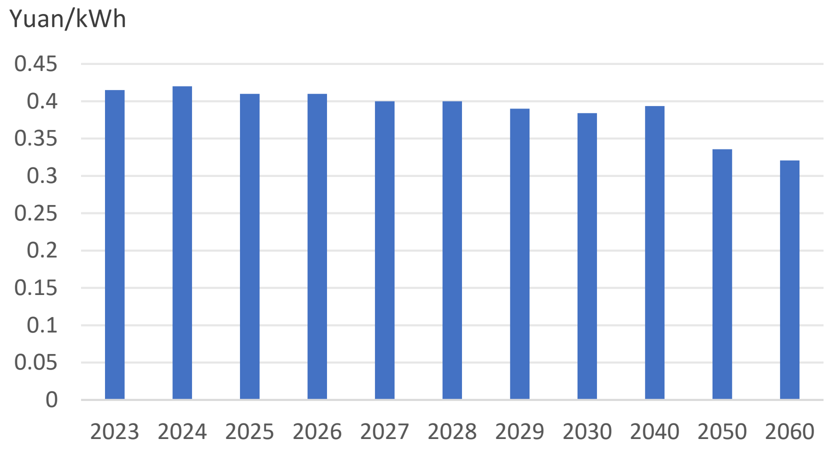


**Figure 6.** Trend of pumped hydro costs in Gansu Province.

The changing trend of coal power costs in Gansu Province is shown in Figure 1.

For coal-fired power generation units, due to the decline in the number of annual utilization hours, the future price of thermal coal may rise, inflation factors and coal power flexibility transformation cost input and other factors, the cost of coal electricity shows a continuously rising trend.

The changing trend of wind power costs in Gansu Province is shown in Figure 2.

In order to meet the load demand of small generation, the installed capacity of wind power will be greatly increased, resulting in a decline in the utilization rate of wind turbines, which will lead to an increase in the cost of wind power.

The changing trend of solar power costs in Gansu Province is shown in Figure 3.

The cost trend of photovoltaic power generation is broadly consistent with that of wind power, and the reasons behind the impact are similar.

The changing trend of hydropower costs in Gansu Province is shown in Figure 4.

Because the hydropower resources that are easy to develop have been utilized, the development of the remaining hydropower resources is more difficult, the development cost is higher, and the comprehensive electricity cost of hydropower is on the rise.

The changing trend of energy storage system costs in Gansu Province is shown in Figure 5.

With the large-scale application of energy storage in the future, the cost shows a downward trend, mainly for three reasons: first, the expansion of energy storage scale, the scale effect brings the reduction of production and construction costs; second, the energy management technology is continuously optimized, and the battery life may be increased to more than 10 years; and, third, new battery material technology has made breakthroughs, and raw material costs are expected to decrease significantly.

The changing trend of pumped hydro costs in Gansu Province is shown in Figure 6.

As can be seen in Figure 7, the overall cost of pumped storage shows a downward trend. On the one hand, with the gradual reduction of excellent pumped storage resources, the cost of pumped storage is expected to increase gradually. On the other hand, the utilization rate of pumped storage will increase in the future to reduce costs.

The power grid costs changing trend is shown in Figure 8. According to estimates, it is expected that the comprehensive electricity cost of the power side in Gansu Province will gradually rise. Before 2040, because the power supply structure in Gansu Province will not change much, the kWh cost will show a slower growth trend, and, after 2040, due to the acceleration of new energy and energy storage construction, the kWh cost will increase.

The terminal electricity price changing trend is shown in Figure 9. With the increase in the proportion of installed capacity and power generation of new energy in the future, investment in new energy transmission channels and networks continues to increase, but the utilization efficiency of new energy transmission and transmission channels gradually declines. At the same time, with the increase in the capacity of energy storage, especially pumped storage (through transmission and transformation capacity cost recovery investment), the transmission and transformation cost is further increased, but the overall change of electricity price on the grid side is small.

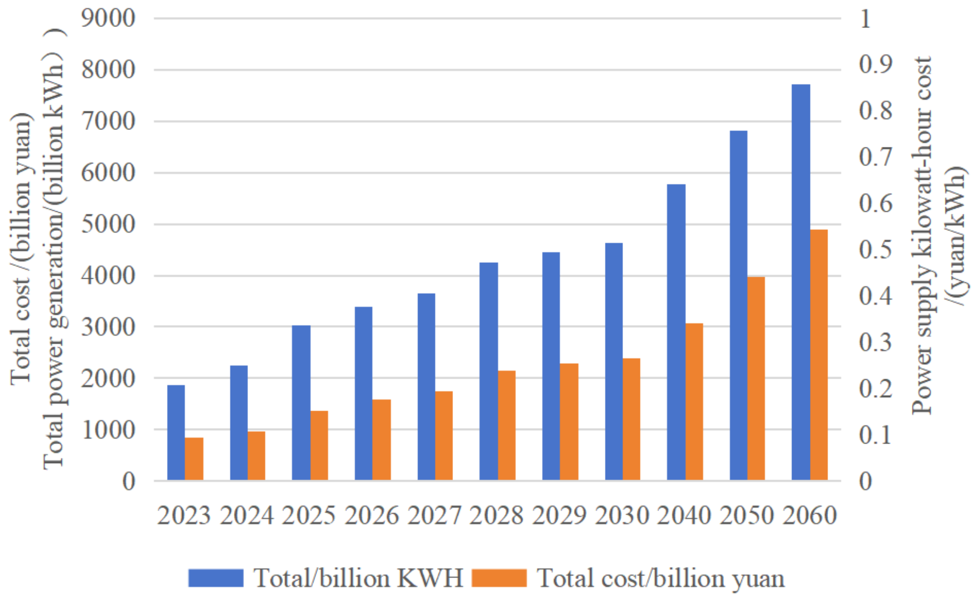


**Figure 7.** Trend of source side costs in Gansu Province.

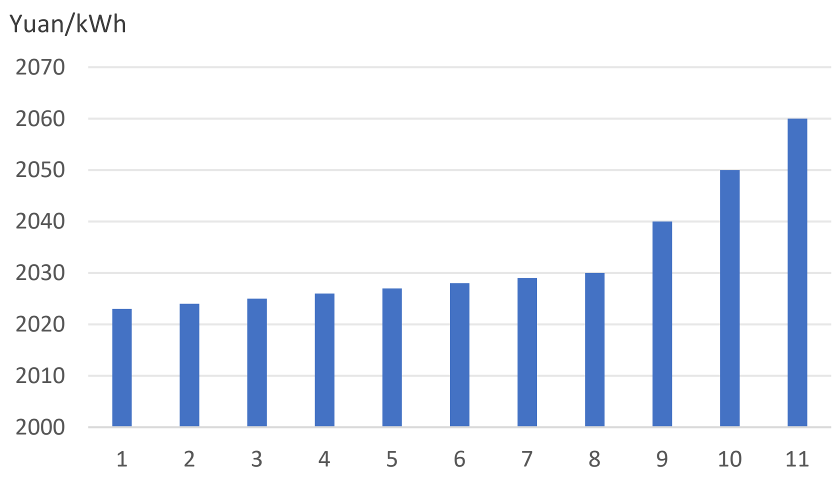


**Figure 8.** Trend of transmission and distribution costs in Gansu Province.

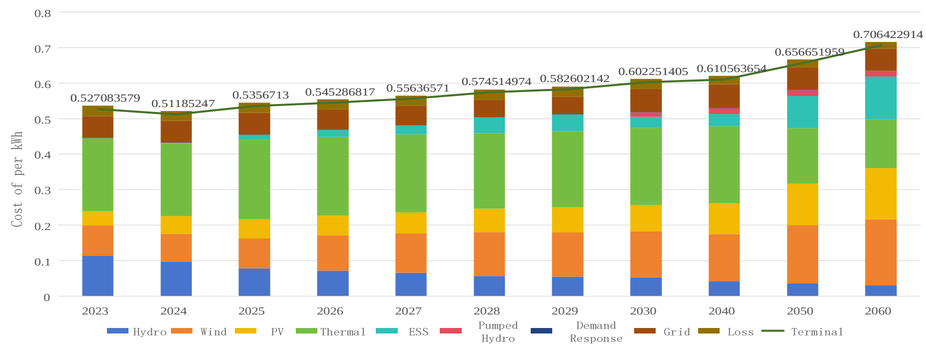


**Figure 9.** Trend of terminal cost and its components in Gansu Province.

As can be seen from the figure above, in the process of achieving the dual carbon goal, the overall kWh cost of the Gansu power system will show an upward trend.

## 7. Conclusions

Based on the development trend of electricity prices in Gansu Province during the period of carbon neutrality from the present stage to 2060, this paper predicts the future installed capacity of various types of power supply in Gansu Province through morphological evolution, analyzes the future power generation situation based on production and operation simulation, and analyzes the influencing factors of future electricity price from the power supply side and the grid side, and draws the following conclusions:

(1) In the future, the terminal electricity price of Gansu Province will show an overall rising trend. In the composition of the terminal electricity price, the proportion of wind power, photovoltaic, and energy storage will gradually increase, while the proportion of thermal power and hydropower will gradually decrease.
(2) In terms of the growth of electricity price, the main growth of electricity price comes from the power supply side, and the change of electricity price on the grid side is small.
(3) The prediction in this paper is based on the current technical and economic status quo. Due to the relatively long prediction time, considering that there may be breakthroughs in material science and energy utilization technology in the future, which will bring major innovations to the energy system, the prediction results in this paper are only for reference.

The calculation of future electricity price trends in Gansu can provide a reference for future power supply and power grid planning, and it can also provide a basis for future electricity price policy formulation to achieve a more scientific and economical industrial planning and energy system.

**Author Contributions:** Conceptualization, R.H. and X.W.; methodology, T.L.; software, J.Z.; validation, Y.J. and J.Q.; formal analysis, J.Q.; investigation, J.Z.; resources, T.L.; data curation, J.Z.; writing—original draft preparation, R.H.; writing—review and editing, X.W. and H.L.; visualization, T.L.; supervision, X.W.; project administration, R.H.; funding acquisition, R.H. All authors have read and agreed to the published version of the manuscript.

**Funding:** This paper was funded by the Major Science and Technology Special Project of Gansu Province, the Management Consulting Project of Economic and Technological Research Institute of Gansu Electric Power Company, State Grid (research on construction plan of new power system demonstration zone at typical regional level in Gansu Province), and the 10 key research projects of the State Grid Gansu Electric Power Company in 2023 (grants 22ZD6GA032, SGGSJY00XXWT2310040 and SGGSKY00BGJS2310273).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Data are contained within the article.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Zhang, N. China's new energy power generation has entered a new stage of affordable development. *New Energy Technol.* **2022**, *9*, 1–3.
2. Gao, Y.; Li, S.; Yan, X. Study on the Impact Trend of High-percentage Renewable Energy Access on Electricity Price Based on System Balance. *Water Power* **2023**, *49*, 91–95.
3. Ni, C.; Liu, X. Battery Capacity Configuration and Economic Analysis of Photovoltaics Energy Storage System. *Zhejiang Electr. Power* **2019**, *38*, 1–10.
4. Guo, X.; Huang, X.; Zhang, K.; Han, G.; Han, P.; Zhu, L. Research on Development Status and Price of Natural Gas Power Generation in China. *Zhejiang Electr. Power* **2020**, *39*, 109–117.

5. Shen, X.; Zou, B. Influence of Renewable Energy on Average Electricity rice and Peak Electricity Price. *Ind. Control Comput.* **2023**, *36*, 159–161.
6. Liu, J.; Li, L.; Wu, M.; Chen, H.; Chen, H. A two-stage optimal operation strategy for distributed pumped storage power plant and new energy power generation jointly participating in spot market. *Zhejiang Electr. Power* **2023**, *42*, 50–58.
7. Xiang, Z.; Tang, J.; Xu, L.; Gan, W.; Sun, L.; Yang, L. An optimization model of benchmark electricity price for coal fired power generation considering the uncertainty of carbon price and electricity price. *Zhejiang Electr. Power* **2023**, *42*, 59–65.
8. Yue, J.; Zhang, L. Research on Wind Power Economy Based on Operation Period Price and Externality. *Sci. Technol. Ind.* **2012**, *12*, 141–144+157.
9. Bai, Y.; Wang, X.; Li, X.; Gao, T. Economic and environmental benefits analysis of centralized PV power generation projects in ultra-high altitude areas. *Sol. Energy* **2023**, *10*, 21–29.
10. Zhang, Y.; Chen, N.; Huang, B.; Wang, C.X.; Li, J.T. Methodology for calculating VRE equivalent feed-In tariff based on system cost and its application. *Electr. Power* **2022**, *55*, 1–8.
11. Zhou, J.; He, Y.; Li, R.; Lu, Y.; Huang, C. Dynamic Incentive Mechanism for Transmission and Distribution Tariff Considering Energy Transition Development. *Power Syst. Technol.* **2023**, 1–10. [CrossRef]
12. Li, J.; Luo, X.; Zhu, X.; Li, C.; Jia, C.; Zhang, Z.; Huang, J.; Chen, P. Peak Regulation Control Strategy of Wind-Thermal-Storage Combined Based on Green Certificate-Carbon Trading Mechanism. *Electr. Power Constr.* **2023**, *44*, 11–20.
13. Liu, F.; Che, Y.; Tian, X.; Xu, D.; Zhou, H.; Li, Z. Cost Sharing Mechanisms of Pumped Storage Stations in the New-Type Power System: Reviewand Prospect. *J. Shanghai Jiaotong Univ.* **2023**, *57*, 757–768.
14. Yao, J.; Wang, M.; Zhao, H.; Li, X.; Li, F.; Xie, Q.; Xu, Q. Optimal Allocation of Pumped Storage Capacity in Local Power Grid Considering Cost Recovery. *Water Resour. Power* **2022**, *40*, 208–211+197.
15. Liu, Y.; He, Y.; Li, M.; Zhang, Y. Design of Price Market Linkage Mechanism and Economic Benefit Evaluation of Pumped Storage Power Station Under the Power Market Environment. *Modern Electr. Power* **2023**, *40*, 42–49.
16. Su, Y.; Zhou, M.; Wu, Z.; Liu, J.; Wang, X.; Zhou, Z.; Wu, J. Externality Theory Based Cost Sharing Mechanism of Grid Side Energy Storage. *Power Syst. Technol.* **2024**, *48*, 110–122. [CrossRef]
17. Ni, Y. *Research on the Technical and Economic Aspects of Multi-Form Energy Storage to Promote New Energy Consumption Paths*; Yanshan University: Qinhuangdao, China, 2021.
18. Lu, X.; Chen, S.; Nielsen, C.P.; Zhang, C.; Li, J.; Xu, H.; Wu, Y.; Wang, S.; Song, F.; Wei, C.; et al. Combined solar power and storage as cost-competitive and grid-compatible supply for China's future carbon-neutral electricity system. *Proc. Natl. Acad. Sci. USA* **2021**, *118*, e2103471118. [CrossRef] [PubMed]
19. Chen, H.; Gao, X.Y.; Liu, J.Y.; Zhang, Q.; Yu, S.; Kang, J.N.; Yan, R.; Wei, Y.M. The grid parity analysis of onshore wind power in China: A system cost perspective. *Renew. Energy* **2020**, *148*, 22–30. [CrossRef]
20. Vartiainen, E.; Masson, G.; Breyer, C.; Moser, D.; Román Medina, E. Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity. *Prog. Photovolt. Res. Appl.* **2020**, *28*, 439–453. [CrossRef]
21. Lee, C.Y.; Ahn, J. Stochastic modeling of the levelized cost of electricity for solar PV. *Energies* **2020**, *13*, 3017. [CrossRef]
22. Marqusee, J.; Becker, W.; Ericson, S. Resilience and economics of microgrids with PV, battery storage, and networked diesel generators. *Adv. Appl. Energy* **2021**, *3*, 100049. [CrossRef]
23. Bonkile, M.P.; Ramadesigan, V. Effects of sizing on battery life and generation cost in PV–wind battery hybrid systems. *J. Clean. Prod.* **2022**, *340*, 130341. [CrossRef]
24. Li, Q.; Duan, H.; Xie, M.; Kang, P.; Ma, Y.; Zhong, R.; Gao, T.; Zhong, W.; Wen, B.; Bai, F.; et al. Life cycle assessment and life cycle cost analysis of a 40 MW wind farm with consideration of the infrastructure. *Renew. Sustain. Energy Rev.* **2021**, *138*, 110499. [CrossRef]
25. Martinez, A.; Iglesias, G. Mapping of the levelised cost of energy for floating offshore wind in the European Atlantic. *Renew. Sustain. Energy Rev.* **2022**, *154*, 111889. [CrossRef]
26. Feng, R.; Wencheng, L. LSSA-BP-based cost forecasting for onshore wind power. *Energy Rep.* **2023**, *9*, 362–370. [CrossRef]
27. Johnston, B.; Foley, A.; Doran, J.; Littler, T. Levelised cost of energy, A challenge for offshore wind. *Renew. Energy* **2020**, *160*, 876–885. [CrossRef]
28. Ali, S.; Jiang, J.; Murtaza, G.; Khan, M. Influence of real earning management on subsequent dividend payout decisions and corporate returns: A case of developing economy. *Front. Environ. Sci.* **2022**, *10*, 882809. [CrossRef]
29. Adeyeye, K.A.; Ijumba, N.; Colton, J.S. A techno-economic model for wind energy costs analysis for low wind speed areas. *Processes* **2021**, *9*, 1463. [CrossRef]
30. Chen, Z.; Wang, J.; Huang, S.; Yang, Z.; Zheng, F. Analysis ofeffective assets of' power grid and relevant suggestions. *China Power Enterp. Manag.* **2021**, *22*, 51–54.
31. Ma, B.; Niu, X. Economic Evaluation of Wind-thermal-bundled Cross-regional Power Supply for Electric Heating. *Electr. Econ.* **2020**, *48*, 89–95.
32. Chen, H.; Tan, K.; Xi, S.; Yang, X.; Wang, J.; Wang, Z. A Model for Calculating Operation Period Cost of Offshore Wind Power. *Autom. Electr. Power Syst.* **2014**, *38*, 135–139. [CrossRef]
33. Ran, L.; Guo, J.; Yuan, T. Power System Operation Simulation of Large-Scale Energy Storage on New Energy Station. *Distrib. Energy* **2020**, *5*, 1–8.

34. Zhao, H.; Sui, Z. Cost Analysis and Comparison of Wind photovoltaic-thermalstorageIntegration Project Based on Lcoe. *Guangdong Electr. Power* **2023**, *36*, 39–46.
35. Zhang, Q.; Sui, L. Calculation Methods of Two step Hydropower Net Pricing. *Proc. CSU-EPSA* **2012**, *24*, 116–119.
36. Liu, Y.; Teng, W.; Gu, Q.; Sun, X.; Tan, Y.; Fang, Z.; Li, J. Scaled-up diversified electrochemical energy storage LCOE and its economic analysis. *Energy Storage Sci. Technol.* **2023**, *12*, 312–318.
37. Xu, R.; Zhang, J.; Liu, M.; Cao, C.; Cao, X. Analysis of life cycle cost of electrochemical energy storage and pumped storage. *Adv. Technol. Electr. Eng. Energy* **2021**, *40*, 10–18.
38. Wang, Y.; Wang, K.; Wang, X.; Zhao, Z.; Yu, T.; Feng, M.; Huang, J.; Yang, N. Life Cyele Cost Modeling, Estimation and System Development of Pumped Storage Units. *Electr. Power Inf. Commun. Technol.* **2023**, *21*, 71–77.
39. Sun, Q.; Zhang, C.; Li, C.; You, P.; Gao, X.; Zhao, Q.; Xu, Z.; Liu, S.; Li, Y. Prediction of Power System Cost and Price Level Under the Goal of Carbon Peak and Carbon Neutralization. *Electr. Power* **2023**, *56*, 9–16.
40. Ren, D.; Xiao, J.; Hou, J.; Du, E.; Jin, C.; Zhou, Y. Wide-Area Power System Generation-Transmission-Storage Coordinated Planning Method Based on Multiple Flexibility Constraints and Time-Series Simulation. *Electr. Power* **2022**, *55*, 55–63.
41. Ren, D.; Jin, C.; Hou, J.; Xiao, J.; Du, E.; Zhou, Y. Planning Model for Renewable Energy with Energy Storage Replacing Thermal Power Based on Time Series Operation Simulation. *Electr. Power* **2021**, *54*, 18–26.