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Evaluation of Environmental and Economic Integrated Benefits of Photovoltaic Poverty Alleviation Technology in the Sanjiangyuan Region of Qinghai Province

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Abstract: Low-carbon energy technology is the most fundamental way to control carbon emissions. The Sanjiangyuan region in Qinghai Province must put environmental conservation in first place during development, because of its important function of national ecological protection. The comprehensive benefits of photovoltaic technology in this area need to be evaluated. In this paper, a new multicriteria decision model (MCDM) is established, with the four dimensions of "environment-society-economy-population", and 16 specific indicators are developed by combining the coupling coordination degree (CCD) and the decision-making trial and evaluation laboratory (DEMATEL) method. MCDM can contribute to screening out key indicators that should be of high concern. The evaluation results show that the four dimensions of "environment-society-economy-population" in the Sanjiangyuan region are highly correlated, and the PPAT is creating a coordinated development; the elements of population and environment play a decisive role in the comprehensive benefits based on five key indicators and three indicative indicators. The paper provides suggestions for the local government to further implement the PV poverty alleviation industry, under the condition that the natural environmental capacity of the region and the natural ecosystem are fully respected and undisturbed.

Keywords: photovoltaic poverty alleviation technology (PPAT); comprehensive benefits; coordinated development; coupling coordination degree (CCD); analysis

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1. Introduction

In response to climate change, the greatest threat to humanity, a low-carbon economy has become the consensus and trend of global economic development [1]. At the Global Climate Ambition Summit on 12 December 2020, China indicated the specific arrangements for China's carbon peaking: by 2030, China's CO_2 emissions per unit of GDP will drop by more than 65% compared to 2005, the share of non-fossil energy in primary energy consumption will reach about 25%, forest accumulation will increase by 6 billion cubic meters compared to 2005, and the total installed capacity of wind and solar power generation will reach more than 1.2 billion kW. The development of carbon-free or low-carbon energy technologies is the most fundamental way to control carbon emissions [2], and it can contribute to both economic development and environmental protection [3,4]. There has been considerable research on the development status, main features, and problems of low-carbon energy technologies in China [5–8]; the low-carbon energy industry has also made remarkable achievements in terms of global market share, scale of development and application, and level of technological innovation, and it makes more progress with each passing day.

Photovoltaic poverty alleviation technology (PPAT) is an industry derived from the combination of semiconductor technology and low-carbon energy technology, a means to achieve regional industrial poverty alleviation through energy conversion, emerging rapidly not only in developed regions such as Europe, America, and Japan, but also in the Middle East, South America, and other regional countries. As one of China's strategic emerging industries, the photovoltaic industry has developed into an industry in which China can participate in international competition and achieve a leading edge. Numerous academic studies on the current status, policies, and challenges of PV technology development have been conducted at home and abroad, highlighting the potential problems of PV development and the need for long-term monitoring and maintenance [9,10], and countries and regions such as Ghana [11], South Africa [12], Bangladesh [13], India [14], and South Korea [4] have conducted analyses of the linkages between PV technology and poverty reduction.

2. Materials and Methods

2.1. Overview of China's PPAT

Photovoltaic power generation is clean and environmentally friendly, with reliable technology and stable income, and it can be combined with agriculture and forestry to carry out a variety of "photovoltaic +" applications. Photovoltaic poverty alleviation should be carried out in areas with good light resource conditions according to local conditions, which is consistent with the national strategy of precise poverty alleviation and poverty eradication, as well as the national strategy of clean and low-carbon energy development; it is conducive to expanding the market of photovoltaic power generation and promoting the stable income of the poor, with the dual characteristics of poverty alleviation and energy conservation and emission reduction.

In October 2014, the National Energy Administration and the State Council Poverty Alleviation Office jointly issued a *Notice on the Organization of Photovoltaic Poverty Alleviation Project Pilot Work*, for Anhui, Hebei, Shanxi, Gansu, Ningxia, Qinghai, and other six provinces and regions, taking a total of 30 counties into the pilot scope. As one of the top 10 projects for precise poverty alleviation, the state formulated a package of financial and industrial support policies to promote the use of photovoltaic in poor areas nationwide [15,16]. From 2015 to 2020, the national PV poverty alleviation project construction scale developed rapidly, which is up to about 3GW per year, accounting for 20% of the national annual new PV power generation installed [17]. By 2020, China's annual PV power generation will be 260.5 billion kWh, accounting for about 3.5% of the country's total power generation, with a new grid-connected PV power generation capacity of 48.2GW and a cumulative grid-connected installed capacity of 253 GW (Figure 1), both of which are the first in the world [18].

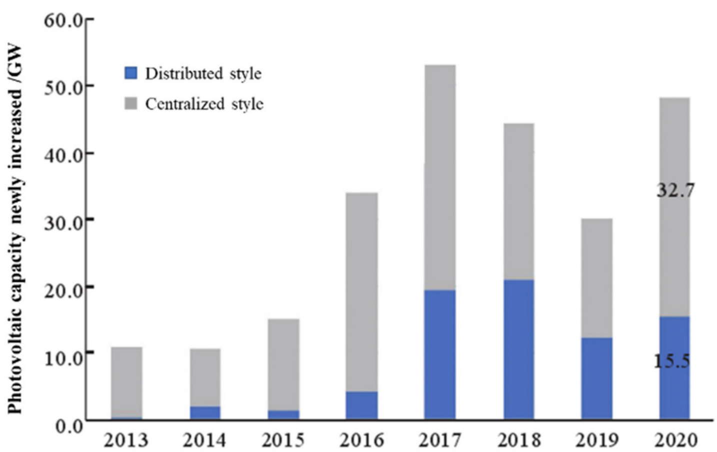


Figure 1. Photovoltaic capacity newly increased from 2013 to 2020 in China (CPIA, 3 February 2021).

China's development of photovoltaic poverty alleviation is mainly at the county level, the government and enterprises shall be the main body, and the poor families can also make contribution of funding. It is available to build photovoltaic power generation systems on agricultural land or on non-agricultural land such as poor households' own roofs, agricultural sheds, barren hills and slopes, river banks, etc., using the photoelectric conversion function of solar panels to convert renewable solar energy into electricity, and the generated electricity can be sold to the national grid at the prescribed price in addition to being used by poor households for their own use and production energy [19]. Farmers can not only get direct income, but also get the power generation subsidy and employment opportunity given by the state (Figure 2). Our local government shall integrate financial support for poverty alleviation and new energy subsidy policy, get the investment and construction of power station and continuous power generation income after operation, and at the same time reduce the energy cost of self-generated development in poor areas to achieve the comprehensive purpose of continuous improvement of people's livelihood, regional ecological environment, and climate improvement.

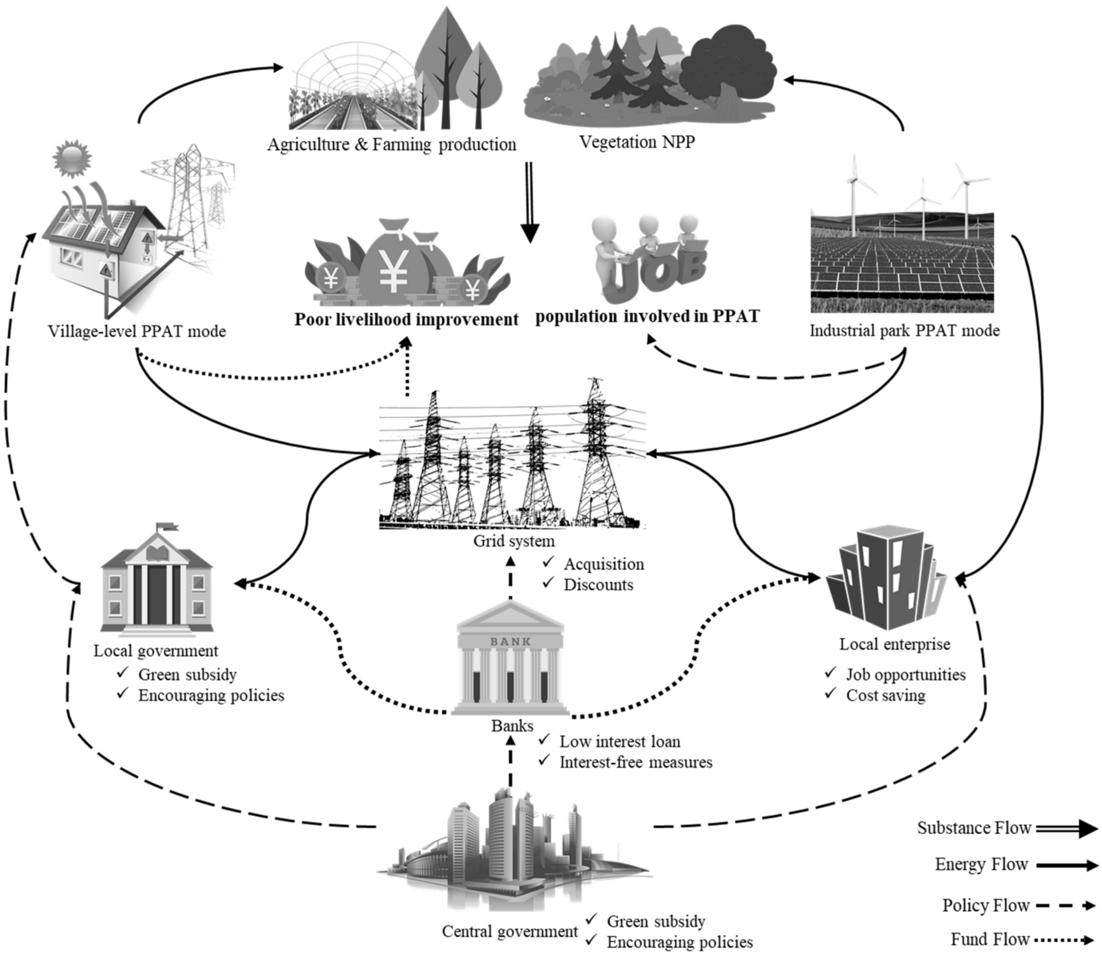


Figure 2. PPAT technique process in China.

There are three main construction modes of poverty alleviation power stations in projects: household PV power stations, centralized PV power stations, and village-level PV power stations. By the end of 2019, China built a total of 26.36 million kilowatts of photovoltaic power stations to alleviate poverty, benefiting 4.15 million households and generating an annual power generation revenue of about 18 billion yuan, of which village-level photovoltaic power stations were the main body with a rough number of 83,000, covering 92,300 villages in total, of which 59,800 are registered impoverished villages.

The implementation of China's photovoltaic poverty alleviation technology has made great achievements, but from the perspective of the overall life cycle of the project, it is still in the early stages of sustainable management and development, and the comprehensive effect of photovoltaic technology on poverty reduction, energy consumption reduction, and air pollution reduction has been recognized [20]. Some studies have analyzed the single benefits of PPAT, such as environmental benefits [21], risk level [22], economic benefits [23], and financial operation of the project, and the methods adopted, such as full-cycle evaluation and hierarchical analysis, can be used as reference for evaluation. However, to carry out the comprehensive benefit analysis of PPAT, more factors such as environmental, economic, social, and even regional ethnic culture need to be considered (Figure 2) [24,25], and a relatively complete set of comprehensive evaluation indexes should be formed under the sustainable perspective to evaluate the comprehensive benefits of project implementation through quantitative methods, which can help improve the scientific utilization of low-carbon energy technologies and enhance the endogenous development capacity of poor regions.

2.2. Comprehensive Benefit Evaluation Model of PPAT

In recent years, more and more project sustainability studies focus on the performance evaluation of environmental, economic, and social perspectives [26,27], and AHP-TOPSIS, factor analysis, and data network analysis (DEA) are commonly used to solve "energy-economy-environment" system interactions and multicriteria decision-making problems [28,29]. Most of the domestic studies were conducted to evaluate the coordination between the two dimensions of socio-economic and water environment quality [30–32] and socio-economic development and carbon emissions at urban and regional scales [33]. Some scholars also established the three dimensions of social, economic, and environmental in Shandong [34], Ningxia [35], and other places to carry out the evaluation of coordination; Xie [36] took the cultural dimension into account in the evaluation of the beautiful countryside.

Summarizing the existing research literature, it was found that there are still some gaps in coordination studies: (1) most evaluations only consider two dimensions (e.g., economic development and environmental quality), which limits the practicality of the research results; (2) limited by the available indicators, almost all studies focus on administrative divisions such as provinces and cities, while urbanization development makes the coordination results of the economic environment all show a gradual stabilization, and the evaluation results are roughly convergent; (3) PPAT has made great achievements, but it is still in the early stage in terms of operation cycle, it has not been put into use for a long time in various places, and there are uncertainties and lack of judgment and forecast in such aspects as insufficient management experience, reliance on subsidy policies, successive operation, and renewal.

The main research framework of this paper is shown in the figure below (Figure 3) and it consists of four main steps, as follows: Step 1: analyze the relationship between the development of PV industry on regional socio-economic and ecological environment (Figure 3) and define the index system (Table 1) according to the existing research literature and expert consultation. Step 2: propose a CCD-DEMATEL integration method to evaluate the comprehensive benefits of PPAT, establish the sub-dimensional development index (LDI) using the entropy weight method, and calculate the coupling coordination degree (CCD) of each dimension of regional development. Step 3: use the evaluation model to evaluate the comprehensive benefits of photovoltaic poverty alleviation technology in the Sanjiangyuan region; take every five years as an evaluation node; establish a time series from 2000 to 2020; combine statistical yearbooks, government work reports, fuzzy evaluations, questionnaires, and other ways to collect survey data; determine the standard weights; and calculate the sub-dimensional development trend and coupling coordination degree. Step 4: use the DEMATEL method to calculate the degree of influence of each factor on other factors and the degree of being influenced, screen the key factors with the highest contribution, predict the change trend of key factors by combining the variable laws of sub-dimensions, and make some suggestions.

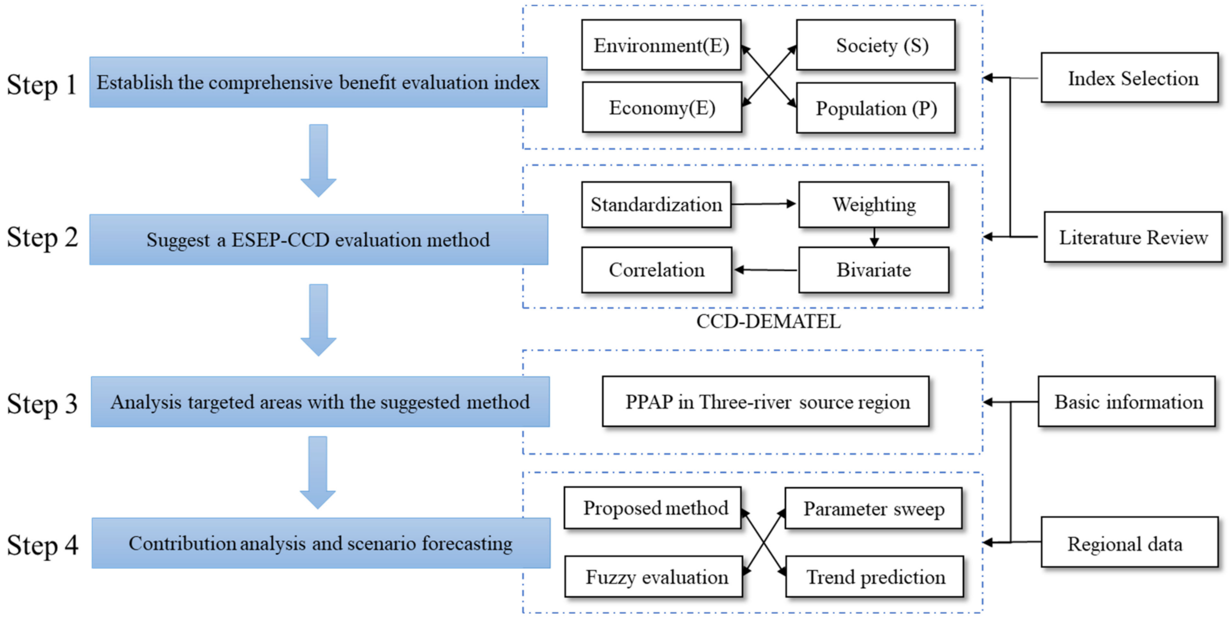


Figure 3. Research design to model spatiotemporal processes of local development.

Table 1. Comprehensive index system of PPAT benefits evaluation.

Dimension		Targets	Computing Method	Reference Sources
Environment (E_1)	T_1	Vegetation NPP (NPP)	Remote sensing estimating model	[37,38]
	T_2	Ecological Index (EI)	*MODIS-NDVI*	[39,40]
	T_3	Energy Consumption per capita	$\frac{Domestic\ Energy\ Amounts}{Regional\ population \times day}$	
	T_4	Air Quality Index	*Regional AQI Platform*	[41]
Society (S)	T_5	Proportion of the environmental protection subsidy in annual finance	$\frac{Eco-compensation\&subsidies\ income}{Annual\ financial\ revenue}$	[42]
	T_6	Ecological civilization policy support	$\frac{Number\ of\ ecological\ civilization\ policies}{policy\ Amounts}$	[41]
	T_7	Popularity of compulsory education	*Regional Statistical Yearbook*	statistical yearbooks
	T_8	Proportion of regional NCMS residents	$\frac{NCMS\ residents}{Annual\ regional\ total\ population}$	statistical yearbooks
Economy (E_2)	T_9	Per capita disposable income		statistical yearbooks
	T_{10}	Ratio of traditional energy		statistical yearbooks
	T_{11}	Per capita income of eco-industry		[42]
	T_{12}	Per capita income of PPAT		
Population (P)	T_{13}	Total population		statistical yearbooks
	T_{14}	Ratio of population involved in photovoltaic industry	$\frac{population\ involved\ in\ PPAT}{Annual\ regional\ total\ population}$	[43]
	T_{15}	Ratio of regional minority population	$\frac{minority\ population}{Annual\ regional\ total\ population}$	
	T_{16}	Ratio of regional ecological caretaker	$\frac{Number\ of\ ecological\ caretaker}{Annual\ regional\ total\ population}$	

2.2.1. Evaluation Index of the Comprehensive Benefits of PPAT

The regional application of PPAT involves various aspects such as energy, economy, and environment. From the perspective of external and internal environment, and taking into account the principles of scientific feasibility, systematic grading, static and dynamic grading, and qualitative and quantitative grading for index selection, the comprehensive benefit evaluation indexes are constructed as 4 primary indexes (E_1-S-E_2-P) and 16 secondary ones (T_n), as shown in Table 1.

- Environment (E_1)

PPAT is aimed at reducing fossil fuel consumption and greenhouse gas emissions, and it is both "green" and "low carbon" in its environmental friendliness. Solar energy is clean, non-polluting, and noiseless, largely reducing the carbon dioxide produced by traditional thermal power generation. The implementation of PPAT in the Henan Province alone led to the shutdown of a total of more than 60 million tons of coal production capacity from 2018 to 2020, the completion of "double replacement" transformation of 4.43 million households for clean heating, and the realization of centralized heating and clean transformation in 183 industrial clusters, thereby dramatically reducing regional carbon emissions [44]. At the same time, photovoltaic power plants have less impact on the surrounding environment during the construction process, and landforms, soil, and vegetation are restored in accordance with national regulations after the completion of the construction. Some studies show that the construction of photovoltaic power plants in the arid and semi-arid regions of China has a greater promotion effect on the soil and vegetation ecosystem than the negative effects brought about by it [45].

- Society (S)

This dimension tends to analyze the interaction between government policies and PPAT, and the latter has advantages of promoting regional poverty alleviation, compulsory education, medical benefits, etc. It has enormous potential to integrate with industries such as construction, engineering, agriculture, transportation, rural industries, and ecological environment, to realize the complementary development between storage/agriculture/forestry/fishery and PV, to provide villagers with a long-term, stable, and high-income guarantee, and to combine poverty alleviation with raising individual's will and wisdom.

- Economy (E_2)

The establishment of solar photovoltaic power plants reduces the electricity expenses of poor households while increasing employment opportunities for local villagers and boosting local economic growth. Clean and environmentally friendly solar power generation is very friendly to the environment, and village-level photovoltaic power stations can provide energy for the development of agriculture, animal husbandry, and fishery industries in rural areas, reducing the use of traditional energy fuels and saving the production and living costs of local residents. The central and local governments and banks at all levels actively promote photovoltaic poverty alleviation policies, providing low-interest or even interest-free loans to residents, and guiding them to invest in ecological industries. Local residents can also receive income dividends from photovoltaic power generation to continuously improve their income levels.

- Population (P)

This dimension pays more attention to the characteristics of population size and ethnic composition in the Sanjiangyuan region, and the role of PPAT plays in the development and career choice of local residents. The rapid development of photovoltaic technology for poverty alleviation in the Sanjiangyuan region of Qinghai Province does not change the national belief and living habits of local residents, but it helps to restore pasture vegetation and creates more ecological caretaker positions, facilitating the life of herders and contributing to the inheritance and development of traditional ethnic culture.

PPAT provides an important technical path for sustainable development in the Sanjiangyuan region of Qinghai Province. However, PPAT still face such problems as over-reliance on subsidies, high initial costs, and operation/maintenance problems [46]. Effective sustainability assessments for projects can help to improve scientifically sound decision making and contribute to the benign development of low-carbon energy technologies.

2.2.2. Comprehensive Benefit Evaluation Model of PPAT

The synergetic theory was proposed by the German physicist Professor Hermann Hacken in 1971, who argued that the occurrence of a phase transition in a system is determined by the control parameters of the system, and that the direction of the system depends on the synergy of the internal variables when the system is in the critical region; Norgaad's theory of coordinated development suggests that through feedback loops [47], co-development can be achieved between social and ecological systems, resulting in a well-coordinated, harmonious, and virtuous cycle of relationships and dynamics between systems or system elements.

The main methods used are as follows:

- Data Standardization

There is an interactive relationship between the dimensions of PV industry and local development, which may have a positive (PE) or negative (NE) influence. Figure 4 shows the interactive relationship between dimensions, and the annual data of the indicators are standardized [48–50] with equations as follows (Equations (1)–(8)):

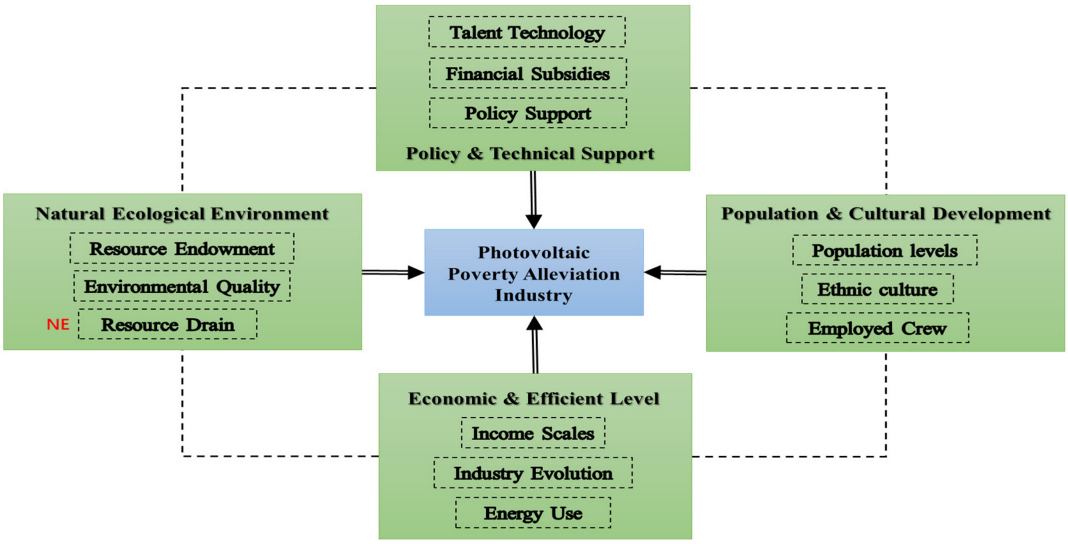


Figure 4. Relationships between dimensions of the local development.

In Equation (1), j is the indicator term, x_{ijt} is the performance value of each indicator at the year(t), and Z_{ijt} is the matrix of standard values of all performance values of all indicators in t years, if the evaluation indicators are divided into 4 dimensions, i.e., d = {1, 2, 3, 4}.

$$Z_{ijt} = \begin{cases} \frac{x_{ijt} - \min\limits_{it}[x_{ijt}]}{\max\limits_{it}[x_{ijt}] - \min\limits_{it}[x_{ijt}]}, x_j \; as \; a \; stimulant \\ \frac{\max\limits_{it}[x_{ijt}] - x_{ijt}}{\max\limits_{it}[x_{ijt}] - \min\limits_{it}[x_{ijt}]}, x_j \; as \; a \; destimulant \\ for \; standard \; value \; calculation \end{cases} \quad Z_{ijt} \in [0, 1] \tag{1}$$

- Entropy Weight Method to CI

The entropy weight method [51,52] is mainly used in the evaluation of development coordination to distinguish the degree of influence of each indicator, which has greater objectivity compared with subjective assignment methods such as the Delphi method and AHP.

$$P_{ijt}^{d} = \frac{\left(Z_{ijt}^{d}+1\right)}{\sum_{t=1}^{T}\sum_{i=1}^{i}(Z_{ijt}^{d}+4)}\ for\ Indicator\ entropy\ weighting \tag{2}$$

$$H_{j}^{d} = -\frac{1}{\ln T_m}\sum_{t=1}^{T}\sum_{i=1}^{m}P_{ijt}^{d}\times \ln P_{ijt}^{d}\ for\ Indicator\ entropy\ calculation \tag{3}$$

$$w_{j}^{d} = \frac{H_{j}^{d}-1}{\sum_{j=1}^{jd}\left(H_{j}^{d}-1\right)}\ for\ Indicator\ weight\ setting\ formula \tag{4}$$

$$w_{j}^{d} \in [0,\ 1], \sum_{j=1}^{m}w_{j}^{d} = 1$$

- Sub-Dimensional Composite Development (LDI) of Index CI

After the weights are determined, the composite development index of each dimension '*d*' can be calculated according to Equation (5). T is the composite coordination index of the composite system (Equation (6)); α, β, γ, and δ are the weights of each dimension, and the sum of each weight is 1. It is necessary to estimate the consistent contribution of each dimension to the balanced development of the region, the value of each weight is set to 1/4, and we can further calculate the coupling degree C between the composite systems using the method of Equation (7).

$$CI_{m}^{d} = \sum_{j=1}^{m}w_{j}^{d}\times Z_{ijt}, \sum_{j=1}^{m}w_{j}^{d} = 1\ for\ LDI \tag{5}$$

$$T = \alpha CI_{m}^{1} + \beta CI_{m}^{2} + \gamma CI_{m}^{3} + \delta CI_{m}^{4}\ for\ Comprehensive\ coordination\ index \tag{6}$$

$$C = 4\left[\frac{CI_{m}^{1}\times CI_{m}^{2}\times CI_{m}^{3}\times CI_{m}^{4}}{\left(CI_{m}^{1}+CI_{m}^{2}+CI_{m}^{3}+CI_{m}^{4}\right)^{4}}\right]^{\frac{1}{4}} C \in [0,\ 1]\ for\ System\ Coupling\ Degree \tag{7}$$

$$CCD = \sqrt{C\times T} CCD \in [0,\ 1] \tag{8}$$

The estimated coupling degree *C* and *CCD* values are between 0 and 1. The closer the *CCD* value is to 1, the more coordinated the regional development is [53]. Through combing the literature and considering the needs of the analysis [36,54–56], this paper roughly divides the *CCD* values into six ranges in Table 2 to measure the degree of dimensional coordination.

Table 2. Coupling coordination evaluation level.

Coupling Coordination Degree	Synergy Development Level
$0.00 \le CCD < 0.25$	Severe disorder
$0.25 \le CCD < 0.50$	On the verge of disorder
$0.50 \le CCD < 0.70$	Primary synergy
$0.70 \le CCD < 0.80$	Medium synergy
$0.80 \le CCD < 0.90$	High synergy
$0.90 \le CCD < 1.00$	Coordinated development

2.2.3. Evaluation of the Contribution of the Index

MCDM evaluation is considered to be a useful method for estimating the relationship between elements within a system. The decision-making trial and evaluation laboratory method (DEMATEL) is a method proposed by the Battelle Institute for solving integrated problems [57], and it is widely used in supply chain management and complex management decisions to calculate the extent to which each factor influences and is influenced by other factors [58]. Therefore, this paper uses the DEMATEL method to calculate the degree of influence and the degree of being influenced by each PPAT factor on other factors, to calculate the centrality and causes of each factor, and to determine the relationship between each factor and its important factor evaluation.

- DEMATEL Implementation Steps

Based on the previous analysis, the system of PPAT's impact factors on regional energy, economy, and environment was determined (Table 1), and the comprehensive impact matrix of each impact factor was analyzed, and the technical flow is shown in Figure 5.

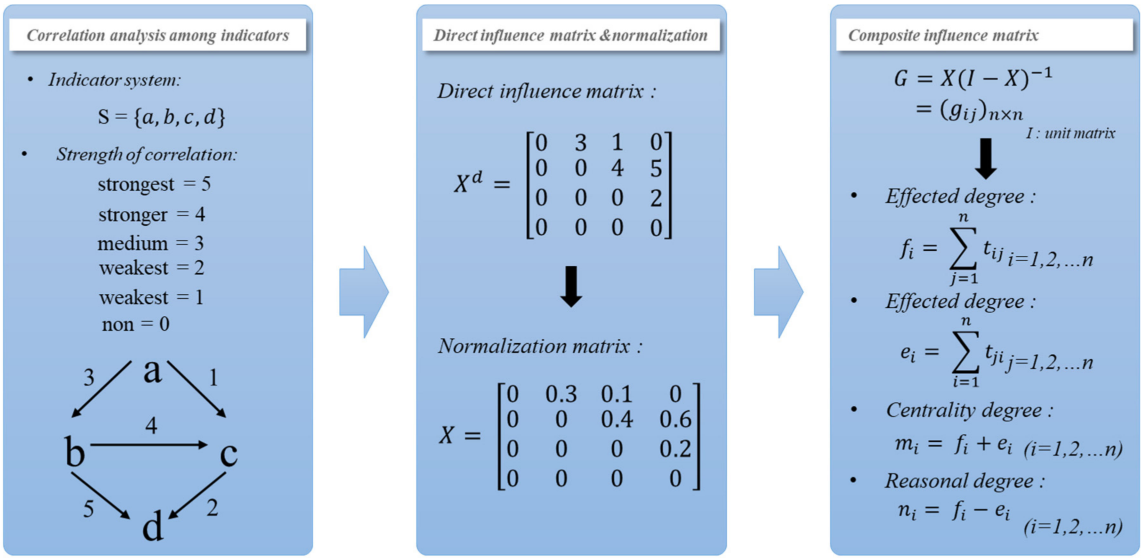


Figure 5. DEMATEL implementation steps.

If the cause degree is greater than 0, it means that the element has a great influence on other elements and becomes a cause factor; if the cause degree is less than 0, it is a result factor. Based on the centrality, the importance of each element in the PPAT comprehensive benefit evaluation system can be determined, the position of each element in the system can be determined according to the magnitude of the cause degree, and corresponding improvement measures can be proposed.

3. Results

The Sanjiangyuan region is located in the hinterland of the Qinghai–Tibet Plateau; it is the birthplace of the Yangtze, Yellow, and Lancang rivers in China, a typical representative of the Central Asian plateau and the world's alpine grasslands (Figure 6), the most concentrated area of plateau biodiversity, and one of the sensitive and important starting areas of climate change in Asia, the northern hemisphere, and even the world [58–60]. Located at 89°50′–99°14′ E and 32°22′–36°47′ N, it covers an area of about 120,000 square kilometers, involving 4 counties such as Zhiduo, Qumarlêb, Maduo, and Zadoi, 12 townships, and 53 administrative villages.

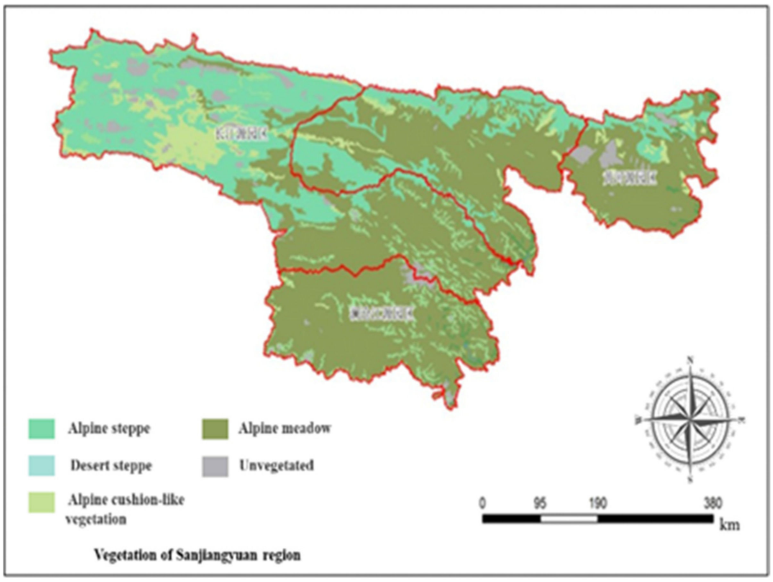


Figure 6. Feature of the Sanjiangyuan region.

In this research context, this paper aims to assess the following: (1) to view PV technology application as a transformation process of regional decarbonization development, and evaluate its comprehensive performance in conjunction with the time series of industrial implementation for dynamic evaluation and even prediction; (2) to take the Sanjiangyuan region, which bears important national ecological protection functions, as the object of evaluation, to consider the special ecological status, which determines that the socio-economic development of this area must take ecological environmental protection as a prerequisite, and investigate how the application of photovoltaic technology has a multifaceted impact on the ecological environment, social economy, and demographic development of the region. This paper combines time series (2000–2020), establishes a multidimensional coupled environmental, social, economic, and demographic coordination evaluation method (coupled analysis), and analyzes and foresees the relationship between PPAT development and the environmental, economic, and demographic development of the Sanjiangyuan region through quantitative methods and the fuzzy evaluation method. This paper also establishes the decision-making implementation and evaluation laboratory (DEMATEL) to evaluate the contribution of screening indicators to the comprehensive benefit assessment and explore ways to promote the coordinated development of PPAT and "E_1-S-E_2-P" in the Sanjiangyuan region.

3.1. Overview of the Development of the Sanjiangyuan Region

Qinghai Province, with an annual sunshine time of 2500 to 3650 h and a developable solar energy capacity of more than 3 billion kilowatts, has the unique advantage that photovoltaic poverty alleviation is by far the largest one-time investment, with the widest coverage, the highest rate of return, and the longest duration of a project to benefit the people. By the end of August 2020, the cumulative power generation of PV power stations for poverty alleviation in Qinghai Province was 2.14 billion kWh, with a total revenue of 1.605 billion yuan, the average village benefit of more than 400,000 yuan, and the highest of more than 1 million yuan; thus, 1622 poor villages in the province fully realized "breaking zero" for the collective economy of villages. The province's photovoltaic power stations take the agriculture and photovoltaic complementary mode and animal husbandry and photovoltaic complementary mode, and the ecology in the photovoltaic array area has been rapidly restored, so that the photovoltaic power station has also become high-quality pasture, leading to a specialty industry of "photovoltaic sheep".

Statistics show that, in 2015, the four counties in the Sanjiangyuan region had a total animal husbandry population of 128,000 and a poverty-stricken population of 39,000, with a significant increase in the intensity of human activities in the region between 2000 and 2007, and a slow increase in the intensity of human activities between 2007 and 2013. In 2013–2020, with the continuous construction of the national park pilot, human activities were concentrated in the vicinity of the counties of Zadoi and Qumarlêb. Maduo, Zadoi, and other counties, through the camping of village-level photovoltaic poverty alleviation power station, set up ecological custodian positions in Sanjiangyuan. Photovoltaic poverty alleviation technology can increase the average annual income of 320,000 yuan for poor villages, and the cumulative cash ecological public welfare job pays 16,500 people 910 million yuan, with per capita monthly wages of 1800 yuan and family annual benefits of 21,600 yuan. The four counties exited the poverty-stricken county list in 2019 and 2020.

3.2. Comprehensive Benefits Evaluation of PPAT

3.2.1. CCD Evaluation

The statistical yearbook of Qinghai Province, annual report on the construction of Three-River-Source National Park, statistical bulletin on national economic and social development of Yushu Tibetan Autonomous Prefecture, results of field research questionnaires, and other information and data were combined to collect the background information and data of the evaluation indexes. To reflect the development variables and trends, the 2000–2020 sequence was selected to form a total of five groups of annual basic data with five years as the time point.

Step 1: data processing was performed according to the *CCD* evaluation model and process to obtain the standard value matrix (Table 3), and the weights of each index were calculated according to the entropy weight method.

Table 3. Results of criteria and weights under the PPAT *CCD* Evaluation.

Dimension		Index	2000	2005	2010	2015	2020	w_j^d
D_1 Environment (E_1)	$Z^T{}_1$	Vegetation NPP (NPP)	0.1515	0.4848	0.0000	0.0909	1.0000	0.0631
	$Z^T{}_2$	Ecological Index (EI)	0.0000	0.0062	0.0062	0.5062	1.0000	0.0612
	$Z^T{}_3$	Energy Consumption per capita	0.0000	0.2247	0.4700	0.8974	1.0000	0.0615
	$Z^T{}_4$	Air Quality Index	0.1563	0.0000	1.0000	0.6563	0.5000	0.0628
D_2 Society (S)	$Z^T{}_5$	Proportion of the environmental protection subsidy in annual finance	0.3099	0.5915	0.0000	0.0845	1.0000	0.0628
	$Z^T{}_6$	Ecological civilization policy support	0.0000	0.1096	0.3014	0.6027	1.0000	0.0629
	$Z^T{}_7$	Popularity of compulsory education	0.0000	0.2857	0.4429	0.1857	1.0000	0.0642
	$Z^T{}_8$	Proportion of regional NCMS residents	0.0000	0.3200	0.6400	0.8800	1.0000	0.0619
D_3 Economy (E_2)	$Z^T{}_9$	Per capita disposable income	0.0000	0.1068	0.3439	0.6450	1.0000	0.0627
	$Z^T{}_{10}$	Ratio of traditional energy	0.8750	0.7500	1.0000	0.5000	0.0000	0.0621
	$Z^T{}_{11}$	Per capita income of eco-industry	0.0000	0.0877	0.1424	0.5077	1.0000	0.0629
	$Z^T{}_{12}$	Per capita income of PPAT	0.0000	0.0128	0.0513	0.1923	1.0000	0.0627
D_4 Population (P)	$Z^T{}_{13}$	Total population	0.0000	0.4048	0.6429	0.7143	1.0000	0.0632
	$Z^T{}_{14}$	Ratio of population involved in photovoltaic industry	0.0000	0.0031	0.1262	0.4154	1.0000	0.0626
	$Z^T{}_{15}$	Ratio of regional minority population	0.0000	0.1053	0.3158	0.5789	1.0000	0.0631
	$Z^T{}_{16}$	Ratio of regional Ecological caretaker	0.0000	0.0164	0.1311	0.7213	1.0000	0.0604

Step 2: Based on the comprehensive benefit evaluation model and the annual index data of the Sanjiangyuan region, the development index (*CI*) of the four dimensions of Environment (E_1), Society (S), Economy (E_2), and Population (P) was calculated (Figure 7), and the annual changes of the development index were used to analyze the development of the four dimensions over the years. Besides, the comprehensive coordination index (T), the system coupling degree (C), and the coupling coordination degree (*CCD*) were also obtained (Table 4).

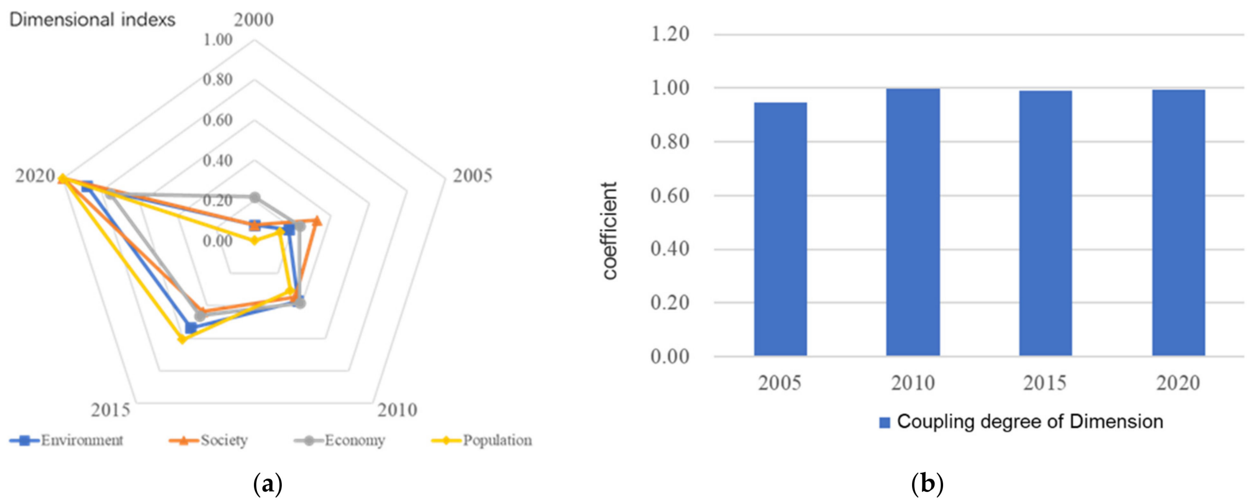


Figure 7. Results and relevance of the sub-dimensions in the Sanjiangyuan region: (**a**) the results of "E_1-S-E_2-P" increased linearly during the study period; and (**b**) the relevance of the four sub-dimensions—the four dimensions maintained between 0.9 and 1.0 since the PPAT was put into use, so the developments of "E_1-S-E_2-P" in the Sanjiangyuan region are highly correlated with each other.

Table 4. Results of the PPAT *CCD* evaluation.

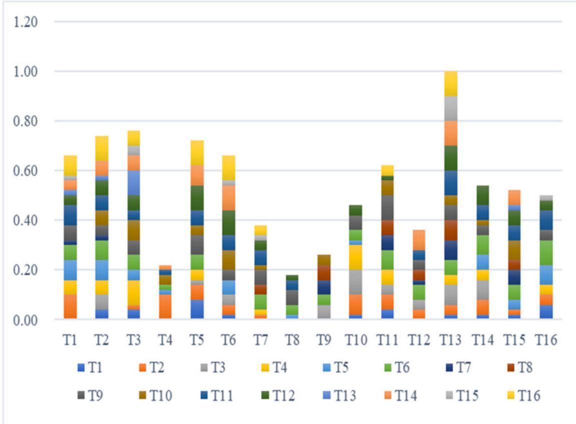
		2000	2005	2010	2015	2020
CI	CI_E	0.0779	0.1801	0.3706	0.5356	0.8736
	CI_S	0.0773	0.3264	0.3455	0.4354	0.9995
	CI_{Ec}	0.2171	0.2380	0.3828	0.4611	0.7519
	CI_P	0.0000	0.1340	0.3063	0.6067	0.9995
T		0.0931	0.2196	0.3513	0.5097	0.9064
C		0.0000	0.9474	0.9964	0.9915	0.9933
CCD		0.0000	0.4562	0.5916	0.7109	0.9488

3.2.2. DEMATEL Evaluation

Considering the objective of comprehensive benefit evaluation, a combination of field investigation, questionnaires, and expert scoring was used to compare and score the degree of interaction of the 16 indicators ($T_{1\text{-}16}$) in Table 1 on a two-by-two basis. The direct influence of each factor on the other ones was estimated based on the scoring results. A direct influence matrix M (Figure 8) was established between each influence factor, and this matrix was scaled using the assignment method (strong = 5, relatively strong = 4, moderate = 3, relatively weak = 2, weak = 1, no influence = 0).

	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	T_{13}	T_{14}	T_{15}	T_{16}
T_1	0	5	0	3	4	3	1	0	3	0	4	2	1	2	1	4
T_2	2	0	3	3	4	4	1	0	2	3	3	3	1	3	0	5
T_3	2	1	0	5	2	3	0	0	3	4	2	3	5	3	2	3
T_4	0	5	0	0	1	1	0	0	0	2	1	0	0	1	0	0
T_5	4	3	1	2	0	3	0	0	4	2	3	5	0	4	0	5
T_6	1	2	2	0	3	0	0	0	2	4	3	5	0	5	1	5
T_7	0	1	0	1	0	3	0	2	3	1	3	2	0	0	1	2
T_8	0	0	0	0	1	2	0	0	3	0	2	1	0	0	0	0
T_9	0	0	3	0	0	2	3	3	0	2	0	0	0	0	0	0
T_{10}	1	4	5	5	1	2	0	0	3	0	0	2	0	0	0	0
T_{11}	2	3	2	3	0	4	3	3	5	3	0	1	0	0	0	2
T_{12}	0	2	2	0	0	3	1	2	2	0	2	0	0	4	0	0
T_{13}	1	2	4	2	0	3	4	4	3	2	5	5	0	5	5	5
T_{14}	1	3	4	2	3	4	0	0	2	1	3	4	0	0	0	0
T_{15}	1	1	0	0	2	3	3	2	0	4	3	3	1	3	0	0
T_{16}	3	2	0	2	4	5	0	0	2	0	4	2	0	0	1	0

(**a**)



(**b**)

Figure 8. Matrix of the index's weights in the Sanjiangyuan region: (**a**) matrix M' is the normalized version of matrix M, showing the direct relation between alternatives; (**b**) matrix M″ is the elements of the direct and indirect relative severity matrix.

The integrated influence matrix was established based on the DEMATEL method, computing equations as follows Equations (1) and (2); the influence degree (f_i), influenced degree (e_i), central degree (m_i), and cause degree (n_i) between PPAT and each element of regional environmental and economic integrated benefits were obtained, as shown in Table 5.

$$m'_{ij} = \frac{1}{\alpha} m_{ij} \alpha = \max_{i=1} \left\{ \sum_{j=1}^{n} m_{ij} \right\} \tag{9}$$

$$G = M' + M'^2 + \cdots + M'^n = \frac{M'(I - M'^n)}{(I - M')} = M\prime (I - M')^{-1} \tag{10}$$

Table 5. PPAT: the integrated influence relationship of each evaluation factor.

Element	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}	T_{13}	T_{14}	T_{15}	T_{16}
f_i	1.43	1.60	1.63	0.53	1.50	1.41	0.74	0.36	0.52	0.98	1.22	0.77	2.03	1.19	1.09	1.10
e_i	0.80	1.46	1.17	1.20	1.10	1.89	0.63	0.64	1.57	1.22	1.53	1.58	0.33	1.27	0.39	1.32
m_i	2.22	3.06	2.81	1.73	2.60	3.30	1.37	1.00	2.09	2.20	2.75	2.35	2.36	2.47	1.49	2.42
n_i	0.63	0.14	0.46	−0.67	0.40	−0.49	0.11	−0.27	−1.05	−0.24	−0.31	−0.81	1.69	−0.08	0.70	−0.22

4. Conclusions

4.1. The Results of CCD Evaluation

Conclusion 1: according to the weight calculation result (Figure 9), the weights of the four dimensions can be ranked as: Society (S)>Economy (E_2) >Population (P) > Environment (E_1), which initially shows that the implementation of PPAT in the Sanjiangyuan region will have a more obvious effect on local socio-economic promotion than population and environmental improvement.

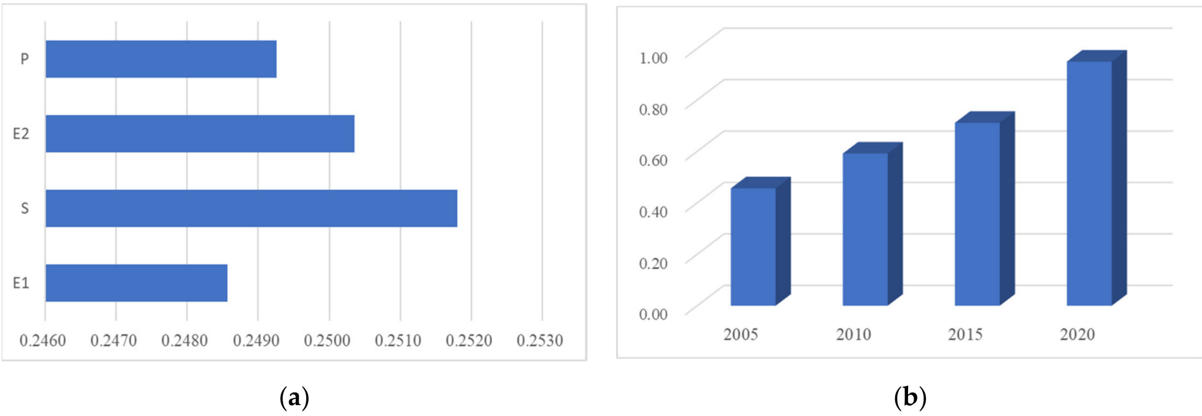


Figure 9. Comprehensive benefits of PPAT in the Sanjiangyuan region: (**a**) weights of the four dimensions and (**b**) *CCD* of PPAT in the Sanjiangyuan region.

Conclusion 2: The results of *CCD* evaluation show that, since the introduction and wide application of PPAT in 2005, the integrated system of "E_1-S-E_2-P" in the Sanjiangyuan region has shown a positive trend of progressive synergistic development (Figure 10). By 2020, the comprehensive system of CCD in the Sanjiangyuan region initially achieved synergistic development (0.9488).

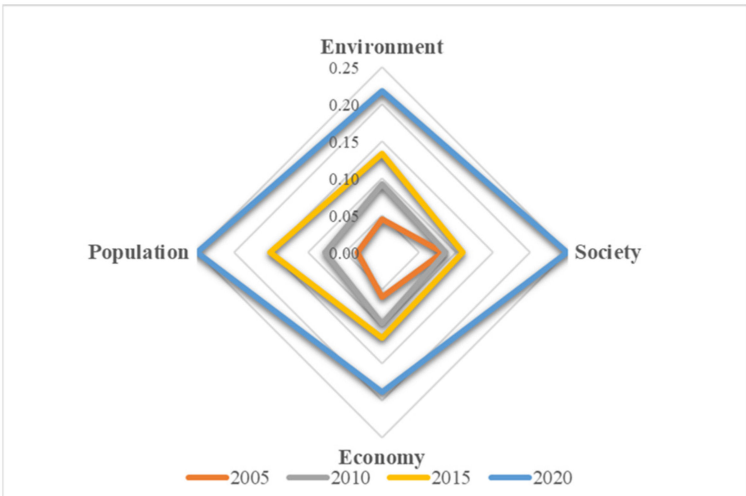
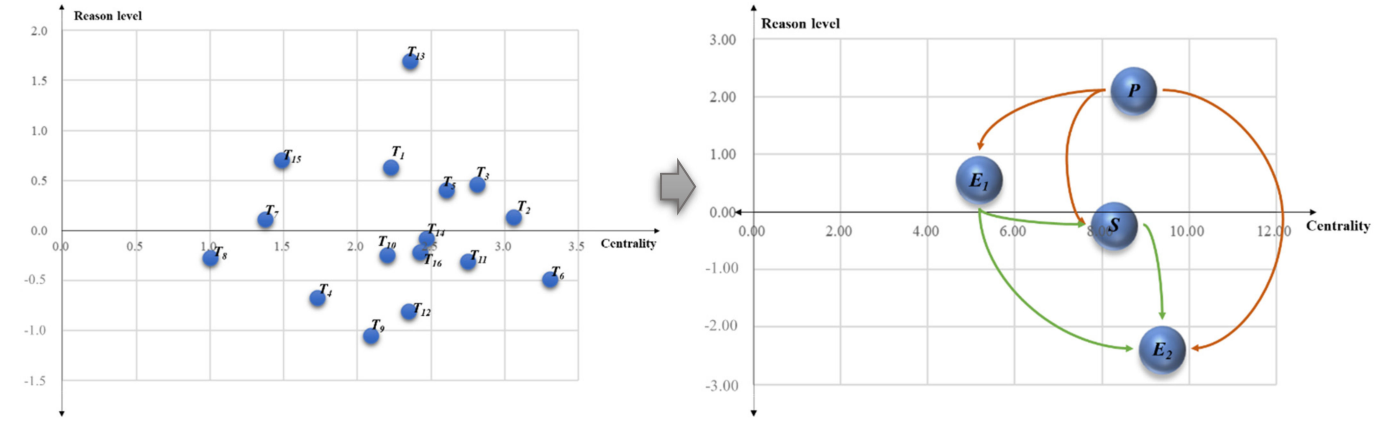


Figure 10. Tendency of the "E_1-S-E_2-P" integrated system.

4.2. The DEMATEL Method

Centrality represents the status and role of the factor in the whole system. The reason level represents the influence among factors: when the reason level is positive, it means that the factor has influence on other factors; when the reason level is negative, it means that the factor is influenced by other factors in the system. Using centrality and the reason level as horizontal and vertical coordinates, respectively, the Tn coordinate set (m_i, n_i) was derived based on Table 5, and the analysis structure between the factors of the "E_1-S- E_2-P" system was drawn (Figure 11) to analyze the key factors of the comprehensive benefits evaluation system. All four elements have a centrality of 5.0 or higher, and all play an important role in the comprehensive benefits of PPAT in the Sanjiangyuan region.



(**a**) (**b**)

Figure 11. The key factors of the comprehensive benefits in the system: (**a**) centrality analysis of the PPAT index in the Sanjiangyuan region; (**b**) centrality analysis of the four dimensions in the Sanjiangyuan region.

Conclusion 3: The population (P) and environment (E_1) play a dominant and decision-making role in the system. In the subsequent development, we need to pay great attention to the population quality of the region, vigorously support ecological public welfare custodians, support the development of minority populations, and promote PPAT under the premise of protecting and improving the ecological environment of the Sanjiangyuan region, with full respect for the natural environmental capacity of the region and undisturbed natural ecosystem.

The results of the ranking (Figure 12) of the combined set of T_n coordinates (Figure 11) and the impact degree (f_i) of each indicator show the following.

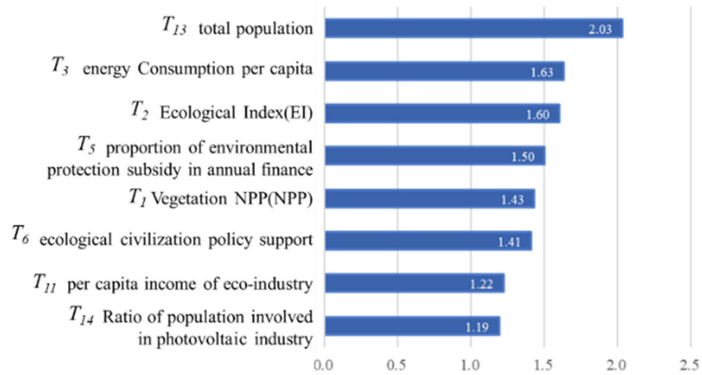


Figure 12. Top eight sub-criteria in PPAT's comprehensive benefits analysis.

Among the PPAT comprehensive benefit evaluation indicators in the Sanjiangyuan region, the factors of total population (T_{13}), energy consumption per capita (T_3), Ecological Index (EI) (T_2), proportion of environmental protection subsidy in annual finance (T_5), and vegetation NPP (NPP) (T_1) are located in the first quadrant and have a high impact, which directly affects the benefits of PPAT application. Three of these five indicators fall under the dimension of environment (E_1), indicating that for the Sanjiangyuan region, the protection and continuous improvement of the environment plays a decisive role in PPAT benefits.

The ecological civilization policy support (T_6), per capita income of eco-industry (T_{11}), and ratio of population involved in photovoltaic industry (T_{14}) indicators are located in the second quadrant, have a higher influence on the effectiveness of PPAT implementation, and they are easily influenced by other key factors, which can be used as important indicators to measure the effectiveness of PPAT implementation in the process of PPAT application and promotion.

5. Discussion

5.1. Research Limitations and Future Research Directions

The Law of the People's Republic of China on the Promotion of Revitalization of Rural Areas sets forth the general requirements of "prosperous industry, ecological livability, civilized countryside, effective governance, and prosperous living". Energy technology upgrading is directly related to the requirements of "ecological livability" including green energy technology, "effective governance" including the development of eco-friendly energy, and "affluent living" including the in-depth application of new energy technology [61]. Qinghai province is the forth largest in the country in terms of area, and the population density is only slightly higher than Tibet, making it one of the most extensive and sparsely populated regions in the country. PV poverty alleviation power stations are located in 39 counties and urban areas in the province. PPAT needs to overcome the problems of harsh natural environment, wide distribution of power stations, and complicated operation links, etc. The sustainability evaluation of PPAT still needs to be verified, and the implementation measures and guiding policies of PPAT need to be continuously improved.

The present study also has some limitations. First of all, in terms of data chains, complete 20-year continuous data have not been collected in the Sanjiangyuan region due to objective conditions, and the development information of the region can only be partially represented through questionnaire surveys and data collation; thus, it is necessary to extend the analysis period or obtain more accurate basic data for further analysis. In terms of evaluation methods, DEMATEL relies mainly on expert scoring, and the subjective judgments of experts may later produce different weights for specific dimensions of regional PPAT development.

5.2. Policy Implications

This paper provides valuable reference for the promotion and application of PPAT in the Sanjiangyuan region of Qinghai Province and for the formulation of policy measures by the central and local governments. The evaluation results show that the protection and continuous improvement of the environment plays a decisive role in the comprehensive benefits of PPAT in the Sanjiangyuan region; the Ecological Index (EI) and vegetation NPP (NPP) under this dimension have great influence. On the one hand, further comprehensive protection and restoration of the ecological environment should be carried out to continuously improve the natural ecological condition and consolidate the foundation of development. On the other hand, the waste recycling mechanism of PV industry should be improved to avoid ecological pollution caused by discarded and replaced capacitor components.

Currently, PPAT reaches a coupled and coordinated development where *CCD* is close to 1.0. Local governments should maintain the good development trend by regularly evaluating the equal and harmonious growth of each dimension. From the perspective of technical development, PPAT displays unique advantages: integrating the development of poverty alleviation and "prosperous industry and livable ecology", it is an environmentally friendly industry, and can be widely used in similar areas such as Qinghai Province with relatively high requirements for ecological and environmental protection.

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Nomenclatures

PPAT	photovoltaic poverty alleviation technology
CCD	coupling coordination degree
DEMATEL	decision-making trial and evaluation laboratory
MCDM	multicriteria decision model
LDI	sub-dimensional development index

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