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Sustainability assessment of individual-level solar energy poverty alleviation program-A case on Jinzhai County, China

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In this paper we study the Solar Energy for Poverty Alleviation Program (SEPAP) in China, which aims to increase the 3,000 Yuan annually for poor people by installing solar panels. SEPAP was initially launched in 2014 and officially ended in 2020 when President Xi announced that absolute poverty was eliminated in China. During the 6 years, China built and put into operation 26.49 million kilowatts of solar PV systems, benefiting 1,472 counties, 138,091 villages, and 4.18 million poor households. We propose a sustainable assessment framework and apply the Analytic hierarchy process (AHP) and Fuzzy comprehensive evaluation method (FCEM) to evaluate individual-level SEPAP in Jinzhai County, China, based on the findings of 80 semi-structured interviews with professionals and poor households. When examining SEPAP sustainability, we discover that the economic dimension is the most crucial one, with income, employment, training for the poor, and solar panel quality being the most weighted sub-indicators. In 2021, SEPAP could increase by roughly 2,700 Yuan for poor households, which is 90% achieved the governmental goals. We obtain a "Medium-high" outcome for the individual-level SEPAP. We provide two policy recommendations for maintenance work that will help the poor maintain a steady income.

KEYWORDS
Solar Energy for Poverty Alleviation Program (SEPAP), solar photovoltaic (PV) energy, extreme poverty, sustainability assessment, Jinzhai County, China

Introduction

There were 17 Sustainable Development Goals (SDGs) endorsed by all UN members in 2015 for global peace and prosperity. All nations, both developed and developing, are urged to act in response to achieving the 17 SDGs. For example, "Goal 1: No poverty" and "Goal 7: Clean and affordable energy" are the two goals tackling poverty and energy issues, respectively. The global poverty rate (at the US $1.90 poverty line) in 2018 was 8.6%, which was <9.1% in 2017 and is equivalent to a decline of 28 million poor people in 2 years (World Bank, 2022). The electrification rate in 2020 was 90.5%, which means there were still 770 million people living without access to electricity (World Bank, 2022). Unfortunately, the COVID-19 pandemic decelerated years of development and worsened poverty and energy access in undeveloped countries. According to the International Energy Agency (2022), after an average annual decrease of 9% in electrification in 2015–2019, there was a little change in the number of people without access to electricity in 2019–2021. Furthermore, the adverse effects of COVID-19 have downgraded poverty levels in some regions to approximately those recorded 30 years ago. The number of people living below poverty might have increased by 420–580 million in the worst-case scenario, with a 20% loss in income or consumption (Sumner et al., 2020).

China is one of the largest developing countries and had 82 million people living in extreme poverty in the year 2013 (National Bureau of Statistics of China, 2020). Despite China's recent declaration of 100% electrification access, 18.9% of Chinese could still be defined as "energy poor," who are in short of modern energy consumption, with most of them are concentrated in central and western China (Lin and Wang, 2020). Therefore, eradicating poverty and providing stable energy to the people in rural areas have been the priority tasks for the Chinese government. In 2014, China launched an ambitious poverty alleviation program (Solar-energy Poverty Alleviation Program, SEPAP) by implementing solar photovoltaic systems in remote rural areas. It aimed to increase energy capacity by more than 10 GW and generate annual income of ∼3,000 yuan for each poor household (National Development Reform Commissions, 2016). The support has been provided to over 2 million households in ∼35,000 villages across the nation. There were four primary choices: individual-level SEPAP, village-level SEPAP, joint-village-level SEPAP, and utility-scale SEPAP. In individual-level SEPAP, governments and photovoltaic companies assisted the poor in installing solar panels on their rooftops or lands. In village-level and joint-village-level SEPAPs, solar power plants were built in the vicinity of the counties or villages. In utility-scale SEPAP, centralized solar power plants were built in the neighborhoods of these counties or villages. Here, poor households and villages could either utilize or sell their generated electricity to the grid companies. According to the National Energy Administration (2020b), as of July 2020, China had built and put into operation 26.49 GW of photovoltaic power stations for poverty alleviation, benefiting 1,472 counties, 138,091 villages, and 4.18 million poor households, averaging more than 6 kW per poor household.

Because China has a large geographical area and large number of poor people, SEPAP has attracted great attention from academia. Zhang et al. (2020) use a panel dataset of 211 pilot counties between 2013 and 2016 to conduct a difference-in-difference (DID) regression and show that the SEPAP raises per-capita disposable income in a county by roughly 7–8%. Further DID regression analyzes by Liu et al. (2021) revealed that SEPAP has significantly improved the economic conditions and social capital[1] of low-income poor families, but that the expected gains in human and natural capital have not materialized. By adopting the Life Cycle Assessment (LCA) and Net Energy Analysis (NEA) methodologies, Wang et al. (2020) discovered that SEPAP had good energy efficiency and environmental advantages. Lo (2021) found that SEPAP has succeeded in achieving a just energy transition because of the just governmental procedures and the just outcome to the poor. There also have been several attempts to study sustainability perspectives and evaluate their impacts on the poor. Tao et al. (2022) evaluated the comprehensive benefits of SEPAP from the sustainability perspective. They identified an index system consisting of 13 sub-criteria derived from four aspects: economics, technology, society, and environment. The triangular intuitionistic fuzzy number and decision-making trial and evaluation laboratory were applied to calculate the weight of indicators, and the improved matter element extension method with the cloud model was applied to obtain final results. The results of the case study of four projects in Yunnan province demonstrated that the SEPAP has the potential for further development, and its overall benefits are generally at a good level. Huang et al. (2021) conducted a social impact evaluation of SEPAP, which was a multi-criteria analysis of four categories (human life, safety guarantee, and social resources), forming 13 indicators. They found that SEPAP improved poor families' economic conditions and social capital; however, the expected increases in human and natural capital were not observed. Wei (2021) constructed a 16-criteria system based on BOCR[2] theory from the perspectives of benefits, opportunities, costs, and risks and proposed a combined BOCR-AHP-IT2FTOPSIS method to analyze ambiguous data and perform a comprehensive sustainability assessment. In their empirical study in Guangxi Province, China, comparative and sensitivity analyses were used to rank the alternative SEPAP. According to the results of the criteria analysis, investment costs, poor collaboration, cleaner production, creation of jobs, and a reduction in the need for fuel are the major influencing factors for SEPAP sustainability.

On conducting a literature review, two research gaps were found. First, the institutional perspective is missing from the earlier literature on the SEPAP sustainability study. The implementation mechanism requires collaboration between the government and solar enterprises. However, no study has attempted quantification of the efforts made by the government and solar industry, incorporating both technological and institutional perspectives into the evaluation framework. Second, the literature often focuses on village-level SEPAP,

1 "Social capital" measures social attributes (e.g., social relations, social trust, formal and informal social networks), collective appeals, and opportunities to participate in decision-making.

2 BCOR stands for benefit, cost, opportunity and risk.

utility-scale SEPAP, or assessing the SEPAP in one region as a whole. As the four types of SEPAP are different in many ways, there is a lack of sustainability assessment on individual-level SEPAP. The main reason indeed is the lack of data. The majority of the individual-level solar modules have been installed in front of the poor people's home or on its rooftop. It is challenging to collect data because the majority of the poor live in remote areas that are difficult to access. Another reason could be that the Chinese government had designated village-level SEPAP as the main option between 2016 and 2020. However, given the technological advancements and falling cost of distributed solar panels, individual-level solar power plants are now considered as the new growth point for the solar expansion and the most suitable option for small investors in rural area as compared to large-scale solar power plants. In fact, the capacity of individual-level solar power plant has been increasing. The capacity of newly installed individual-level solar power plants in 2021 reached 21.6 GW (National Energy Administration, 2022), while the number in 2020 was 10.12 GW (National Energy Administration, 2020a). Further, 21.5 GW accounts for 41% of the total newly installed solar capacity and 75% of the newly installed distributed solar capacity (National Energy Administration, 2022). The reason is that most recently the Chinese government has been encouraging the installation of individual-level solar power plants, which is suitable for smaller investors. Although utility-scale solar power plants generally have a higher investment return than individual-level solar power plants, smaller investors may not be able to afford such a big investment. China being a vast country makes the evaluation of SEPAP implementation covering all the geographical areas difficult. This study chose Jinzhai County as the study area, because it is one of the earliest counties to implement SEPAP, and 7,803 individual-level SEPAP have been constructed since 2013. With its rich experience with SEPAP, it has also been promoted as the most successful model of SEPAP implementation in China. Before SEPAP initiation, Jinzhai County's poverty rate was 21.72%, but gradually, the poor people all escaped from poverty until 2020. This research intends to conduct a sustainability study on the factors affecting project sustainability and evaluate individual-level SEPAP in order to determine the most important factors/sustainability indicators for the sustainability of individual-level SEPAP and provide recommendations to policymakers regarding future poverty reduction policies using solar energy in rural areas. Figure 1 shows the research framework of sustainability assessment of individual-level SEPAP.

The remaining paper is divided into six sections. Section Sustainable framework and identification of sustainable indicators explains the sustainability framework and the selected sustainability indicators. Section Research methodology discusses the model and steps for analysis. Section Results shows the results of the indicator weight and SEPAP scores. Section Discussion discusses the results and provides policy recommendations for future poverty reduction policies using solar energy in rural areas. Section Conclusion presents the study's conclusions.

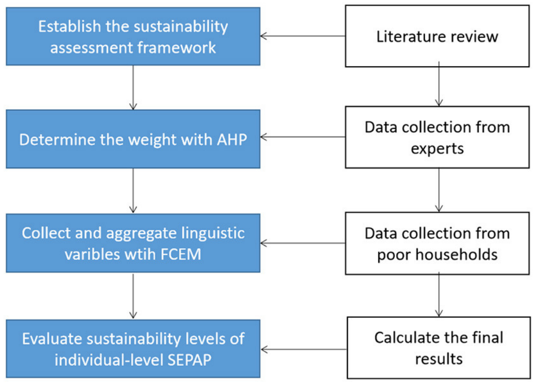

FIGURE 1
Research framework of sustainability assessment of individual-level SEPAP.

Sustainable framework and identification of sustainable indicators

As we entered the 21st century, the "sustainability" of human beings has become the paramount issue globally. With the launch of the SDGs and the effort to achieve the goals, researchers have been increasingly applying sustainability assessment frameworks to evaluate the sustainability in a certain area. The sustainability assessment framework creates a set of indicators that are connected to the SDGs, especially the economic, social, and environmental aspects. Typically, this approach has been used to evaluate electrification and poverty reduction programs in developing countries. In fact, the need to improve energy access continues to be a major motivator for reducing poverty in their rural areas (Thiam, 2011; Cheng et al., 2021). Modern energy's accessibility makes it easier to promote industrial development and raise human living standards.

The sustainability assessment framework suggested by Ilskog (2008) was based on 39 indicators. The proposed indicators cover the five dimensions of sustainability: technical, economic, social/ethical, environmental, and institutional sustainability. In the study by Ilskog and Kjellström (2008), fieldwork data from seven rural electrification projects in Kenya, Tanzania, and Zambia were presented, together with an explanation of how the chosen indicators and proposed framework could be applied to evaluate and compare different electrification programs. The authors suggested concentrating on providing rural electrification through small private and local community-based organizations, as they are the most effective in fostering sustainable development in their rural communities.

TABLE 1 Sustainability assessment framework (five dimensions and 17 indicators).

Economic	Social	Environmental	Technical	Institutional
A1. Affordability	B1. Smaller number of young people leaving the rural areas for the cities	C1. Replaced traditional energy (kerosene/wood)	D1. Quality of solar panel	E1. Information disclosure
A2. Income	B2. Education	C2. Reduced carbon emission	D2. Service availability	E2. Training provided by government to the poor households
A3. Employment	B3. Health		D3. Grid access improvement	E3. Accessibility of the local government and for issue reporting
	B4. Social Activities			E4. Trust between the poor people and the local government
				E5. Trust between the poor people and the maintenance company

Yadoo and Cruickshank (2012) applied the sustainability assessment framework to three case areas in Nepal, Peru, and Kenya to explore sustainable welfare benefits generated by renewable energy mini-grids. Due to the data availability and the unique local context, they adapted a framework with 44 set indicators in the five dimensions. To stimulate private sector investment, the authors proposed that policy efforts should concentrate on increasing public knowledge of renewable energy mini-grids, enhancing institutional, technical, and regulatory frameworks and establishing creative financing methods.

Boliko and Ialnazov (2019) compared four electricity projects in rural Kenya to ensure future sustainable development, following the methodologies employed by Ilskog (2008) and Yadoo and Cruickshank (2012). Their findings show that private sector-led off-grid solar electrification programs performed better than the others under evaluation, and hence, policymakers should continue to support these activities.

In our paper we use the sustainability assessment framework constructed by Ilskog (2008), Yadoo and Cruickshank (2012), and Boliko and Ialnazov (2019) with improvements to fit the local context in Jinzhai County, China. Our sustainability assessment framework (five dimensions and 17 indicators) is shown in Table 1. Below are the descriptions of the undertaken sustainability assessment framework.

The economic dimension assesses the economic impact of the project on poor households in Jinzhai County. Affordability is the capability of poor households to pay the cost of solar system. Income is the measure of whether SEPAP has raised the income of poor households. The employment indicator points at whether SEPAP has resulted in new employment opportunities.

The social dimension of the framework focuses on the impact that SEPAP has had on various aspects of the daily lives of the poor people living in Jinzhai County. Education and health evaluate its impacts on children's education and physical health, respectively, and social activities point at additional social activities that have been made possible as a result of SEPAP (such as increased social entertainment). The percentage of young individuals staying in rural areas reveals whether young poor people stayed or have returned to Jinzhai County in search of employment. The reason for adding this indicator is to check whether the introduction of solar energy has had an impact on the number of young people leaving the rural areas for the cities. If that number was smaller, then this result would help to prevent the further decline of the rural areas.

The environmental dimension focuses on how SEPAP has been able to lessen reliance on conventional energy sources, particularly the use of traditional biomass for energy production in rural areas, which often has negative effects on overall health, climate, and nearby natural environment. Kerosene for lighting and charcoal or firewood for cooking are examples of traditional biomass sources. Thus, this study examines whether SEPAP has reduced carbon emissions and substituted traditional biomass in terms of energy consumption (replacing kerosene, wood, and charcoal).

The technical dimension focuses on the technical performance of the SEPAP-related equipment and services. Therefore, the indicators that are included in the dimension are grid access improvement, service availability, and solar panel durability. The term "quality of solar panel" was measured by the time of professional maintenance work needed. Service availability measures the speed and quality of maintenance operations. The grid access improvement shows whether the grid service has been improved so that the poor can use stable electricity.

The institutional dimension examines how well the government and solar companies can support SEPAP's overall operation. Poor households' information disclosure reflects whether they could assess various SEPAP related information. Training for the poor households shows whether the government provided the necessary training to the poor households. Accessibility of the local government for issue reporting refers to the ease with which poor households (consumers) can report a particular issue on SEPAP. Trust between the poor and local government indicates the extent to which the poor could trust the local government during the entire program period. Similarly, trust between the poor and the maintenance company checks if they trust the maintenance company during the program period. The trust indicators are important because they demonstrate the degree of satisfaction of the poor people with the overall operation of the SEPAP.

Research methodology

After preparing the sustainability assessment framework for SEPAP, an appropriate method was required to weight the indicators and calculate the SEPAP scores. In this study, we used an analytic hierarchy process (AHP) to calculate the weight of each indicator. AHP not only enables multi-criteria comparison but also combines both quantitative and qualitative indicators together to rank both the indicators and alternatives. Then, the general fuzzy evaluation model was used to create a fuzzy mapping between each of the evaluation factors and transform a set of categorical appraisal grades into a numeral for final evaluation. Below are the descriptions of each method.

Designing the comparison matrix and obtaining the weight of each indicator

Upon setting the index system, the weights of indices denominating their relative importance are defined in Table 2.

According to the first-level evaluation indicator and the second-level evaluation indicator after classification, the following comparison matrix is constructed. The weight of the indicator was determined by calculating the specific feature vector through the comparison matrix:

$$P = \left[p_{ij}\right] = \begin{bmatrix} 1 & p_{12} & \cdots & p_{1n} \\ 1/p_{12} & 1 & \cdots & p_{2n} \\ \vdots & \ldots & \ddots & \vdots \\ 1/p_{1n} & 1/p_{2n} & \cdots & 1 \end{bmatrix}$$

TABLE 2 Analytic hierarchy process (AHP) matrix scale and definition.

Standard value	Definition
1	Equally important
3	Slightly important
5	More important
7	Obviously important
9	Absolutely important

Calculate consistency ratio

The priorities were derived as the normalized values of the right-hand eigenvector, which were associated with the largest eigenvalue (lmax) of the reciprocal matrix formed from the pairwise comparisons. The closer the lmax is to n (the number of elements being compared), the more consistent the judgments are. If judgments are perfectly consistent, lmax will be equal to n. Thus, the difference between lmax and n can be used as a measure of inconsistency. Instead of using this difference directly, a consistency index (CI) is shown as follows:

$$CI = \frac{(l\ \max - n)}{(n-1)}$$

Then, the consistency ratio (CR) can be calculated after obtaining the value of random index (RI). RI is the average random consistency index, which is listed in Table 3. If CR < 0.1, it can be considered that the judgment matrix has satisfactory consistency.

$$CR = \frac{CI}{RI}$$

Evaluating each indicator

The poor households and government officials (interviewees) were also given a qualitative indicator based on the 5-scale evaluation as {High, Medium high, Medium, Medium low, low}. Quantitative data of indicators was transformed to its actual number on the 5-scale evaluation, as shown in Table 4. Then, the probability of each choice for each indicator was mapped using a fuzzy matrix, R, such that if there are n factors and m levels of evaluation grades.

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix}$$

Obtaining the final score of different types of SEPAP

The linear weighted sum function method was used to calculate the results of each stratified evaluation. The final indicator can be calculated as follows:

$$G = \sum_{1}^{N} w_{ij} r_{ij}$$

TABLE 3 Random consistency indicator RI coefficient table.

N	1	2	3	4	5	6	7	8	9	10	11
RI	0	0	0.52	0.89	1.12	1.24	1.32	1.41	1.45	1.49	1.51

TABLE 4 Indicators using quantitative data and the transformation criteria to fuzzy evaluation.

Indicator	High	Medium high	Medium	Medium low	Low
Income (yuan/year)	≥3,000	(2,400, 3,000)	(1,800, 2400)	(1,000, 1,800)	(0, 1,000)
Reduced Carbon emission (kg/year)	≥2,430	(1,944, 2,430)	(1,458, 1,944)	(802, 1,458)	(0, 802)
Quality of solar panel (Times of maintenance needed)	0	1	2	3	≥4

where G represents the final score of the SEPAP, and w_{ij} and r_{ij} represent the weighting factor and evaluation result of each indicator, respectively.

Results

Field study

We conducted 80 semi-structured interviews using a questionnaire with 20 professionals, including professors, government officials, and project managers, who have rich experience in SEPAP, and 60 poor households, who have installed individual-level SEPAP in August–September 2022. To reduce in part the sample bias, we have interviewed poor households in three different villages in Jinzhai County. The data collected from the professionals were used for indicator weighting, and the household data was used for indicator evaluation.

The individual-level SEPAP was initially an experiment conducted by the Jinzhai government in 2013. The Jinzhai government helped eight poor households install solar photovoltaic (PV) in different areas of the county. All projects were completely funded by the local government, and each of them had a capacity of 3 kW. After 1 year, the government found that each poor household could earn an average of 3,000 yuan by selling the generated electricity to the grid company for 20 years. Therefore, in 2014–2015, large-scale installations were completed for 7,803 poor households. Similar to the experiment, each solar PV project had a capacity of 3 kW, and each individual-level SEPAP had a total investment of 24,000 Chinese yuan, of which the local government provided 8,000 yuan; another 8,000 yuan came from the donation by the solar PV company, and the remaining 8,000 yuan from the poor households. Because most of the poor households could not afford the initial investment of 8,000 yuan, the local banks provided an interest-free loan to them. The bank loans were agreed to be repaid by half of the annual income gained by selling the generated electricity until 2020. All the individual-level SEPAP were connected to the grid. The electricity generated was sold to the grid company at a selling price of 1 yuan/kWh along with the government subsidy on this price.

Indicator weighting

There were six comparison matrices determined based on the average weightage given by 20 researchers. Specifically, in this study, judgment matrices was constructed with a comparison matrix of primary indicators and five comparison matrices of sub-indicators. The values obtained from the judgment matrix are shown in Table 5, and the weighting results are shown in Table 6.

As seen from the Table 5, all CR values are lower than 0.1; therefore, they all passed the consistency test.

As can be seen from Figure 2 and Table 6, the economic dimension received the largest weight, making up more than half of all the weights. Therefore, it is clear that the SEPAP program has reduced poverty, whose sustainability was mostly determined by economic indicators. The institutional dimension came second after the economic dimension, demonstrating the importance of the roles played by the government and solar companies in the implementation of SEPAP. Additionally, the social and technological dimensions accounted for more than 10%. Lastly, the environmental indicators cannot be ignored.

Figure 3 shows the rank of normalized weights of each sub-indicator. It appears that higher income, which was also SEPAP's original goal, is the most crucial factor for benefiting poor households. Second, promoting employment is important, because it can provide the poor a reliable source of income. The training of the poor, quality of solar panels, education, trust

TABLE 5 Eigenvector, largest eigenvalue, consistency indicator, and consistency check coefficient comparison matrices.

	W	CI	RI	CR
Main criteria layer	(0.5161, 0.1353, 0.0532, 0.1117, 0.1882)	0.044	1.120	0.039
Economic	(0.1062, 0.6334, 0.2605)	0.029	0.520	0.037
Social	(0.1414, 0.4360, 0.3407, 0.0819)	0.064	0.890	0.072
Environmental	(0.7500, 0.2500)	0	0	Null[a]
Technological	(0.6434, 0.2828, 0.0738)	0.033	0.520	0.063
Institutional	(0.0722, 0.4489, 0.0722, 0.2428, 0.1640)	0.052	1.120	0.047

[a]Because the environmental dimension has only two indicators, it does not need to take a consistency test.

TABLE 6 Weighting factor of sustainability framework indicators.

Criteria layer	Weights	Sub-criteria layer	Weights	Normalized weights	Rank
Economic	0.5161	Affordability	0.1062	0.0548	6
		Income	0.6334	0.3269	1
		Employment	0.2605	0.1344	2
Social	0.1353	Smaller number of young people leaving the rural areas for the cities	0.1414	0.0191	12
		Education	0.4360	0.0590	5
		Health	0.3407	0.0461	7
		Social activities	0.0819	0.0111	16
Environmental	0.0532	Replaced traditional energy	0.7500	0.0399	9
		Reduced carbon emission	0.2500	0.0133	15
Technological	0.1117	The quality of solar panel	0.6434	0.0719	4
		Service availability	0.2828	0.0316	10
		Grid access improvement	0.0738	0.0082	17
Institutional	0.1882	Information disclosure (transparency)	0.0722	0.0136	13
		Training to the poor	0.4489	0.0845	3
		Issuing reporting	0.0722	0.0136	13
		Trust between the poor people and the local government	0.2428	0.0457	8
		Trust between the poor people and the maintenance company	0.1640	0.0309	11

between the local government and the poor, and affordability are also essential and account for more than 5% of the total weight.

Indicator evaluation

The data gained from the interviews with poor households was normalized, converted into the probability of each choice for each indicator, and then mapped using the fuzzy matrix R, as shown in Table 7. On the Left side, A1 to D5 are the codes of the indicators. On the first line, the classifications from "High" to "Low" are the evaluation levels. For instance, the value "0.55" in the second line indicates that 55% of the interviewees rated their income as "high," while "0" in the second line indicates that no one reported their income as "low".

$$G = \sum_{1}^{N} w_{ij} r_{ij} = \{0.250, 0.336, 0.194, 0.133, \ 0.086\}$$

Therefore, the final evaluation result of Individual-level SEPAP was "medium high."

Economic sustainability

Generally speaking, the majority of poor households were satisfied with the loan policy for the installation fees. This is due

TABLE 7 Evaluation results based on 60 interviews with individual-level Solar-energy Poverty Alleviation Program (SEPAP) households.

	High	Medium high	Medium	Medium low	Low
A1	0.55	0.27	0.13	0.05	0
A2	0.28	0.52	0.17	0.03	0
A3	0.10	0.07	0.18	0.40	0.25
B1	0.03	0.07	0.10	0.20	0.60
B2	0.15	0.35	0.22	0.12	0.17
B3	0.20	0.32	0.30	0.10	0.08
B4	0.32	0.27	0.25	0.13	0.03
C1	0.10	0.13	0.12	0.30	0.35
C2	0.28	0.52	0.17	0.03	0
D1	0.48	0.32	0.15	0.05	0
D2	0.30	0.33	0.18	0.13	0.05
D3	0.42	0.27	0.17	0.08	0.07
E1	0.25	0.45	0.25	0.03	0.02
E2	0.13	0.22	0.32	0.23	0.10
E3	0.18	0.37	0.30	0.12	0.03
E4	0.32	0.35	0.23	0.08	0.02
E5	0.25	0.32	0.23	0.15	0.05

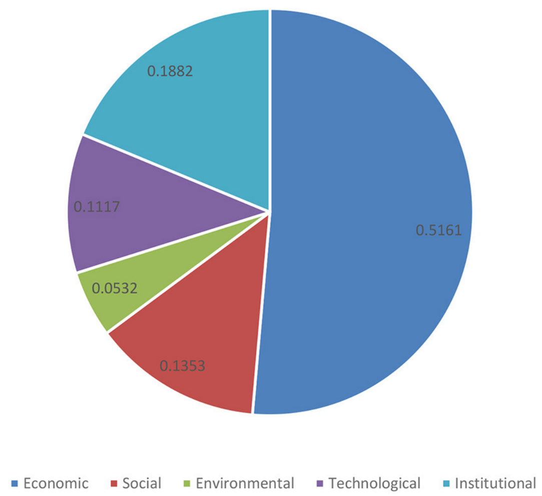

FIGURE 2
Weights of each main dimension.

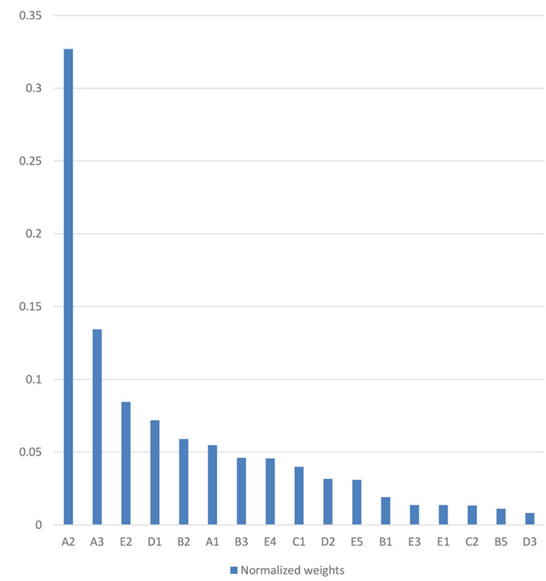

FIGURE 3
Normalized weights of each sub-indicator.

to the fact that, out of the entire 24,000 yuan installation fees, only a third was to be paid by them, and the rest was covered by the government and solar companies. For the poor households, local banks offered no-interest loans, which would be repaid by taking a deduction from SEPAP revenue each year until 2020. As a result, the poor households paid nothing for the installation. However, the poor households who installed SEPAP before mid-2014 were not eligible for the no-interest loan policy, as it was implemented after that. In fact, 8,000 yuan took up a marked percentage of their savings, and some of them borrowed money from their relatives.

In terms of increase in income, individual-level SEPAP has enabled poor households to gain ∼2,700 yuan by 2021, which was 90% of the government's goals (3,000 yuan). Less than 30% of interviewees reported having an income of >3,000 yuan, and over 50% of households received money ranging from 2,400 to

3,000 yuan. Additionally, the interview revealed that 20% of the respondents earn <2,400 yuan annually. Even worse, in 2021, two people earned an annual income from SEPAP ranging from 1,000 to 1,800 yuan. The primary cause was the malfunctioning of their solar panels for a while, which the poor households were unaware of.

The factor of increased employment had both direct and indirect impacts. In the direct impact, the villagers were employed as PV power plant maintenance personnel, and the new employment was produced by the PV company in the county. For example, one solar company built a factory to produce solar module components, and hired some local people. There were two types of indirect impacts: first, the money earned through the PV poverty alleviation program was used for skill development to increase steady employment with the acquired skills; second, there have been some attempts to combine solar energy with agriculture and fishing, which was a new "Solar+" business model that has the potential to expand employment. However, it was clear from the interview that both direct and indirect impacts were limited. Regarding the direct effects, each village only employs one maintenance worker for maintenance tasks, and PV companies prefer to hire employees with extensive experience for jobs involving PV rather than poor households, who would need expensive training. As for the indirect impacts, only 16% of interviewees mentioned that they used the income to learn more skills, and 21% of interviewees gained benefits from the "Solar+" industrial development.

Social sustainability

From the interview, it is hard to say that there was a trend of young people returning to the rural area for work. Most young people decide to stay in big cities. It must be acknowledged that there are more job opportunities in big cities; thus, the income there would be considerably higher than in rural areas. The poor might quickly escape poverty by working in large cities. Each province in China sets its own minimum monthly salary. According to the interview, poor households in Jinchai County were more likely to move to Shanghai for employment than any other large city, owing to the geographical closeness of the county to Shanghai. Shanghai's minimum monthly wage is 2,590 yuan (Shanghai Municipal Bureau of Human Resources Social Security, 2022); therefore, 2 months of work there would allow one to overcome poverty according to the Chinese poverty standard. As a result, the majority of young people do not choose to move back to the country. Despite difficulties for the majority of elderly individuals in commuting outside for work, some have stated that if they were younger, they would like to move out for work.

The effects of SEPAP on education varied widely among poor households. Some poor households believe that the effects are positive. Twenty five percent of poor households indicated that they could purchase stationery and reference books, and 30% of interviewees mentioned the increase in the nighttime study. However, some other poor households did not recognize the importance of SEPAP on education. Over 30% of households choose "medium-low" and "low" impacts for education. Below are some of their explanations:

> *Interviewee A: "The tuition and book fees were already exempted, and 9-year compulsory education was guaranteed by the government; I do not find any relation between SEPAP and education."*
> *Interviewee B: "I have never paid any educational fees with money I received from SEPAP."*
> *Interviewee C: "It is hard to say. Although we have benefited from SEPAP as our income increased, this is not related to education."*

The health effects of SEPAP appeared to be more positive than those of education. In fact, the "351" policy, where the government guaranteed that an annual self-pay medical fee would not be more than 3,000, 5,000, and 10,000 yuan for medical treatment within the county, municipality, and provincial medical institutions in Anhui province, respectively, has actually helped in covering the majority of the medical costs. Approximately 20% of impoverished households indicated using the money they received from SEPAP to pay for the portion that the government was unable to cover. In addition, nearly 70% of poor households said that after the implementation of SEPAP, their quality of life has improved and they feel much healthier.

> *Interviewee A: "Before 2014, meat could only be eaten at festivals. Due to the increase in income after SEPAP installation, my family can eat more high-protein food."*
> *Interviewee B: "My child was a bit malnourished and thin before, but since the government's poverty alleviation program came up, we can now afford more food and the child's health has improved."*

The impact of increased social activities was also discovered during the interview. Poor households had more time to participate in daily social activities after the implementation of SEPAP than before it. The interviewee's village arranged more social activities, including watching movies and live sporting events, after the launch of the SEPAP program in 2014. The poor also have more time to play cards and chess together than they had before.

Environmental sustainability

There was no marked impact of SEPAP on poor households as an alternative to traditional energy sources. SEPAP connects individual-level solar PV to the grid, and the electricity generated is all sold to the grid company; hence, there is no noteworthy change in the way poor households use electricity. According to the interviews, most poor households maintain the habit of using wood for cooking and heating. Because most of the wood burned comes from the woods of the nearby mountains, it costs nothing. On the contrary, using electricity from the grid for cooking and heating would add an extra monthly expense. It should be noted that ∼10% of poor households have relocated with government assistance. They also changed their energy consumption and began utilizing more clean energy. Additionally, some poor households have increased their incomes because of SEPAP and other poverty alleviation programs. Consequently, they moved out of poverty and can now afford more electricity consumption from the grid.

As compared to replacing traditional energy, the impact on reducing CO_2 emissions was much better. The amount of CO_2 emissions was affected by the actual electricity generated. Yanzhe et al. (2021) estimated that coal-fired electricity generation emits 0.839 kg/kWh of CO_2, whereas solar energy generation emits 0.029 kg/kWh of CO_2. The government aimed to increase the poor's income by 3,000 yuan per year by installing 3 kW of solar power plants, which would produce 3,000 kWh of electricity and be sold at a price of 1 yuan/kWh. Thus, SEPAP would ideally cause an annual decrease of 2,430 kg in CO_2 emissions.

Technological sustainability

Most of the existing literature uses the decay rate as an indicator of solar technical performance (Tao et al., 2022). However, this study uses the actual times of maintenance work as an indicator to show the actual quality of solar panels. According to the questionnaire results, ∼50% of the respondents said that their solar panels are in good condition and they have never called a maintenance company for professional maintenance work. However, 30% of households asked about the maintenance work once, but they stated that most of their panels did not have a major problem. Approximately 10% of the solar panels were broken and required replacement. These solar panels were all constructed in 2013 and early 2014. Because there were no strict rules concerning the project entry requirements at that time, all solar companies were able to install solar panels for poor households. In order to lower the cost, some solar companies used low-quality solar panels, which broke afterwards. Even worse, many of these solar companies have gone bankrupt, which has caused big problems for maintenance work.

As for the speed and quality of the maintenance work, in general, poor households were satisfied. The interviewees claimed that the majority of issues are quickly solved. The technicians arrive on the second day after they call the maintenance company. Minor problems are solved on the same day, whereas some major problems that need replacement are solved within a week.

As individual-level SEPAP are connected to the grid, Jinzhai County has completed several rounds of grid upgrade work. Simultaneously, poor households have claimed that the electricity supply is more reliable now than it was before. Before 2014, frequent blackouts occurred during the summer and winter. However, after the grid upgrade, these situations improved. Nevertheless, some poor households asserted that a few extreme weather events had caused power outages.

Institutional sustainability

The respondents gave information disclosure a good rating. First, majority of the SEPAP related policy documents are available online. Poor households can also access the government website and enquire online regarding SEPAP. Second, the majority of the interviewees demonstrated that SEPAP was explained during the village residents' meeting at the beginning of the program. Additionally, it was disclosed who was eligible for SEPAP at that time. In addition, the list of poor households that joined SEPAP can also be found on the government website.

The interviews revealed that the training given to the poor was insufficient. Most of the poor said that there was no official training provided by the government, and therefore, they were unaware of the maintenance work. In addition, some of the poor households complained that they did not even realize the solar panel was broken for months. This caused lower revenue generation from SEPAP for the poor. In fact, we also interviewed government officials in Jinzhai County in 2021 and found that the frequency of SEPAP training for government officials varies among government agencies, with at least one time for the past SEPAP period. The majority of county-level agencies hold annual meetings to summarize the progress of the past year and make specific action plans. The most common pattern for government officials was to be trained when a new policy is initiated.

As for the accessibility to the government for issue reporting, most poor households responded positively. The interviewees generally consult with village-level government officials about SEPAP-related questions. However, it should be emphasized that the reaction takes considerably longer if the village-level government officials are unable to resolve the issue and have to refer it to the higher levels.

The program's sustainability was built on the trust of the poor. It was clear from the interview that people trusted the government and maintenance company both. However, trust in the maintenance company was weaker than that in the government for two primary reasons. First, despite not knowing what the solar panel would be used for, most households agreed to install it. Some admitted that they had a kind of blind trust in the government. They explained that "the government would not lie to us" and "the government serves the people." Second, the goal of an average increase in income by 3,000 yuan annually was achieved by some poor households as the government promised, which further enhanced their trust in the local government. However, if the electricity generation and revenue earned by SEPAP decrease, the trust in the government and the maintenance company will gradually erode.

Discussion

SEPAP was a government-led program with the primary purpose of increasing the income of poor households. The scheme enabled poor households to earn ∼3,000 yuan per year from the program owing to the government's substantial subsidy. Therefore, the sustainability of SEPAP is mostly dependent on the economic aspects, i.e., the actual income increased with the project, increased employment, and affordability. The technical and governmental aspects of the project are undoubtedly important, as they have a considerable impact on SEPAP's actual revenue, and it is also necessary to consider the social and environmental benefits of SEPAP, because the program cannot be sustained without these benefits.

Overall, it is difficult to say that SEPAP has succeeded in Jinzhai County, as 70% of the impoverished households were unable to boost their yearly income by 3,000 yuan. However, the income increase effect is still positive. According to the seventh national population census in Anhui Provincial Bureau of Statistics (2021), the average population per family household was 2.61 people. The poverty threshold was 2,800 yuan in 2014 (National Bureau of Statistics of China, 2018). We used this data to calculate the average income growth rate. If the loan was paid off with half of the SEPAP income and the remaining half was regarded as net revenue, the average income growth rate in 2014 was 18.47% (=2,700/2/2.61/2,800), which was a large increase for poor households. If thanks to SEPAP poor households' income increased each year, this could help them to cross the line and escape poverty. Nevertheless, it is important to remember that PV poverty alleviation has little impact on new employment. Additionally, the evaluation of both income and affordability would have deteriorated without the subsidies to the initial installation costs and electricity selling prices to the grid company. The social and environmental impacts were also somehow limited. For some indicators, such as improved education, improved health, increased social activities, and reduction of CO_2 emissions, the impacts were positive, but for others, such as the smaller number of young people leaving the rural areas for the cities and changing energy consumption structures, there has been no fundamental change so far. Technically speaking, most of the solar panels were of good quality, but low-quality PV exists, and it may have had an adverse effect on the sustainability of SEPAP. The stable grid can meet the electricity demand of poor households, and the quality and speed of maintenance work provided by the maintenance company are acceptable for poor households.

SEPAP have considerable short-term advantages, as it can immediately raise the income of poor households and allow them to escape poverty. Additionally, the 20 years of the program provided the poor with a stable income and simultaneously prevented them from slipping into poverty again. However, SEPAP was more alike to a direct income transfer program given the significant role that governmental funding plays in the program. Meanwhile, SEPAP cannot fundamentally solve the poverty problem from the root level because it does not increase the capability of most poor households to work. Hence, we argue that the combination of SEPAP and other poverty alleviation projects can achieve better poverty alleviation results. It was evident from the interview that the combination of SEPAP and 9-year compulsory education had covered most of the education fees of the poor children and increased their education, the combination of SEPAP and "351" medical insurance policy made medical treatments affordable for poor households, and the combination of SEPAP and relocation programs gradually changed the traditional energy consumption source of poor households.

However, we should also note that SEPAP is not suitable for every poor household. The government has already given some low-income households a living subsidy to ensure their basic needs before the launching of SEPAP, and joining SEPAP may lead these people to become lazier. They would believe that they could survive without work and would not look for a job, which equates to utilizing more government assistance to feed lazy people. Such poverty alleviation is definitely not an effective solution. Finally, based on the interview results, we have suggested the following two policy recommendations for future governmental actions on SEPAP maintenance.

Develop a remote monitoring system and help poor households to install this system on their cell phones

The importance of maintenance is self-evident, and understanding the power generation situation of PV at all times is of utmost importance. From the interviews, we noted that that most poor households have smartphones; therefore, they can install an online monitoring application. At the same time, there are already some applications of remote monitoring systems in other provinces and counties. Therefore, developing such a system is necessary and feasible, which enables the poor to access real-time power generation data and real-time income, where poor households can immediately report any noticeable abnormalities to the maintenance company for quick resolution of the problem.

Training for poor households on maintenance knowledge

From the interview, we noted that most poor households have received some kind of explanation about SEPAP, but they lack the knowledge of how to carry out maintenance work correctly. However, the amount of PV power output is being hampered by the weeds in front of their houses and the dust on the solar panels. Therefore, the government must provide training on maintenance work knowledge to poor households. It is suggested that training can be given to village workers first, and then, village cadres can guide poor households to carry out proper maintenance work, thereby lowering the amount lost because of improper maintenance labor.

Conclusion

By assessing individual-level SEPAP in Jinzhai County through a sustainability framework and an AHP-based fussy comprehensive method, this study contributes to a deeper understanding of the impacts and implementation status of SEPAP in rural China. Furthermore, this research is also important to future sustainable development, especially in the context of the transition from poverty alleviation to rural revitalization, as solar energy has been recognized as an important energy source in the process of rural revitalization (State Council, 2018).

However, our research has some limitations. First, the small sample of interviews of only individual-level SEPAP stakeholders limited our ability to compare different types of SEPAP in Jinzhai County. Second, the limited results of our fieldwork in Jinzhai County restrict our conclusions and policy recommendations to being applicable to other rural areas in China. To overcome these issues, more research should be conducted in the future with a larger sample size, on different types of SEPAP, and with field data from other counties as well.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

ZJ: conceptualization, methodology, data analysis, and writing original draft. DI: conceptualization, reviewing, and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Anhui Provincial Bureau of Statistics (2021). *The Main Data of the Seventh National Population Census in Anhui Province* (in Chinese). Available online at: http://tjj.ah.gov.cn/ssah/qwfbjd/tjgb/sjtjgb/145782311.html (accessed September 21, 2022).

Boliko, C. M., and Ialnazov, D. S. (2019). An assessment of rural electrification projects in Kenya using a sustainability framework. *Energy Policy* 133, 110928. doi: 10.1016/j.enpol.2019.110928

Cheng, X., Chen, J., Jiang, S., Dai, Y., Zeng, J., Shuai, C., et al. (2021). Pursuing sustainable development goals: a review of renewable energy and poverty alleviation nexus. *Environ. Dev.* 40, 100679. doi: 10.1016/j.envdev.2021.100679

Huang, Y., Huang, B., Song, J., Xu, X., Chen, X., Zhang, Z., et al. (2021). Social impact assessment of photovoltaic poverty alleviation program in China. *J. Clean. Prod.* 290, 125208. doi: 10.1016/j.jclepro.2020.125208

Ilskog, E. (2008). Indicators for assessment of rural electrification—An approach for the comparison of apples and pears. *Energy Policy* 36, 2665–2673. doi: 10.1016/j.enpol.2008.03.023

Ilskog, E., and Kjellström, B. (2008). And then they lived sustainably ever after?—Assessment of rural electrification cases by means of indicators. *Energy Policy* 36, 2674–2684. doi: 10.1016/j.enpol.2008.03.022

International Energy Agency (2022). *Access to Electricity*. Available online at: https://www.iea.org/reports/sdg7-data-and-projections/access-to-electricity (accessed August 15, 2022).

Lin, B., and Wang, Y. (2020). Does energy poverty really exist in China? From the perspective of residential electricity consumption. *Energy Policy* 143, 111557. doi: 10.1016/j.enpol.2020.111557

Liu, J., Huang, F., Wang, Z., and Shuai, C. (2021). What is the anti-poverty effect of solar PV poverty alleviation projects? Evidence from rural China. *Energy* 218, 119498. doi: 10.1016/j.energy.2020.119498

Lo, K. (2021). Can authoritarian regimes achieve just energy transition? Evidence from China's solar photovoltaic poverty alleviation initiative. *Energy Res. Soc. Sci.* 82, 102315. doi: 10.1016/j.erss.2021.102315

National Bureau of Statistics of China (2018). *Rural Poverty Monitoring Report 2018* (in Chinese). Available online at: https://www.yearbookchina.com/navibooklist-n3019032313-1.html (accessed September 23, 2022).

National Bureau of Statistics of China (2020). *Poverty Monitoring Report in China 2020* (in Chinese). Available online at: https://www.yearbookchina.com/navibooklist-n3021031904-1.html (accessed September 23, 2022).

National Development and Reform Commissions (2016). *Opinions on the Implementation of SEPAP* (in Chinese). Available online at: https://www.ndrc.gov.cn/xxgk/zcfb/tz/201604/t20160401_963011.html?code=&state=123 (accessed August 10, 2022).

National Energy Administration (2020a). *Household Solar PV Project Information* (in Chinese). Available online at: http://www.nea.gov.cn/2020-12/16/c_139594051.htm (accessed October 28, 2022).

National Energy Administration (2020b). *Solar Energy for Poverty Alleviation: Construction Tasks Are Fully Completed, and Poverty Alleviation Methods Are Widely Popular* (in Chinese). Available online at: http://www.nea.gov.cn/2020-10/30/c_139478911.htm (accessed August 9, 2022).

National Energy Administration (2022). *Household Solar PV Project Information* (in Chinese). Available online at: http://www.nea.gov.cn/2022-01/19/c_1310431338.htm (accessed October 26, 2022).

Shanghai Municipal Bureau of Human Resources and Social Security (2022). *The City's Minimum Wage Will Not Be Adjusted in 2022, and the Monthly Minimum Wage Will Continue to be 2590 Yuan* (in Chinese). Available online at: https://m12333.cn/policy/kbcf.html (accessed September 26, 2022).

State Council (2018). *The Strategy of Rural Revitalization* (in Chinese). Available online at: http://www.gov.cn/zhengce/2018-09/26/content_5325534.htm (accessed September 25, 2022).

Sumner, A., Hoy, C., and Ortiz-Juarez, E. (2020). "Estimates of the impact of COVID-19 on global poverty (No. 2020/43)," in *WIDER Working Paper*. doi: 10.35188/UNU-WIDER/2020/800-9

Tao, Y., Wu, Y., Wu, M., Luo, X., He, F., Gao, R., et al. (2022). Multi-criteria decision making for comprehensive benefits assessment of photovoltaic poverty alleviation project under sustainability perspective: a case study in Yunnan, China. *J. Clean. Prod.* 346, 131175. doi: 10.1016/j.jclepro.2022.131175

Thiam, D. R. (2011). Renewable energy, poverty alleviation and developing nations: evidence from Senegal. *J. Energy South Afr.* 22, 23–34. doi: 10.17159/2413-3051/2011/v22i3a3219

Wang, C., Cheng, X., Shuai, C., Huang, F., Zhang, P., Zhou, M., et al. (2020). Evaluation of energy and environmental performances of solar photovoltaic-based targeted poverty alleviation plants in China. *Energy Sustain. Dev.* 56, 73–87. doi: 10.1016/j.esd.2020.04.003

Wei, Q. (2021). Sustainability evaluation of photovoltaic poverty alleviation projects using an integrated MCDM method: a case study in Guangxi, China. *J. Clean. Prod.* 302, 127040. doi: 10.1016/j.jclepro.2021.127040

World Bank (2022). *Access to Electricity (% of Population)*. Available online at: https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS (accessed August 20, 2022).

Yadoo, A., and Cruickshank, H. (2012). The role for low carbon electrification technologies in poverty reduction and climate change strategies: a focus on renewable energy mini-grids with case studies in Nepal, Peru and Kenya. *Energy Policy* 42, 591–602 doi: 10.1016/j.enpol.2011.12.029

Yanzhe, W., Sheng, Z., Yu, W., Xuying, Q., Fubing, C., and Xunmin, O. (2021). Comprehensive assessment of the environmental impact of China's nuclear and other power generation technologies. *Tsinghua Sci. Technol.* 61, 377–384. doi: 10.16511/j.cnki.qhdxxb.2021.25.006

Zhang, H., Wu, K., Qiu, Y., Chan, G., Wang, S., Zhou, D., et al. (2020). Solar photovoltaic interventions have reduced rural poverty in China. *Nat. Commun.* 11, 1–10. doi: 10.1038/s41467-020-15826-4