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The Most Economical Mode of Power Supply for Remote and Less Developed Areas in China: Power Grid Extension or Micro-Grid?

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Abstract: There are still residents without access to electricity in some remote and less developed areas of China, which lead to low living standards and hinder sustainable development for these residents. In order to achieve the strategic targets of solving China's energy poverty, realizing basic energy service equalization, and comprehensively building up a moderately prosperous society, several policies have been successively promulgated in recent years, which aim to solve the electricity access issue for residents living in remote and less developed areas. It is of great importance to determine the most economical mode of power supply in remote and less developed areas, which directly affects the economic efficiency of public investment projects. Therefore, this paper focuses on how to select the most economical power supply mode for rural electrification in China. Firstly, the primary modes to supply electricity for residents living in the remote and less developed areas are discussed, which include power grid extension mode and micro-grid mode. Secondly, based on the levelized cost of electricity (LCOE) technique, the life cycle economic cost accounting model for different power supply modes are built. Finally, taking a minority nationality village in Yunnan province as an example, the empirical analysis is performed, and the LCOEs of various possible modes for rural electrification are accounted. The results show that the photovoltaic (PV)-based independent micro-grid system is the most economical due to the minimum LCOE, namely 0.658 RMB/kWh. However, other power supply modes have much higher LCOEs. The LCOEs of power grid extension model, wind-based independent micro-grid system and biomass-based independent micro-grid system are 1.078 RMB/kWh, 0.704 RMB/kWh and 0.885 RMB/kWh, respectively. The proposed approach is effective and practical, which can provide reference for rural electrification in China.

Keywords: power supply; economical mode; levelized cost of electricity (LCOE); rural electrification; China

1. Introduction

Energy is necessary for the production and operation of modern society, which is also the important material basis for human survival and important driving force for the development of human society as well as economy [1,2]. Energy can provide power for people's daily production and life activities, which is also the significant factor to eliminate poverty, improve education level and promote sustainable development [3]. The electric power industry is a critical basic and leading industry for economic and social development in China [4]. As a kind of network-oriented public infrastructure industry with the characteristic of natural monopoly, China's electric power industry has the property of universal service, which indicates that it should provide affordable electricity products and services with no discriminations regarding price, quality, and regions for any residents [5–7]. The electric universal service level not only reflects the guarantee for the rights of Chinese survival and development, but also is regarded as an important symbol of realizing basic energy service equalization and comprehensively building up a moderately prosperous society. In recent years, a number of policies have been promulgated in succession to promote the electric universal service for providing electric energy to residents living in remote and less developed areas, such as 'China's Energy Policy (2012)' promulgated by the State Council of China [8], 'Three-year action plan for comprehensively solving electric usage problems for rural residents (2013–2015)' issued by the National Energy Administration [9], and 'Implementation opinions of speeding up energy development in poor areas to promote poverty alleviation (2016)' proclaimed by the National Energy Administration [10]. The relevant policies point out that the power grid extension and new energy-based micro-grid are the primary modes to tackle the issues of residents' access to electricity in remote and less developed regions, such as Tibet, Xinjiang, and Inner Mongolia autonomous regions [11].

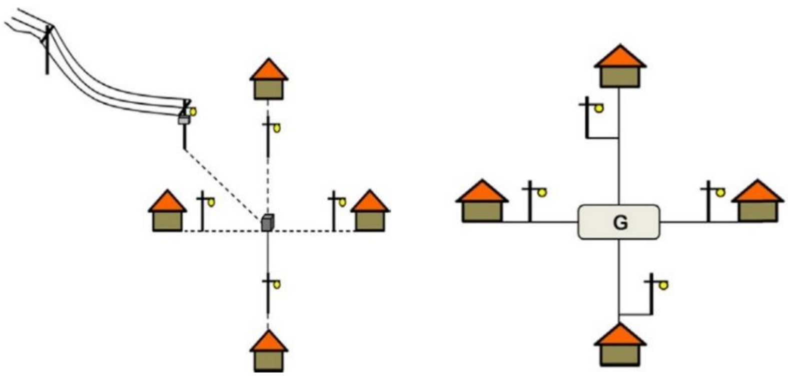
The provision and implementation of electric universal service can give the residents living in remote and less developed regions access to electricity, which can improve the living quality and education level of residents in these areas, guarantee their basic rights of survival and development, and promote sustainable development of individuals and regional society [5,12]. The electric power supply in remote and less developed regions, namely rural electrification holds the characteristics of low load density, poor load factor and high investment operation cost [13,14]. Meanwhile, the residents in these areas mainly work in agriculture, who usually have low incomes, poor education and weak electricity consumption. Therefore, the unit cost of electricity supply in these regions is usually higher than that of other developed regions. In China, the electricity provision for remote and less developed regions is promoted by government and implemented by power grid enterprises, which mainly takes two modes, i.e., power grid extension and micro-grid [6,11].

At the aim of allocating the resources more rationally and effectively, the economy of power supply projects implemented by power grid enterprises in remote and less developed regions should be considered. There are some differences among the abovementioned power supply modes, such as power generation types and technologies, investment and operation cost, and life cycle. Therefore, it is quite necessary to determine the most economical one, which contributes to improving the economic efficiency of power supply and investment efficiency of government public projects. Considering the abovementioned differences between power grid extension mode and micro-grid mode, the traditional technical economic analysis methods, such as net present value (NPV) and internal rate of return (IRR) are difficult to rationally and effectively compare and evaluate different power supply modes. Levelized cost of electricity (LCOE), as a new technique used to evaluate the economy of power supply projects based on whole life-cycle thinking, can fairly and reasonably compare the economic costs of different power supply modes with different power supply technologies, power generating capacities, and investment payoff periods [15–18]. In recent years, the LCOE technique has been employed in some practical issues, such as solar PV and CSP electricity costs [19], wave energy [20], waste-to-energy facilities [21], tidal kinetic self-balancing turbine [22], and wind power [23]. Therefore, on the basis of LCOE technique, this paper proposes an optimal selection approach regarding power supply modes for rural electrification, which can achieve comparative analysis on economic cost of different power supply modes (namely power grid extension mode and micro-grid mode) and determine the most economical power supply mode. It can provide references for the reasonable construction of power supply project in remote and less developed regions and effective implementation of electric universal service policy in China.

Section 2 introduces the power supply modes for rural electrification, which includes power grid extension mode and micro-grid mode. The optimal selection approach regarding power supply modes for residents living in remote and less developed regions is elaborated in Section 3. Section 4 conducts the empirical analysis by taking a national minority village of China as an example. Section 5 gives the conclusions.

2. Power Supply Modes in Remote and Less Developed Areas

Power suppliers need to provide basic electricity services with undifferentiated quality and price within the scope of their production capacity for residents living in remote and less developed areas. In China, there are mainly two corporations, State Grid Corporation of China (SGCC) and Southern Power Grid Corporation (SPGC), which are able to provide electricity services for residents living in remote and less developed areas by taking power grid extension mode. Simultaneously, the abovementioned grid corporations and some power generation enterprises can also provide electricity for residents living in remote and less developed areas by constructing micro-grid, which consists of new energy-based generating units, power load and energy storage system. The schematic diagram of two modes for rural electrification is shown as Figure 1 [24].



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

Figure 1. Schematic diagram of two modes for rural electrification. (**a**) Grid extension; (**b**) Micro-grid.

2.1. Power Grid Extension Mode

Power grid extension refers to that the power supply network is extended to the remote and less developed areas through the erection of medium-voltage transmission lines and the establishment of low-voltage distribution network. Electric power systems are complex and comprehensive systems of electricity generation, transmission, distribution and consumption, which are consisted of power station, power substation, electric transmission line, electric distribution line, and electricity consumption equipment. In China, the output rated voltage of generator unit in power station is in the range of 3.15 kV and 20 kV. In order to reduce transmission energy losses in the process of electricity transmission, the electric energy generated by generator units will experience several procedures, and then it can finally be transmitted to terminal users. The procedures include voltage rise by transformer, electricity transmission by high-voltage transmission lines, voltage reduction by transformer, electricity transmission by distribution lines, and voltage reduction by distribution substation. A diagram of a generic portion of China's electric power system is shown as Figure 2.

In China, the technological process of providing electricity for residents living in remote and less developed areas by taking power grid extension mode is illustrated in Figure 3. Firstly, the electric power corporation selects a 35/10 kV substation near the remote and less developed area as the starting point of urban power grid extending to rural power grid. Then, the electric power corporation installs a 10 kV/380 V distribution transformer in a selected rural village, and connects the selected 35/10 kV substation to the newly installed 10 kV/380 V distribution transformer by erecting 6–10 kV distribution line. Two types of power load exist in rural area, of which one is the residential electrical load, such as lights and televisions. For this kind of power load, the electric energy is stepped down by 10 kV/380 V distribution transformer and then delivered through single phase 220 V low-voltage transmission line. Another type of power load is small factory-related electrical load, such as the electrical load of individual workshops and food processing plants operated by residents. For this kind of power load, the electric energy needs to be stepped down by 10 kV/380 V distribution transformer and then conveyed through three-phase 380 V low-voltage transmission line. Therefore, when the rural electrification is realized by power grid extension mode, the distribution line and distribution transformer are needed to construct by electric power corporation.

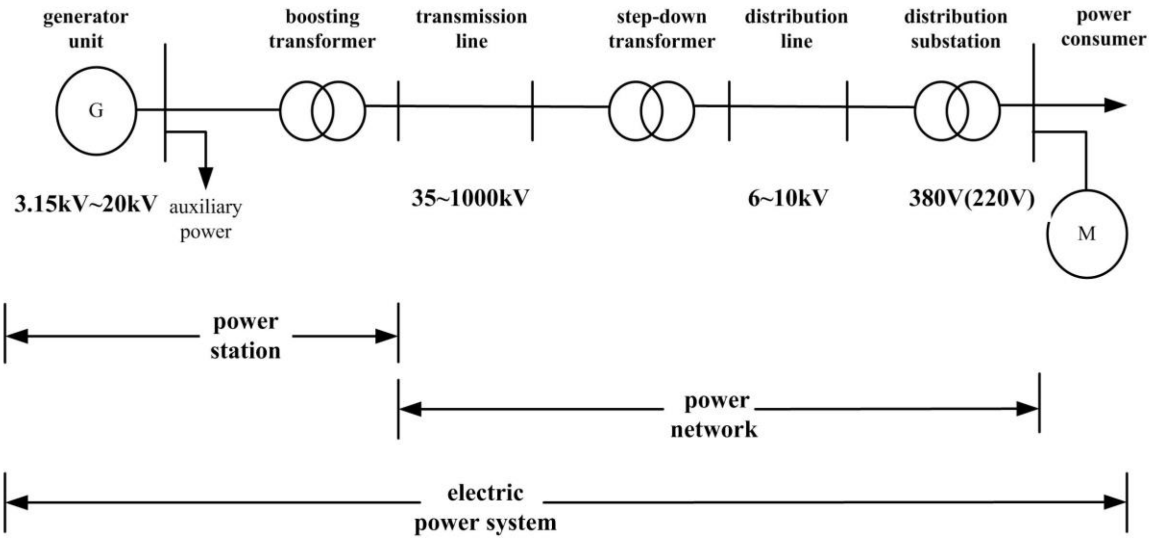


Figure 2. Schematic diagram of a generic portion of China's electric power system.

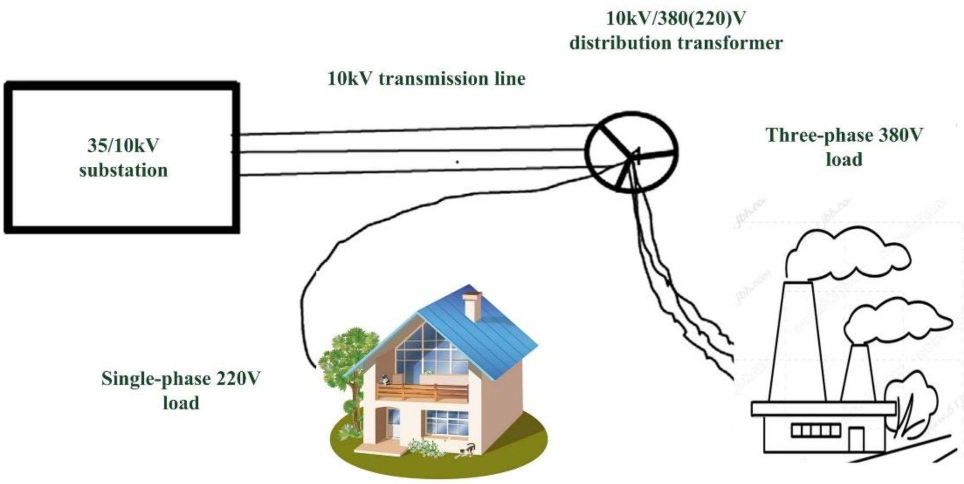


Figure 3. Schematic diagram of rural electrification by taking power grid extension mode.

2.2. Micro-Grid Mode

With the development of science and technology as well as the continuous growth of energy demand and power grid, China has entered into an era of super intelligent interconnected electric network with ultra-high voltage and long distance transmission [25–28]. However, with the constraints of regional different resources endowment and power grid characteristics, the dependence of receiving-end grid on external electricity under the condition of long distance transmission is constantly strengthening [29,30]. So, people increasingly pay attentions to the security and stability of interconnected power grid operation [31]. Currently, the traditional fossil fuel gradually depletes, and the human living environment increasingly deteriorates. Meanwhile, more and more people concern the stability of large interconnected network system, and show diversified power demands. Under these conditions, the distributed power generation with environmental, efficient and flexible characteristics gets more and more attentions [32–34]. Distributed power generation usually supplies electric energy for users by constructing relatively small power generation device with capacity of under 50 MW, which has the advantages of high energy utilization efficiency and less environmental pollution. However, the distributed power generation also has some disadvantages, such as being difficult to control and high cost of single machine intervention. Moreover, when the power system breaks down, the distributed power generation is usually isolated and may quit running in the first place, which largely weakens the advantages of distributed power generation [35–37].

At the aim of exploring the values of distributed power generation and coordinating the contradiction between distributed power generation and power grid, the concept of micro-grid was proposed, which has been developed in practice [38,39]. Micro-grid is a kind of new-type network structure grid connecting electric generators, energy storing devices, control equipment and load together via topological structure, which can achieve self-control, protection and management [40–42]. The power supply in micro-grid is mostly miniature generator unit with installed capacity of less than 100 kW, such as mini-type wind turbine generator, photovoltaic power generator and biomass power generator. Micro-grid not only exhibits strengths of economic, social and environmental advantages of distributed power generation, but also brings benefits to users [43,44].

The micro-grid in China is still in its infancy. In 2015, the National Energy Board issued 'Guidance on the construction promotion of new energy micro-grid demonstration projects', which pointed out that new energy micro-grid is the significant developmental and innovational direction of renewable energy and distributed energy, and it is also the innovative application in the field of 'energy internet plus'. Currently, China is vigorously promoting micro-grid demonstration projects, which are mainly divided into three categories: new energy micro-grid in remote areas, micro-grid in urban areas and micro-grid in islands. The traditional grid extension has some shortcomings, such as high transmission line construction cost because of the long distance between rural power load center and transformer substation location, and environmental pollution induced by the transmitted electricity generated by non-renewable power generating units. However, the independent micro-grid system can tackle abovementioned issues, because it is usually constructed near the rural power load center and employs renewable energy to produce electricity. Nowadays, the independent micro-grid projects are constructing in the remote areas of China, which can effectively achieve rural electrification and is regards as an effective way of electric universal service in China.

Regarding micro-grid mode for rural electrification, in case of high load and large electricity demand, the hybrid micro-grid mode consisting wind power generator, solar photovoltaic power generator and biomass power generator can be employed, as shown in Figure 4a. If the load remains low and electricity demand is small, independent power generator micro-grid mode can be adopted, such as wind-based independent micro-grid, PV-based independent micro-grid, and biomass-based independent micro-grid, as shown in Figure 4b.

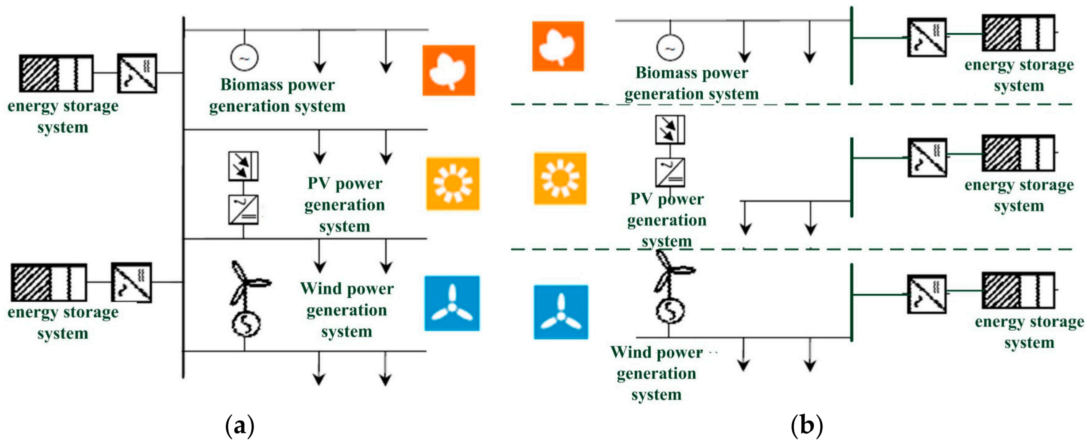


Figure 4. Micro-grid mode for rural electrification. (**a**) Hybrid micro-grid; (**b**) Independent micro-grid.

3. Method

In this paper, the economies of two power supply modes for residents living in remote and less developed areas will be evaluated based on LCOE technique. By comparing the economies of power grid extension mode and micro-grid mode, the most economical model for rural electrification can be selected.

3.1. The Basic Theory of LCOE

Levelized cost of electricity (LCOE) is the life cycle cost of per kWh power generation considering the capital time value [18,23]. The time value of capital reflects resource scarcity, which indicates the same amount of money have different values at different time nodes. The time value of capital can be reflected by discounted cash flow (DCF), that is, the current value of future cash flows at different time nodes is calculated by discount rate r [45,46].

It is necessary to consider all processes related to power generation when the generation costs of different generating units are calculated based on life cycle thought, which include power plant construction, operation, maintenance, and out of commission. Therefore, LCOE of generating units can be determined according to the principle that the sum of present value for power generation income at each period is equal to the sum of present value for power generation life cycle cost at each period, namely

$$\sum_{n=0}^{N} \frac{R_n}{(1+r)^n} = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n} \quad (1)$$

where R_n is the revenue of generating units in the year of n, C_n is the generation cost of generating units in the year of n, r is discounting rate, and N is project lifetime.

At this point, the net present value (NPV) of power generation project is equal to 0, that is

$$NPV = \sum_{n=0}^{N} PV_i = 0 \quad (2)$$

where PV_i represents the present value of power generation project at time i.

As we can see from Equation (2), LCOE is the average price of electricity which makes the net present value of project cash flow equals to 0.

The sum of discounted value of $LCOE_n$ multiplied by power generation amount E_n should be equal to the sum of discounted value of annual life cycle cost of power generation project, that is

$$\sum_{n=0}^{N} \frac{LCOE_n \times E_n}{(1+r)^n} = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n} \quad (3)$$

Assuming that the LCOE of each year is same, namely

$$LCOE_1 = LCOE_2 = \cdots = LCOE_n = LCOE \quad (4)$$

Then, Equation (3) can be rewritten as

$$\sum_{n=0}^{N} \frac{LCOE \times E_n}{(1+r)^n} = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n} \quad (5)$$

Therefore, we can obtain

$$LCOE = \frac{\sum_{n=0}^{N} \frac{C_n}{(1+r)^n}}{\sum_{n=0}^{N} \frac{E_n}{(1+r)^n}} \quad (6)$$

Equation (6) indicates that the LCOE of project is equal to the sum of discounted value of cost at each period in the life cycle divided by the total power generation amount considering time value. It should be noted that the initial investment of project does not need to be discounted since it occurs in the first year.

The LCOE of power generation project can be calculated according to Equation (7):

$$LCOE = \sum_{n=1}^{N} \frac{CA_n + O_n + T_n}{(1+r)^n} / \sum_{n=1}^{N} \frac{IC \times h_n \times (1-s)}{(1+r)^n} \tag{7}$$

where CA_n represents the discounted value of initial investment of generating units at the year of n, O_n indicates the expenditure of production, operation, and maintenance for generating units at the year of n, T_n implies the taxes paid at the year of n, IC is the rated capacity of generating units, h_n is power generation utilization hours in the year of n, and s is the own electricity consumption rate.

In China, the financial net present value (NPV) method is always employed in economic feasibility assessment of power generation projects, that is, determining whether the net present value of project is greater than 0 [47,48]. The NPV method determines the project feasibility according to the profit and loss of project investment, but it cannot reflect the unit investment income of the project, especially it cannot make proper judgment on investment projects with different installed power generation capacity and power generation technology. However, LCOE not only takes the time value of capital and life cycle benefits and costs into account, but also overcomes the weakness of NPV.

3.2. LCOE Model for Power Grid Extension Mode

Employing the power grid extension mode to supply electricity for residents living in remote and less developed areas, the distribution lines and transformers need to be newly constructed, which will bring about distribution LCOE. Meanwhile, this mode needs to consider power generation LCOE and power transmission LCOE [49]. Therefore, the LCOE of power grid extension mode for rural electrification is consisted of three parts: power generation LCOE, power transmission LCOE, and power distribution LCOE.

3.2.1. Power Generation LCOE

LCOE method is an effective method to compare different types of power generation projects with different power generation technologies, life cycles, investment costs, and operation as well as fuel costs. Generally, the electricity consumed by terminal consumers may come from different types of power generation units, such as coal-fired units, hydroelectric generating sets, and new energy generating units. Therefore, LCOE of power generation can be calculated by

$$LCOE_g = \sum_{i=1}^{m} w_i \times LCOE_i \tag{8}$$

where $LCOE_g$ is the power generation LCOE of power grid extension mode, $LCOE_i$ represents the LCOE of the ith power generation technology, w_i indicates the proportion of the ith technology-related power generation in total power generation amount, and i represents the type of power generation technology, which can be coal, hydroelectricity, and gas.

3.2.2. Power Transmission LCOE

Power transmission cost mainly contains construction cost, operation and maintenance cost, tax, and other expenses. Of which, construction cost includes the expenses of transmission lines erection and transformer installation. Operation and maintenance cost is composed of materials expense, wages as well as welfare, maintenance cost, management cost, added-value tax, urban construction tax, and extra charges of education funds. Tax mainly brings out by investment construction loan.

Simultaneously, the transmission cost is also affected by power transmission loss. Power transmission LCOE can be calculated by

$$LCOE_t = \sum_{n=1}^{N} \frac{CA_n + O_n + T_n}{(1+r)^n} / \sum_{n=1}^{N} \frac{E_n \times (1-s)}{(1+r)^n} \quad (9)$$

where CA_n represents the discounted value of initial investment for transmission lines and transformers in the year of n, O_n is the operation and maintenance cost in the year of n, T_n is the taxes paid in the year of n, E_n indicates the amount of electricity transmitted by transmission lines in the year of n, and s is the loss of transmission and voltage transformer.

3.2.3. Power Distribution LCOE

New distribution lines and transformers are required to be set up on the side of distribution network when power grid extension mode is employed to supply electricity. The 35 kV electric energy needs to be stepped down to 10 kV level through transformers, and transmitted to rural areas via medium-voltage distribution lines. After that, the 10 kV electric energy is converted to 380 V or 220 V through the transformer substation located in rural areas. This process requires the erection of three-phase 10 kV medium voltage distribution lines, three-phase or single-phase 380 V and 220 V low voltage distribution lines and transformer substation. In order to reduce construction costs of power grid extension, the Energy Sector Management Assistance Program (ESMAP) suggested that it is better to make full use of single-phase distribution lines in the case of technical feasibility for distribution lines construction [50,51].

Power distribution LCOE can be calculated by Equation (10):

$$LCOE_d = \frac{\left(C_T P_{PL}/p_f + x_{10}C_{10} + x_{220}C_{220} + x_{380}C_{380}\right) \times (CRF_d + \beta_d)}{8760 \times P_{PL} \times \Psi^{LF}} \quad (10)$$

where $LCOE_d$ is power distribution LCOE, C_T represents the unit investment cost of transformers in distribution side, P_{PL} is the expected load in rural areas, p_f is the power factor of transformer, x_{10}, x_{220}, x_{380} respectively represents the length of 10 kV, 220 V, and 380 V distribution lines, C_{10}, C_{220}, C_{380} respectively indicates the unit investment cost of 10 kV distribution line, 220 V single-phase line, and 380 V three-phase line, CRF_d implies capital recovery factor which can be calculated by $CRF_d = r(1+r)^t/(1+r)^t - 1$, β_d is the share of annual operation and maintenance fee in total distribution network construction investment, and Ψ^{LF} demonstrates the power factor of new constructed distribution network.

3.2.4. LCOE of Power Grid Extension Mode

Above all, the LCOE of power supply for residents living in remote and less developed areas by taking power grid extension mode can be calculated as follow:

$$LCOE_{ge} = \frac{LCOE_g}{1 - l_{td}} + LCOE_t + LCOE_d \quad (11)$$

where $LCOE_{ge}$ represents the LCOE of power grid extension mode, $LCOE_g$, $LCOE_t$, $LCOE_d$ are the levelized cost of power generation, transmission, and distribution respectively, and l_{td} is the loss rate of transmission and distribution line.

3.3. LCOE Model for Micro-Grid Mode

The new energy micro-grid mainly consists of new energy generating units, energy storage system, and distribution lines. Considering the energy resource endowment, transport condition and renewable energy development as well as related supporting policies in China, the main new energy generating units can be divided into wind-based generating unit, solar PV-based generating unit, and biomass-based generating unit.

The LCOE of wind-based micro-grid mode can be calculated by Equation (12):

$$LCOE_{wind} = \sum_{n=1}^{N} \frac{CA_n + O_n + T_n + (x_l C_l)_n + Con_n + ESB_n}{(1+r)^n} / \sum_{n=1}^{N} \frac{IC \times h_n \times (1-s)}{(1+r)^n} \quad (12)$$

where x_l represents the length of distribution line in micro-grid, C_l represents the unit cost of distribution line, Con_n represents annualized converter investment cost, and ESB_n represents annualized cost of energy storage battery.

Different from wind power generation, the solar photovoltaic components are affected by sunlight, wind and rain to a large degree. So, the annual power generation amount of PV generating unit will decline. Therefore, the LCOE of PV-based micro-grid can be computed as

$$LCOE_{pv} = \sum_{n=1}^{N} \frac{CA_n + O_n + T_n + (x_l C_l)_n + Con_n + ESB_n}{(1+r)^n} / \sum_{n=1}^{N} \frac{IC \times h_n \times (1-d)^n (1-s)}{(1+r)^n} \quad (13)$$

where d represents annual degradation rate of photovoltaic modules.

The LCOE of biomass-based micro-grid mode can be calculated as

$$LCOE_{biomass} = \sum_{n=1}^{N} \frac{CA_n + O_n + T_n + (x_l C_l)_n + Con_n + ESB_n}{(1+r)^n} / \sum_{n=1}^{N} \frac{IC \times h_n \times (1-s)}{(1+r)^n} \quad (14)$$

The most economical mode of power supply for residents living in remote and less developed areas is the mode with the minimum LCOE. So, after the LCOEs of different power supply modes are calculated, the most economical mode for rural electrification can be decided.

4. Empirical Analysis

There are still residents living in China's remote and less developed areas such as Yunnan province, Xinjiang autonomous region, Qinghai autonomous region and Inner Mongolia autonomous without access to electricity. Yunnan province, located in the southwest border with characteristics of frontier areas, ethnic minorities, mountains and poverty, is an important province related to electric universal service implementation in China. In 2005, the project of 'electrical engineering construction in the areas without electricity' was launched in Yunnan province, which has solved the electricity consumption issue of 319.3 thousand households and made the electrified rate reach 99.2%. In this paper, we select an ethnic minority village located in Yunnan province, named Luomian village as the empirical object. Luomian village has 75 peasant households and 322 rural populations, dominated by the Yi nationality and Miao nationality. The earnings from planting and livestock breeding are the main income sources of residents in this village. The expected monthly average electricity consumption per household is 123.6 kWh. Therefore, the annual electricity consumption amount of this ethnic minority village is about 111.24 MWh.

4.1. LCOE Calculation for Power Grid Extension Mode

The electrical energy is supplied by grid extension mode for this ethnic minority village, and the LCOE includes power generation LCOE, power transmission LCOE and power distribution LCOE.

4.1.1. LCOE Accounting of Power Generation

The electrical energy in Yunnan province are mainly generated by hydroelectricity which accounted for 70% of total generated electricity, and the rest are mainly generated from coal-fired units. Therefore, regarding the LCOE accounting of power generation for power grid extension mode, hydroelectric power generation and coal-fired power generation are selected which respectively account for 70% and 30% of total generated electricity amount. Typical hydroelectric power stations and coal-fired power plants are selected, and the relevant parameters are listed in Table 1, the data of which come from the feasibility study reports of hydroelectricity units construction and coal-fired units construction. The generating capacities of typical hydroelectric units and coal-fired units are 250 MW and 600 MW, respectively. The planned power generating hours of hydroelectric units are higher than that of coal-fired units, which are respectively 4500 h and 4200 h. The life cycle and construction period of hydroelectric unit and coal-fired unit are quite different, and the hydroelectric units has longer construction period and life cycle. Meanwhile, the feed-in tariffs of hydroelectric units are lower than that of coal-fired units, which indicates hydroelectric units have more competitive. The wage and welfare of coal-fired unit are much higher than that of hydroelectric unit, which mainly relate to the number of employees and treatment. The other parameters between hydroelectric unit and coal-fired unit are basically same, such as own capital ratio, premium rate, loan interest rate, and tax.

According to Table 1 and Equation (7), the power generation LCOEs of hydroelectric unit and coal-fired unit can be calculated. Then, the power generation levelized cost of electricity $LCOE_g$ of power grid extension mode can be obtained based on Equation (8), which is equal to 0.242 RMB/kWh.

Table 1. Parameters of hydroelectric unit and coal-fired unit.

Parameters	250 MW Hydroelectric Units	600 MW Coal-Fired Units
Generating capacity	250 MW	600 MW
Planned power generating hours	4500 h	4200 h
Own power consumption rate	4%	6%
Life cycle	50 years	25 years
Construction period	4 years	1 year
Construction investment cost	1.75 billion RMB	2.31 billion RMB
Own capital ratio	20%	20%
Feed-in tariffs	0.27 RMB/kWh	0.336 RMB/kWh
The proportion of operation and maintenance costs in total investment	2%	2.5%
	increase 1% annually	increase 1% annually
Premium rate	0.25%	0.25%
Loan interest rate	6.12%	6.12%
The share of other expenses in annual income	2%	2%
Wage and welfare	6.05 million RMB	63.47 million RMB
	increase 2% annually	increase 2% annually
Residual value of fixed assets	5%	5%
Value added tax	17%	17%
Urban maintenance and Construction tax	5%	4%
Education surtax	3%	3%
Corporate income tax	25%	25%

4.1.2. LCOE Accounting of Power Transmission

China's transmission line can be classified into several types, such as 1000 kV ultra high voltage transmission line, 500 kV extra high voltage transmission line, and 220 kV/110 kV/35 kV high voltage transmission line. Considering the characteristics of power grid structure near Luomian village, the 110 kV transmission project is selected to account power transmission LCOE of power grid extension mode.

The selected typical 110 kV transmission project includes two 50 MWA main transformers, GIS device, four overhead outlets and LGJ-150135-type wire. The related cost parameters of this 110 kV transmission project are listed in Table 2, the data of which come from the feasibility study report of transmission and transformation project construction. The construction period is one year, and the life cycle is 25 years. The initial construction investment is 16 million RMB, of which the equity capital accounts for 20% and the loan accounts for 80% with 6.12% of loan interest rate. The residual value of construction project is 5%, and the loss rates of lines and transformers are 2% and 1.8% respectively. The annual transmission capacity is 0.104 billion kWh. Four kind of taxes are needed to pay, which include value added tax (17%), urban maintenance and construction tax (5%), education surtax (3%), and corporate income tax (25%).

According to Table 2 and Equation (9), the power transmission levelized cost of electricity $LCOE_t$ of power grid extension mode can be calculated, which is equals to 0.075 RMB/kWh.

Table 2. Cost parameters of 110 kV transmission project.

Parameters	Value
Transmission scale	110 kV
Annual transmission capacity	0.104 billion kWh
Line loss	2%
Transformers loss	1.8%
Construction time	1 year
Construction investment cost	16 million RMB
Life cycle	25 years
Own capital ratio	20%
The proportion of operation and maintenance costs in fixed investment	1.6%
Premium rate	0.25%
Loan interests rate	6.12%
The proportion of wage and welfare in fixed investment	1.22%
Residual value of fixed assets	5%
Value added tax	17%
Urban maintenance and construction tax	5%
Education surtax	3%
Corporate income tax	25%

4.1.3. LCOE Accounting of Power Distribution

The residents in this village live by planting and livestock breeding, no small workshops, such as individual workshops and processing plants. Therefore, 10 kV and only 220 V distribution lines are needed to erect the distribution lines. The 380 V distribution lines are not needed because there are no small workshops. According to the distance of this village from the nearest urban power distribution station and the living environment, there needs 21.5 km of 10 kV medium voltage distribution line and 2.9 km of 220 V low-voltage distribution line. The power factor of rural distribution grid is 0.8–0.9. With consideration of effective utilization on electrical equipment, this paper takes 0.9 as the power factor of newly-built rural distribution grid. The maximum load is 42 kW, and the load factor is 0.8.

According to Equation (10), the power distribution levelized cost of electricity $LCOE_d$ of power grid extension mode can be calculated, which is equal to 0.68 RMB/kWh.

After obtaining the power generation $LCOE_g$, the power transmission $LCOE_t$, and power distribution $LCOE_d$, we set the loss rate of power transmission and distribution as 0.25, and then the LCOE of power grid extension mode for rural electrification in Luomin village can be calculated according to Equation (11), which is equal to 1.078 RMB/kWh.

4.2. LCOE Calculation for Micro-Grid Mode

According to the foregoing analysis, the annual electricity consumption of this village is about 111.24 MWh. On the basis of this, considering the utilization hours of the new energy-based power generating units, it can be found that if the wind-based independent micro-grid system is installed, the capacity should be 60 kW; if PV-based independent power generation system is installed, the capacity should be 80 kW; if biomass-based independent power generation system is installed, the capacity should be 30 kW. Although Yunnan province is very rich in hydropower, according to the location of this village and actual water resource endowment, it is not suitable to install small hydroelectric generating set to provide electricity for this village. Moreover, due to the small load in this village, the installed capacity of generating unit of each independent power generation system is relatively small. Therefore, there is no need to use hybrid micro-grid system, such as wind + PV, wind + biomass, or PV + biomass.

Wind-based independent micro-grid system mainly includes two wind power generating sets with FD12.5–30 kW type, converter, fuel battery, and distribution lines, which is shown in Figure 5. The initial investment of wind power generation system is 425 thousand RMB, and the service life is 20 years. The share of residual value in total investment is 5%. Operation and maintenance cost accounts for 2% of initial investment, and the own electricity consumption rate is 2%. The investment cost comes from own assets. This village locates in Category IV wind resource area, and annual equivalent operating hours are 1900 h [23]. In the operation period of micro-grid, two persons are employed to be in charge of the work for daily production operation and maintenance, and the monthly salary for per person is 1000 RMB. For energy storage system, the investment of batteries is 1500 RMB/kWh, and total acquisition cost of converter is 45 thousand RMB. The micro-grid requires 2.9 km distribution lines. These data are from the feasibility study report of wind-based independent micro-grid system construction.

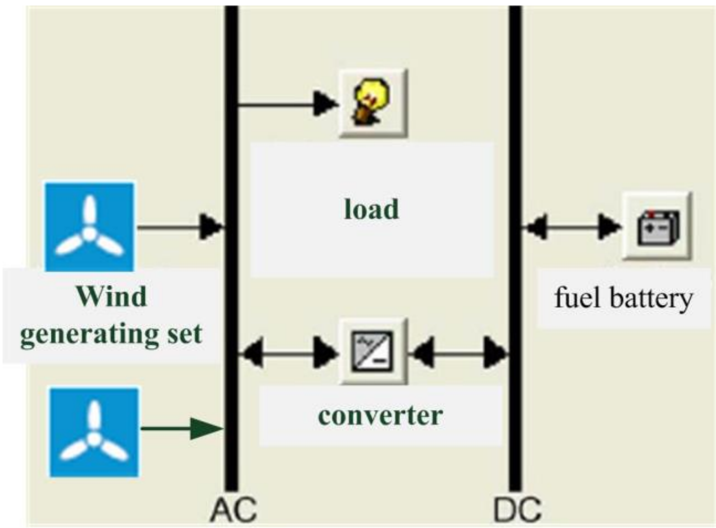


Figure 5. Wind -based independent micro-grid system.

For wind-based independent micro-grid system, total investment of this micro-grid system includes initial investment of wind power system and energy storage system. According to the investment parameters and operation parameters, the LCOE of wind-based independent micro-grid system built in this village can be calculated, which is equal to 0.704 RMB/kWh.

PV-based independent micro-grid system mainly includes 60 kW photovoltaic generating set, converter, fuel battery, and distribution lines, which is shown in Figure 6. The construction cost of photovoltaic module is 8 RMB/W, and the service life is 25 years. The share of residual value in total investment is 5%. Operation and maintenance cost accounts for 0.2% of initial investment in the first year, 0.5% in the second to eighth year, and 1% in the resting years. The share of other expenditure in total revenue is 0.5%. The own electricity consumption rate is 2%. The investment cost comes from own assets. This village locates in Category II solar resource area, and annual equivalent operating hours are 1500 h [52]. In the operation period of micro-grid, two persons are employed to be in charge of the work for daily production operation and maintenance, and the monthly salary for per person is 1000 RMB. The micro-grid requires 2.9 km distribution lines, and the investment of battery is 1500 RMB/kWh, and total acquisition cost of converter is 45 thousand RMB. These data are from the feasibility study report of PV-based independent micro-grid system construction.

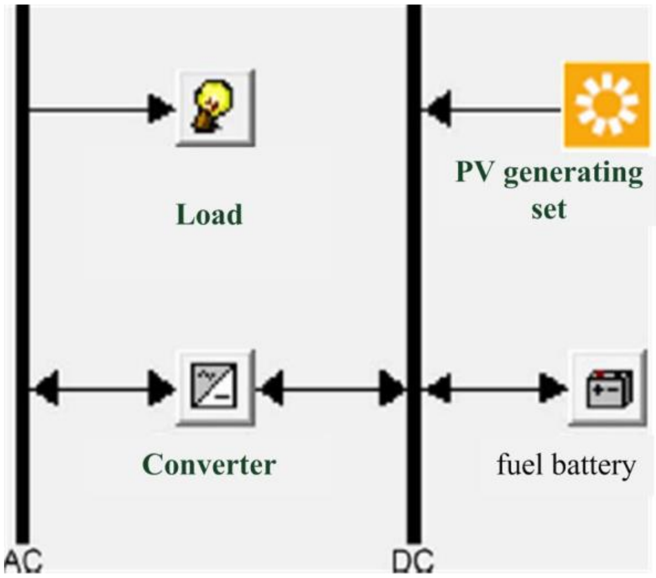


Figure 6. PV-based independent micro-grid system.

For PV-based independent micro-grid system, total investment of this micro-grid system includes initial investment of PV power system and energy storage system. According to the investment parameters and operation parameters, the LCOE of PV-based independent micro-grid system built in this village can be calculated, which is 0.658 RMB/kWh.

Biomass-based independent micro-grid system mainly includes 30 kW biomass power generation set, converter, fuel battery, and distribution lines, which is shown in Figure 7. The construction cost of biomass power generating set is 10.5 thousand RMB/kW, and the service life is 20 years. The investment cost comes from own assets. The share of residual value in total investment is 5%. Operation and maintenance cost accounts for 2% of initial investment. The share of other expenditure in total revenue is 1%. The own electricity consumption rate is 10%. Annual equivalent operating hours are 5500 h. In the operation period of micro-grid, two persons are employed to be in charge of the work for daily production operation and maintenance, and the monthly salary for per person is 2000 RMB due to the relatively heavy workload. The fuel of biomass-based power generation is mainly crop straw. The relative cost for biomass power generation contains fuel purchase cost, fuel package cost, and fuel transportation cost, which reaches 200 RMB/ton totally. Considering the installed capacity and actual operation condition of biomass-based power generation, there needs 180 ton biomass fuel each year. This biomass-based independent micro-grid requires 2.9 km distribution lines, and the investment of battery is 1500 RMB/kWh, and total acquisition cost of converter is 45 thousand RMB. These data are from the feasibility study report of biomass-based independent micro-grid system construction.

For biomass-based independent micro-grid system, total investment of this micro-grid system includes initial investment of biomass power system and energy storage system. According to the investment parameters and operation parameters, the LCOE of biomass-based independent micro-grid system built in this village can be calculated, which is 0.885 RMB/kWh.

The related parameters and LCOEs of three independent micro-grid systems are listed in Table 3.

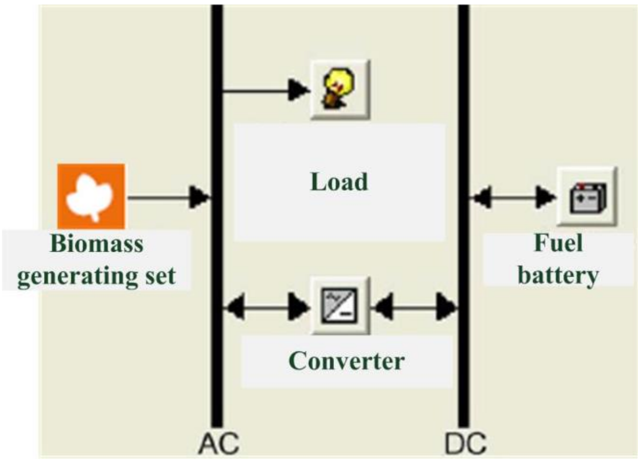


Figure 7. Biomass-based independent micro-grid system.

Table 3. Parameters and LCOEs of three independent micro-grid systems.

Parameters	Wind-Based Independent Micro-Grid System	PV-Based Independent Micro-Grid System	Biomass-Based Independent Micro-Grid System
System composition	two wind power generating sets with FD12.5–30 kW type; converter; fuel battery; and distribution lines	60 kW photovoltaic generating set; converter; fuel battery; and distribution lines	30 kW biomass power generation set; converter; fuel battery; and distribution lines
Initial investment	425 thousand RMB	8 RMB/W	10.5 thousand RMB/kW
Service life	20 years	25 years	20 years
The share of residual value	5%	5%	5%
The share of Operation and maintenance cost	2%	0.2% in the first year; 0.5% in the second to eighth year, and 1% in the resting years	2%
Own electricity consumption rate	2%	2%	10%
Annual equivalent operating hours	1900 h	1500 h	5500 h
Employment	Two employees	Two employees	Two employees
Monthly salary	1000 RMB	1000 RMB	2000 RMB
Battery investment	1500 RMB/kWh	1500 RMB/kWh	1500 RMB/kWh
Total acquisition cost of converter	45 thousand RMB	45 thousand RMB	45 thousand RMB
Distribution lines length	2.9 km	2.9 km	2.9 km
Others			Fuel cost: 200RMB/ton
LCOE	0.704 RMB/kWh	0.658 RMB/kWh	0.885 RMB/kWh

4.3. The Most Economical Mode Selection

The levelized costs of electricity of different power supply modes are displayed in Figure 8. It can be seen that the LCOE of PV-based independent micro-grid system is the smallest (i.e., 0.658 RMB/kWh) among all the modes, followed by wind-based independent micro-grid (i.e., 0.704 RMB/kWh) and biomass-based independent micro-grid (i.e., 0.885 RMB/kWh). The LCOE of power grid extension mode is 1.078 RMB/kWh, which is the highest. This is due to the high distribution cost, which is 0.68 RMB /kWh accounting 63.08% for total power supply cost.

From the above analysis, it can be learnt that the most economical mode of power supply for Luomiao village in Yunan province is PV-based independent micro-grid.

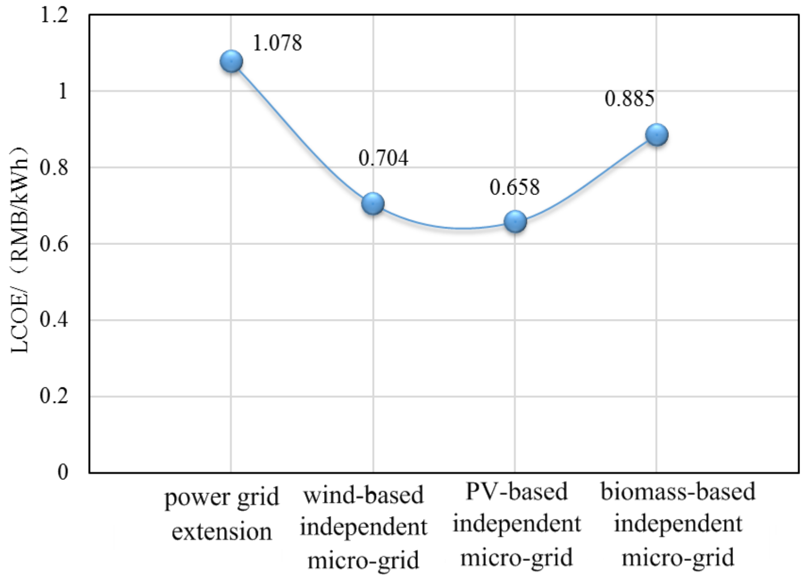


Figure 8. Economy comparison of different power supply modes.

5. Conclusions

Power supply for residents living in remote and less developed areas is a significant way to improve the living standards of residents in this area, solve regional energy poverty, and realize equalization of basic energy services. It is also the critical embodiment of ensuring the right to live and develop. It is of great importance to take the more economical and efficient mode to achieve rural electrification in China. Based on the LCOE method, the optimal (most economical) mode selection model for power supply in remote and less developed areas is established. Taking an ethnic minority village in Yunnan province as an example, the proposed model is verified, and the most economical mode for rural electrification is selected. The empirical result indicates that the PV-based independent micro-grid system with 0.658 RMB/kWh LCOE is the most economical for rural electrification in this village, while the LCOEs of another two new energy-based micro-grid modes are relatively higher. The LCOE of wind-based independent micro-grid is 0.704 RMB/kWh, and LCOE of biomass-based independent micro-grid is 0.885 RMB /kWh. The empirical accounting also shows that the power grid extension mode is the most uneconomical way to supply electricity for this village due to the highest 1.078 RMB/kWh LCOE. This is mainly due to the high distribution cost, which is 0.68 RMB /kWh accounting 63.08% for total power supply cost.

It should be pointed out that the optimal selection model of power supply mode for remote and less developed areas established in this paper is generally applicable. This model is employed to conduct an empirical analysis on a national minority region in Yunnan province, which verifies its feasibility and effectiveness. The proposed approach can also be applied to other areas in China, such as less developed rural areas in Tibet, Xinjiang, and Inner Mongolia autonomous regions. Meanwhile, the optimal selection method of power supply mode for remote and less developed areas proposed in this paper can also be employed in other developing countries, such as India and Bangladesh.

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