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A review on research and application of multi-energy complementary system containing high proportion of renewable energy based on different attributes

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Abstract To better understand the latest development of renewable energy systems, recent studies on multi-energy complementary power systems with a high proportion of renewable energy are reviewed in this paper. The connection modes of power grids and economic system analysis are summarized and discussed respectively, putting forward some suggestions on the system design and operation optimization. Firstly, the characteristics and differences between an integrated system and an off-grid system are reviewed, concluding that an integrated system is more reliable and cost-effective based on a few case studies. Secondly, the commonly used economic parameters and cost evaluation methods of the hybrid power system are reviewed. Those methods offer crucial tools to optimize the system, and they

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are able to analyze the system feasibility, enabling the most economical configuration. The results of several cases prove that the hybrid multi-energy system is more economical than the single-energy system. Finally, there are few articles focusing on technical details assessments and environmental impacts, which leaves room for future study.

Keywords: Off-grid system; Integrated system; Renewable energy; Multiple complementary systems; Economic analysis

Acronyms

ASC	–	annual systematic cost
ABC	–	artificial bee colony
BG	–	biomass generator
COE	–	cost of energy
CRF	–	capacity recovery factor
GA	–	genetic algorithm
HOMER	–	renewable energy from hybrid optimization model
NDR	–	nominal discount rate
NPC	–	net present cost
LCOE	–	levelized cost of electricity
LPSP	–	loss of power supply probability
PSO	–	particle swarm optimization
REF	–	Renewable Energy Foundation

1 Introduction

Global energy demand is gradually increasing, even in rural and remote areas scattered in developing countries [1]. These areas are far from the city centers which are normally covered by national grid, though the population and electric power demand is large [2]. At present, fossil fuel is the main energy source of power plants, among which coal accounts for the largest proportion. However, coal combustion is considered as one of the major carbon emission sources, which brings much challenge to global environment.

As a substitute for traditional energy, renewable energy has attracted the attention of scientists and decision-makers [3]. In fact, both solar and wind energy are sufficiently competitive now compared with other existing forms of energy. However, each of them has apparent economic and technical defects. For example, it is the fact that power demands follow peak-trough curves, whereas the productions of solar power are subject to the diurnal cycle and uncontrollable weather factors. While the latter could be alleviated by optimal engineering designs like oversizing, which leads to a requirement for energy storage to reduce the system cost. Based on the energy conservation principle, mismatch which is between the solar generation curve and grid demand, defines the minimum size of storage units. For instance, the average daily total demand in Australia's eastern power grid follows a typical duck-shaped curve with the biggest peak between 18:00–19:00 (local time) of a day. If the grid supplies electricity solely by PV, it would require battery capacity of around 300 GWh at least, which is simply depicted as the area of enclosure (1) on the chart (Fig. 1), or the sum of enclosures (2) and (3). The area of the enclosures embodies the amount of battery required.

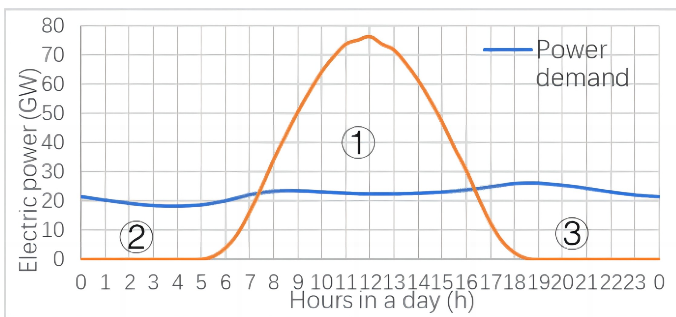

Figure 1: Averaged daily grid demand curve and solar power generation curve in Australia.

In addition, wind energy exhibits much more irregularity due to frequent variations of wind intensity and direction, which makes prediction more difficult. The outputs of wind farms vary in different regions and periods. Apart from wind energy, Biomass fuel is often considered an important energy source because it has the same dispatch ability as traditional fossil fuel-based power generation. However, its renewability is often questioned because a majority of crop waste is mainly produced in the harvest process of 2–3 months per year [4].

To solve those problems, a concept of hybrid renewable energy systems is established so that each type of defect can be made up and the problem of high storage cost is solved. Combined utilization of solar energy and biomass energy can complement each other; likewise, wind and solar energy are complementary in time and intensity [5–8]. Biomass system plays an important role in solar intermission periods [9]. The introduction of biomass energy reduces the negative impacts of only using the combination of solar energy and wind energy [10]. Research also proves that hybrid systems are more efficient and economical than any single renewable energy system. This kind of hybridization helps to overcome the problems of single systems [11]. At the same time, integrating renewable energy systems can significantly reduce operating costs [12].

In recent years, hybrid renewable energy systems have been widely deployed. Multi-energy complementary systems have adjustable resources and flexible operation modes, such as integrated or off-grid systems [13]. This review discusses the similarities and differences between the two kinds of system via some specific cases. In addition, this paper summarizes the optimization and economic feasibility analysis of each energy system to realize the cost reduction.

In addition, in order to improve the grid-connected safety and stability of renewable energy systems, it is also crucial to configure the corresponding energy storage devices. The performance of different batteries is also different, for example, the charge and discharge response speed of electrochemical energy storage system is fast, the technology is mature, but the charge and discharge life is limited. Lithium-ion batteries are widely used by electric vehicles because of their high energy density and long cycle life [14, 15].

In this paper, the existing energy systems in areas based on different situations including climates, economic, and environment are listed respectively, which provide reference for economic optimization or feasibility analysis of multi-energy complementary hybrid energy storage system. In addition, the actual situation in various places and optimization methods are able to attract scholars' interest in multi-energy complementary hybrid energy storage systems.

In conclusion, this review article provides a comprehensive overview of the research and application of multi-energy complementary systems with a high proportion of renewable energy. The review emphasizes the advantages of hybrid renewable energy systems over single systems in terms of problem-solving and cost-reducing. Through a few case studies, the similarities and differences between the integrated and off-grid systems are analyzed. Furthermore, this article summarizes optimization along with economic feasibility analysis approaches to achieve cost saving. As renewable energy plays an increasingly important role in energy transition and environmental protection, the hybrid system optimizations, which combine various renewable energy sources together, become a vital research topic. By addressing the challenges and opportunities in this field, this review article contributes to the advancement of renewable energy technology and sustainable energy utilization, which can promote global energy transition.

The rest of this article is shown as follows: Section 2 mainly examines the characteristics of the integrated and off-grid systems, investigating the differences between them. Section 3 summarizes the parameters of economic analysis and the methods used in the analyses. In addition, the system optimizations in various regions with different power load situations are studied and compared, followed by conclusions in Section 4.

2 The characteristics and differences between the integrated and off-grid multi-energy complementary systems

2.1 Characteristics

Integrated system is referred to a local power system in which home power grid and national power grid are linked. Take solar system for example: Photovoltaic panel converts solar irradiation into the voltage required by the national grid through invertors. It is typically seen in roof-top installations of residential buildings. When the electricity generated by solar energy exceeds the electricity requested by domestic appliances, the excess electricity is sent to the public grid. When solar energy cannot meet domestic demands, the integrated system is automatically supplemented by the national power grid [14].

Off-grid system is an independent solar power generation system, which is a system that operates without power grid. It mainly comprises solar panels, energy storage (e.g. batteries), charge and discharge controllers, inverters and other components. The electricity generated by the solar panels is directly either applied for costumers or being stored in the batteries. When it comes to supply for electrical appliances, the direct current in the batteries is converted into the requested voltage by national grid through inverters [15].

Distinguishing the integrated system from the off-grid system depends on the connection way with national grid. Besides, there are other differences between them. For example, the off-grid system must be equipped with batteries, while the integrated system rarely does. The off-grid system is not limited by geographic locations, and it can be applied as long as there is sunlight. So it is very suitable for remote areas without a power grid, such as isolated islands, fishing boats, outdoor breeding bases, etc. It can also be used as emergency power generation equipment in areas with frequent power outages. The integrated grid system not necessarily have to include batteries, so the cost is greatly reduced. In villages or communities, where the energy demand requirements meet, the integrated grid system which uses hybrid renewable energy sources can be applied via sending electricity to the power grid, which further reduce the system cost.

2.2 Study cases of the integrated complementary system

In recent years, studies on selecting and allocating renewable energy technologies into combined hybrid systems have achieved remarkable achievements. These efforts focus on improving the performance of the hybrid renewable energy system, making accurate prediction, ensuring reliability and reducing cost. A typical layout of integrated systems is shown in the following figure [16]. The purposes and effort of designing and applying hybrid combined system basically include two aspects: renewable energy output stability and system cost. The following two parts review the above two aspects, respectively.

2.2.1 From view-sights of stability

Solar energy and wind energy are stochastic sometimes. Technical and economic feasibility analysis of solar-biomass systems in the Ludhiana area of Punjab is studied, using the hybrid system to provide electricity in different areas. This case can overcome the shortcomings from applying only a single renewable energy source [4].

Similarly, by comparing the reliability of the solar-biomass hybrid energy system with that of the photovoltaic system, it is found that the reliability of the former is 75.01%, far superior to that of the latter's 28.37%. At the same time, it also reduces the cost, mainly due to the large number of cattle in Cole Hapoel. Animal waste can be used as the feedstock of biogas power plants, with a biomass potential energy of 44.8 MWe, and the biomass potential obtained from forests and wasteland is 46.3 MWe. The system's reliability can be increased by adding an energy source or keeping an energy storage battery [5]. Here, the reliability is usually evaluated by loss of power supply probability (LPSP) [17–19].

Hydropower is added when the cascade reservoirs is taken part in the multi-energy complementary system. A hydropower plant is an engineering facility that converts gravitational potential energy of water into electric energy through the joint operation of the water turbine and the generator. Its capacity is constrained by factors such as atmospheric precipitation, river runoff, reservoir capacity and turbine characteristics. In a short time (such as one day or several hours), the atmospheric precipitation and water flow change little, so the hydropower station is relatively stable [20].

From the above cases, the hybrid energy system is able to overcome the shortcomings caused by a single energy source, making the energy system more continuous and more stable [21].

2.2.2 From view-sights of cost

Firstly the local solar irradiation and wind speed data of the interested place should be obtained, followed by the climatic and geographical characteristics. Secondly, the actual energy consumption and load distribution of the case building should be determined through the water and electricity bills along with dynamic energy simulation [21]. In addition, the ratio of solar and wind energy is also a key issue. In order to evaluate the ability of the wind/solar hybrid power to afford the load of Brazil's northeast grid, 11 wind/solar scenarios have been evaluated by minimizing the need for energy storage systems. The result is shown in Fig. 2. The combination scenario which is 40% of wind and 60% of solar energy is the optimal result to meet the load in Northeast Brazil [22].

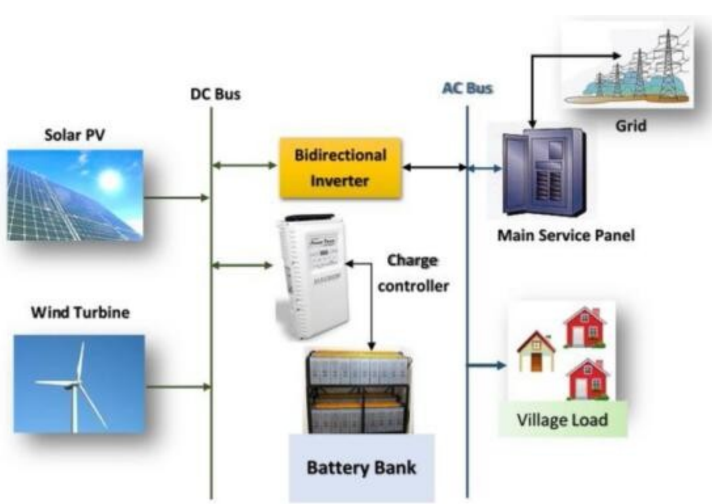

Figure 2: A schematic diagram of the integrated grid system.

The resource evaluation of wind power, biomass energy and solar energy in Pakistan is studied to optimize the integrated system, and HOMER (renewable energy from hybrid optimization model) is used for simulation and optimization so that a total load of wind energy, photovoltaic and biomass resources can be well utilized to the maximum extent. When the local energy demand is low, the extra power will be sent to the grid. The energy cost is calculated under different peak loads, energy demand curves and grid availability. Under the peak load of 73.6 MW, the energy cost of the integrated grid hybrid system is 180 million USD, and the horizontal cost of energy (COE) is 0.0574 USD/kWh [23–26]. In order to minimize the operation cost, a hybrid energy system consisting of wind energy, photovoltaic, gas turbine and energy storage are established via an operation optimization model. A moth flame optimization algorithm is applied for unit scheduling [27–33]. Finally, a micro-grid project is taken as case study for optimization in three configurations, which includes wind power, photovoltaic and energy storage. The case study shows that the operation optimization model can effectively reduce the system's operating cost and obtain the optimal output mode of each unit. It proves that the model has a certain guiding role in the economic dispatch of hybrid energy systems [38]. In the rice mill in Tripura, northeast India, about 24 tons of rice hulls are produced annually. The photovoltaic-biomass hybrid power grid model can save more than 90% of power grid electricity and significantly reduce the system operation cost [39]. Taking slaughterhouses in southern Nigeria as an example, an integrated distributed hybrid power system of solar energy and biomass is proposed in South Australia. The feasibility study shows that the integrated grid hybrid power system is an economical and environment-friendly solution for the annually changing power load [40]. All the above cases show the advantages of hybrid energy system in terms of cost against single energy system.

2.3 Study cases of the off-grid complementary system

Electricity demand is a key bottleneck for the development of remote areas. Due to the complex terrain and massive investment, the installation and application of power grid cable to the remote areas have been limited. Even in electrified villages in remote areas, the quality and availability of electricity are sometimes poor and unstable. In remote areas, traditional power supply methods include grid extension and diesel generators. The extension of the power grid faces much challenge, such as a long distance from the power grid, complex terrain, and huge investment. To solve the above problems, a more efficient distributed off-grid hybrid renewable energy system is established, improving the reliability of power supply in remote rural areas.

The off-grid model alleviates a lot of financial and procedural deficiency, such as huge investment cost and the need of obtaining government permission. High degree of dispersion, low population density and little energy demand usually characterize rural communities. Electricity demand is generally concentrated at night. In many countries, some villages are still far from the power grid center, which brings much challenge to system economic [41, 42].

Due to the intermittency of renewable energy, using single renewable energy system usually leads to defects such as system instability and excessive cost. It can be solved by integrating two or more renewable energy sources. In designing process, it is necessary to consider the type of local renewable energy sources. The schematic diagram of a typical hybrid energy system is shown in Fig. 3.

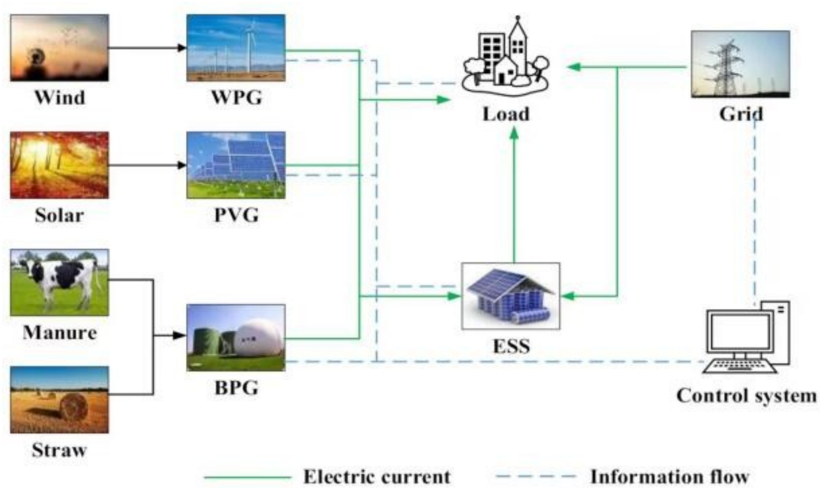

Figure 3: Wind-solar-biomass hybrid energy system: WPG – wind power generator, PVG – photovoltaic generators, BPG – biomass generator, ESS – energy storage system.

In addition, an energy storage unit helps to improve the system stability, reliability and flexibility by adjusting the charging and discharging time and rate. After comparing each battery's cycle efficiency and cost, the lithium battery energy storage method is adopted [43–46].

The battery unit and diesel generator maintain the operation of the hybrid power system, eliminating reliability and power supply problems. The dispatch strategy is used to control the process of battery and diesel generator sets. It depends on factors such as the nature of renewable energy, fuel costs, the capacity of batteries and generators, along with renewable energy amount. A hybrid power system design mainly adopts two scheduling strategies: cyclic charging and load-following [47–51].

2.3.1 Wind-photovoltaic combined system

Solar power and wind power are combined to form a hybrid system. The peak of photovoltaic power is usually around noon, when solar irradiance is the highest, while the peak of wind power is usually at a different time. Regions with large power loads often have poor wind energy density, while situations in other regions are just the opposite, which brings difficulties to the economic development of wind power [52,53]. In some cases, using solar and wind energy alone may lead to unreliable energy sources and much cost [54, 55]. However, their combination is technically and economically conductive to generating electricity for remote areas [56–62].

Solar energy and wind energy have higher requirements in the geographical environment. Scholars have analyzed the electrification cost of small wind power system in rural Africa. The result shows that photovoltaic and diesel systems are the most economical and feasible methods for rural electrification in Africa, while wind power system has economic advantages only in the Horn of Africa and a few scattered areas [63].

The application of photovoltaic/wind/diesel hybrid power generation system in rural electrification in three isolated villages with different climatic characteristics in Colombia is analyzed. According to observations, hybrid energy options in remote rural areas usually consider a limited set of renewable energy technologies, such as photovoltaic arrays and wind turbines, with batteries or diesel generators as backup facilities [64,65].

The system performances of solar-wind energy, solar-pumped storage and wind energy-pumped storage are compared under loss probability with the range of 0–5%. Because the cost of the wind-driven generator is exceptionally high, and they have to withstand typhoons on the island, only one wind-driven generator is considered in the hybrid system. Therefore, the combination of wind and solar energy should be considered when design the optimal power supply system. Energy balance analysis shows that the overall efficiency of the pumped storage system is 52.5%. Sensitivity analysis shows that load demand is a key factor affecting system cost. Compared with battery energy storage, the life cycle cost of pumped storage is significantly reduced, especially when some variables are controlled, such as storage capacity [66].

2.3.2 Photovoltaic-biomass combined system

Wind power generation has many advantages however it is challenged by integrating restricts and equipment utilization ratio. Instead, biomass power generation capacity is higher than its nominal installed capacity, indicating that biomass power generation has a higher capacity factor than other power generation [29]. Compared with solar and wind energy, storage and transportation of biomasses are also more convenient. Biomass materials can be converted into organic fertilizers through natural fermentation, such as composting and returning to the fields. Therefore, the proper use of biomass resources is necessary and feasible [67].

Rural areas are often taken as the preferred options in terms of site selections for biomass power plants [68]. In some areas, abundant biomass resources can be easily obtained from agricultural, industrial, and factory wastes, such as 1) burning wood; 2) anaerobic degradation of high organic moderate waste; 3) gasification of wood chips, agricultural waste and particles; 4) high-temperature decomposition [69]. Besides, the biogas system is better than diesel generators as a backup system [70, 71].

If heat, electricity and gas are required for remote areas, a distributed solar-biomass residential integrated energy system can be adopted [72–77]. This kind of system is a solar-biogas industrial combination scheme, making use of solar energy and biomass energy, reducing the dependence level on battery energy storage systems, along with satisfying diverse energy demand in rural areas [78].

2.3.3 Wind-photovoltaic-biomass complementary system

Take the remote area of Bhawani India as an example. Based on the annual hourly average resource data, the optimization results of the genetic algorithm (GA) and the particle swarm optimization (PSO) algorithm are compared. In addition, the power loss probability technology is used for system reliability analysis. The optimal configurations of the hybrid renewable energy system are ranked based on the minimizing COE of the system. Compared with GA, PSO is able to effectively optimize the annual

PV (photovoltaic) output power, wind energy output power, diesel generator output power and dump load which is based on load tracking strategy. The above results indicates that with PSO optimization, the PV output power can be increased, and the load-following strategy of PSO is able to obtain more appropriate parameters. Therefore, in the optimization planning, compared with the load tracking strategy, the cyclic charging strategy is more effective [79].

Another case comes from a rural area in western China. The daily and seasonal characteristics of energy supply, the area scale and energy demand mode in remote rural areas are considered. In the Hybrid Optimization Model of Renewable Energy (HOMER), different combination scenarios including photovoltaic panels, wind turbines and biogas generators are modeled and optimized. The most cost-competitive configuration is determined. At the same time, the reliable power supply is obtained to ensure the village's residential, community, commercial and agricultural needs. The input data includes meteorological data, availability of renewable resources, load distribution and technical data. According to the solar radiation data, ambient temperature and monthly mean wind resources obtained, the hourly power generation of solar modules and the output power of wind turbines are calculated in. Biomass can be used as a backup to ensure a stable power supply to a certain extent. The storage battery serves as a supplementary backup facility. The results are shown in Table 1: 104 kW photovoltaic module, three 10 kW wind turbines, 50 kW biogas fueled diesel generator, 331 kWh battery and 99 kW converter are the most economical and reliable configuration schemes for off-grid hybrid power system [23].

Besides, a solar-wind-biomass hybrid system is proposed in Egypt's Monshaet Taher village at Beni-Suef Governorate to solve the problem of unreliable electricity in the village. According to the daily energy availability and load demand data, six energy scenarios are simulated in HOMER to design an optimal renewable energy system to minimize energy costs. Considering the solar and wind energy available in the area, most of the electricity in the optimal solution comes from biomass generators, which provide a cheap source of electricity for the local area [36]. In addition, hybrid energy systems including the traditional energy along with photovoltaic, wind, biomass and battery are analyzed and compared under different climatic conditions in seven selected locations in Australia. The result showes that compared with traditional energy, hybrid energy system has the advantages of lower cost and emission reduction [37]. It can be seen that the hybrid multi-energy system is superior to the traditional energy system to some

Table 1: The different characteristics of the integrated and off-grid systems.

Ref.	Publication date	Study area	Network mode	Energy composition	Average daily (kW)	Features
[31]	2019	A remote rural village in Ethiopia	Off-grid	PV, WT, battery, diesel generator	19.6	Determine the optimal system configuration through sensitivity analysis
[21]	2016	Shivaji University, Kolhapur	Off-grid	Wind-solar, PV-biomass	17.591	Modelling without energy storage based on data that has been tested in the field for a year
[4]	2020	India	Grid	Solar, biomass	–	Study the advantages of the combined use of solar energy and biomass energy
[38]	2015	Nijhum Dwip of Bangladesh	Off-grid	PV, WT, BG	–	Compare the economic and environmental aspects of hybrid renewable energy systems with traditional systems
[33]	2020	An institutional building	Off-grid	Biomass, PV, WT, batteries	87.6	Sensitivity analysis of hybrid renewable energy systems
[39]	2014	Tripura	Grid	PV, biomass	–	Analyze the impact of the system on the power grid
[28]	2020	A rural community in Ismailia Governorate, Egypt	Grid	PV, WT	463	Three scenarios are proposed to study the relationship between the grid and the hybrid renewable energy system
[40]	2021	Morocco	Off-grid	PV, biomass	–	Sensitivity analysis on the amount of biomass resources
[26]	2016	–	Off-grid	PV, wind, biomass, battery	–	Artificial bee colony algorithm has good convergence and the ability to provide high-quality results

BG – biomass generation, WT – wind turbine, PV – photovoltaic.

extent, not only technically overcoming the shortcomings of conventional energy, but also significantly reducing the cost [80].

2.4 Summary

The use of renewable energy is increasing. Due to the instability of these resources at different times and locations, using only a single resource may lead to the unreliability of power output. The integrated system can be directly supplied by the grid to ensure reliability when renewable energy can't satisfy the load requirements. At the same time, it can also sell excessed electricity to the grid when there is a surplus, further reducing energy cost. In isolated islands or rural areas which are far away from the power grid, the off-grid mode can be adopted due to the high cost of installing the power grid. According to the local natural and geographical environments considering sunlight, wind speed, and biomass, suitable renewable energy types is selected. For example, wind power generation is more ideal for areas with high wind speeds, such as the seaside. In addition, an energy source or energy storage battery can be added to improve reliability.

3 Economic analysis of multi-energy complementary system

3.1 The parameters of economic analysis

It is essential to know the parameters in the economic analysis of a multi-energy complementary system. Firstly, it is necessary to understand that the economic parameters used in the analysis mainly include cost parameters (COE, NPC, LCOE, etc.), benefit parameters (NPC, etc.). Secondly, there are closed relations among economic parameters, so it is necessary to further analyze how economic parameters interact with each other and what are the influence. Finally, environment and economy are inseparable, so it is essential to analyze the system environment. Therefore, the environmental parameters are briefly introduced in this article.

3.1.1 Economic parameters of system cost

Net present cost (NPC): The total net present cost of a system is the present value of all the costs in which the system incurs over its lifetime minus the present value of all the revenue which it earns over its lifetime. Costs include capital costs, replacement costs, operational and management costs and fuel costs [81,82]:

$$C_{\text{NPC}} = \sum_{t=0}^{T} C_{\text{Cap},t} + C_{\text{O \& M},t} + C_{\text{Replace},t} + C_{\text{Fuel},t} - R_{\text{Salvage},t}\,, \quad (1)$$

where, $C_{\text{Cap},t}$ is the capital cost at time moment t, $C_{O\ \&\ M,t}$ is the operational management cost at time t, $C_{\text{Replace},t}$ is the replacement cost at time t, $C_{\text{Fuel},t}$ is the fuel cost at time t, $R_{\text{Salvage},t}$ is the present value of all the revenue which it earns over its lifetime at time t.

Cost of energy (COE): COE divides the annualized cost of the system by the electrical load [42]:

$$C_{\text{COE}} = \frac{C_{\text{AT}}}{\text{Load}}\,, \tag{2}$$

where, C_{AT} is the annualized cost of the system and Load is the electrical load.

Levelized Cost of Energy (LCOE): It is the power generation cost calculated after leveling the cost and power generation in the life cycle of the project. LCOE is the ratio of the present cost value to the present value of the power generation in the life cycle [83]:

$$\text{LOCE} = \frac{\text{Total life cycle cost}}{\text{Total lifetime energy production}}\,. \tag{3}$$

For an energy system, total NPC refers to the difference between the present value of all costs generated in the life cycle and the present value of all revenues obtained. HOMER is used to indicate the life cycle cost of the system. This value may be positive or negative [84]. NPC plays a very important role in the optimization analysis of a multi-energy storage system. It should be reduced as much as possible in the optimization process. In addition to the optimization process, NPC is also considered in the economic analysis of the energy system. COE is another parameter that is equally important, and it is usually taken into account with NPC. The most economical system with the fewest NPC and COE, is obtained through optimization. An index called AT (annual total cost) should be introduced in the calculation of NPC and COE, both NPC and COE of the system will be affected by it with positive influence results [85]. Now, the LCOE can be calculated by leveling the cost and power generation in the life cycle of the project, which is defined by HOMER software as the average cost of useful power generated by the system per kilowatt hour [86].

3.1.2 Economic parameters of benefit

Nominal discount rate (NDR): It mainly reflects some changes in discount rate under the influence of inflation because money suppliers must require an increase in the interest rate to compensate for the loss of their purchasing power in the case of inflation, which leads to changes in the cost of capital and the rate of return on investment.

Inflation rate (IR): It refers to the rate of increase in the general price level within a certain period (usually one year).

In economic analysis the parameters of the cost are more intuitive, and the parameters of benefit will lead to some impact on the cost parameters to a certain extent. In a long-life cycle, the cost of operation will inevitably increase, which affects NPC of the whole system. According to NDR calculation formula , the value of NDR will increase as the rate of inflation rising, and the impact of NDR on these two cost economic parameters is opposite to the life cycle. A higher NDR will lead to higher COE and lower NPC, so the inflation rate will indirectly affect the COE of the system through NDR.

In addition, the solar energy and wind speed of each region also leads to some influence on the cost of a multi-energy complementary system. If solar and wind resources are abundant in an area, the cost may be low. Take wind energy as an example, the wind resource reduces the COE and NPC of the system according to different values of Weibull shape parameter k. In this case, the cost of the system will be greatly reduced in areas with abundant easy-access biomass resources [87]. However, if the biomass price is too high, the cost will increase accordingly [50]. Similarly, the renewable energy (REN) factor for wind is also one of the inevitable influencing factors of cost. The sensitivity analysis shows that the higher the value of REN factor is, the lower the value of LCOE will be [88].

Based on keeping similar charge and discharge efficiency, as round-trip efficiency increasing, LCOE decreases sharply. Battery efficiency is also a factor which is affecting LCOE. To make the study more simple, charge and discharge efficiency is set as the same value. Different round-trip efficiency values are compared to find that LCOE would decline sharply as round-trip efficiency increases [89].

As is shown in Table 2, the corresponding relationship between cost parameters and multiple indicators are listed. where , '+' indicates positive influence, and '–' indicates negative influence. For NPC case, 'life cycle' and 'biomass price' lead to positive effects. For NDR, "inflation rate", 'solar radiation' and 'wind speed' lead to negative effects. For COE, NDR and 'biomass prices' lead to positive effects, while 'inflation rate', 'life cycle', 'solar radiation' and 'wind speed' lead to negative effects. For LCOE, the effects of 'REN factor' and 'battery efficiency' are both negative.

Table 2: Influence factors of cost economic parameters ('+' – positive influence, '–' – negative influence).

	NDR	Inflation rate	Life cycle	Solar radiation	Wind speed	Biomass price	REN factor	Battery efficiency
NPC	–	–	–	–	–	+		
COE	+	–	–	–	–	+		
LCOE							–	–

3.1.3 Environment parameter

Modified combustion efficiency (MCE): It is defined as the excess mole fraction of CO_2 divided by the sum of the excess mole fractions of CO_2 and CO [52]:

$$\mathrm{MCE} = \frac{\Delta \mathrm{CO_2}}{\Delta \mathrm{CO_2} + \Delta \mathrm{CO}}\,, \tag{4}$$

where, $\triangle CO_2$ is the excess mole fraction of CO_2, $\triangle CO$ is the excess mole fraction of CO.Power generation carbon intensity is defined as the amount of carbon generated by each degree of power generation in a given region and time [54]. Equivalent carbon emission of power generation side within the region is defined as

$$e = e_{\mathrm{up},k} + e_{\mathrm{constr},k} + e_{\mathrm{comb},k}\,, \tag{5}$$

where $e_{co2eq,k}$ is the equivalent carbon emissions of power generation side in region k, $e_{\mathrm{up},k}$ is the equivalent carbon emission generated in the upstream production process of fuel in region k, $e_{\mathrm{constr},k}$ is the equivalent carbon emissions generated by the construction of power plant in region k, $e_{\mathrm{comb},k}$ is the equivalent carbon emission generated by combustion for power generation in regional k.

The equivalent carbon emission of the power side within the region is defined as

$$e_{\mathrm{use},k} = e_{\mathrm{CO_{2eq},}k} - e_{\mathrm{pump},k} + e_{k,i} - e_{k,e} - e_{\mathrm{loss},k}\,, \tag{6}$$

where $e_{\mathrm{use},k}$ is the equivalent carbon emission generated by electricity consumption in region k; $e_{\mathrm{pump},k}$ is the equivalent carbon emission generated by the pumping load used in region k; $e_{k,i}$ and $e_{k,e}$ are the equivalent carbon emissions generated by imported power obtained from station i and exported to station e in region k, $e_{\text{loss},k}$ is the equivalent carbon emission generated from the loss of transmission and distribution network in regional k.

The center of low-carbon development is technological innovation, institutional innovation and the change of development concept, which will involve the readjustment of production mode, lifestyle and view of value. As the most important energy sector in China, the power industry should strive to achieve low-carbon electricity and shoulder the responsibility of leading the low-carbon development of the whole society.

In addition to the above economic parameters, the analysis of multi-energy systems is often inseparable from the environment. The relationship between the environment and the economy is always inseparable, and protecting the environment is our obligatory responsibility. Emissions is regarded as an important index of environmental analysis [52, 53]. In the process of optimization, emissions, especially carbon dioxide emissions, will be reduced as much as possible against environmental pollution [90].

3.2 Research methods or platforms

When using software for optimization or economic analysis of multi-energy storage systems, different software and algorithms will perform different economic results. In addition to platforms and algorithms, the optimization of the system and economic analysis are inseparable from economic research methods. The parameters which are taken into consideration and the economic research methods which are used also vary according to different systems and platforms. The above issues will be introduced and analyzed briefly in this section.

3.2.1 Life cycle cost analysis

By comparing life cycle costs (LCC), the optimal system can be selected when studying multiple energy storage systems. The life cycle cost analysis method mainly focuses on the cost occurring in the life cycle of the system. It considers the upgrade and discount rate based on the net present value method. When the inflation rate and discount rate are equal, LCC can be calculated as the current value. LCC is the sum of installation cost, maintenance cost and insurance cost [91, 92]. The calculation formula is as follows

$$\text{LCC} = C_I + C_O + C_M + C_D\,, \tag{7}$$

where C_I is the purchase cost, C_O is the operating cost, C_M is maintenance cost, C_D is the processing cost.

3.2.2 Exergy economic algorithm

Exergy is also known as effective energy when the system changes reversibly from an arbitrary state to a state in equilibrium in the given environment, which can be transformed indefinitely into other forms of energy [93]. Different forms of energy have different abilities to convert into 'higher energy'. If this conversion capacity is used as a scale, the merits and demerits of various forms of energy can be evaluated.

Exergy can be considered as the maximum useful work that can be made or the minimum useful work consumed in theory in a reversible process under given environmental conditions. Correspondingly, all energy that cannot be converted into exergy is called 'anergy'. Exergy (E_x) and anergy (A_n) combine to any energy E [94, 95]:

$$E = E_x + A_n \,. \tag{8}$$

Thermal economic analysis is often used in the economic analysis of solar biomass systems. Exergy destruction is the main problem of low thermal efficiency in all power systems, which is directly related to equipment cost. Exergy economic analysis is designed to minimize those inefficiencies and associated costs. Appropriate modelling systems are characterized by obtaining optimal values for selected criteria leading to efficient systems [96–98]. Conventional exergy analysis results only reveal the exergy damage value of each component without providing more information. Similar to advanced exergy analysis, advanced exergy economic analysis divides exergy destruction cost and investment cost of components into endogenous, exogenous, avoidable and inevitable parts. Exergy economic analysis is a key method to model and optimize cost-benefit systems [99].

3.2.3 Platform for economic analysis

In the analysis of multi-energy storage systems, there are many analysis platforms. HOMER is one of the important software in economic analysis. The hybrid optimization model of electric renewable energy (HOMER) is a tool developed by NREL (National Renewable Energy Laboratory) for the pre-feasibility of any project based on analyzing system cost and optimization. HOMER is a computer model that simplifies the task of evaluating options for remote, independent, and distributed generation systems, both in off-grid and integrated cases. A few studies show that HOMER is very feasible in application [70]. HOMER optimization and sensitivity analysis algorithms can be used to evaluate the economics of the system and the feasibility of technology choices, as well as considering the changes in technology cost and the availability of energy resources. HOMER software has been widely used in modelling, simulation and optimization, and the economic results are extraordinary ideal [71–76]. HOMER can handle all kinds of emerging technologies, such as photovoltaic, wind energy, fuel cell, hydro power and so on.

In addition, PSASP is a comprehensive program for power system analysis developed by China Electric Power Research Institute. Based on the support of basic database in power grid, fixed model library and user-defined model library, PSASP can perform various calculations and analysis of power system (transmission, power supply and distribution system). PSASP has designed as a powerful user-defined modeling method. The model of any component can be freely established as a model base for various calculations. There are intuitive and convenient editing methods of text and graphics, which are simple to call and fast to calculate, but the calculation mode has certain limitations. Besides, PAS (power system application software) power application software is a kind of power grid operation analysis software, which is helpful for automation personnel to monitor and maintain the weak links of automation system according to the state estimation results. Power flow calculation software has the advantages of fast calculation speed, high calculation accuracy and intuitive analysis results. PAS advanced application software will play a greater role in the safe, stable and economic operation of power grid.

3.2.4 System for economic analysis

Optimizing is an important topic when studying the energy system. Taking the integrated solar/wind/biomass hybrid system in Egypt as an example, to solve the problem of unreliable power in this village, it is necessary to design and optimize a renewable energy system. That system has to minimize the energy cost according to the daily data of energy availability and load demand. From the view-sights of system cost, reliability and greenhouse gas emissions, the Arual community in Ilia, Egypt was studied [26]. Under different weather conditions, taking the maximization of the renewable energy foundation (REF) of the system as the objective function and considering the minimization of two objective functions power supply probability (LPSP) and cost of energy (COE), a mathematical model of hybrid system output power estimation is established. The results show the good portion of each component in the total energy to satisfy the power demand. Based on the power selling situation or power purchasing ability of the hybrid system, the relationship between the power grid and the hybrid system is studied. Three scenarios are selected along with this relationship. The results of the multiple objective particle swarm optimization (MOPSO) are divided into three parts: the economically optimal solution (lowest COE), the renewable energy application angle (highest REF) and the environmentally optimal solution (lowest greenhouse gas emission) [27].

3.3 The analysis of economic optimization

3.3.1 Optimization algorithm

There are many optimization algorithms for a multi-energy storage system, such as the artificial bee colony (ABC) algorithm, the genetic algorithm (GA), the particle swarm optimization (PSO) and so on.

Artificial bee colony algorithm is an algorithm inspired by bee colony behavior. It was proposed by the Karaboga group in 2005 to optimize algebra problems. The artificial bee colony algorithm is an optimization method that imitates the behavior of bees, and it is a specific application of the idea of swarm intelligence. It does not need to know the special information of the problem but only needs to compare the advantages and disadvantages of the problem and finally make the global optimal value pop out in the colony through the local optimization behavior of each worker bee. It has a fast convergence rate [77–81].

Genetic algorithm was firstly proposed by John Holland in the 1970s. The Algorithm is designed and proposed according to the laws of biological evolution in nature. It is a computational model of biological evolution that simulates the natural selection and genetic mechanism of Darwin's biological evolution and a method to search for the optimal solution by simulating the natural evolution process [100].

Particle swarm optimization is a random search algorithm based on group cooperation, which was invented by Eberhart and Kennedy. It was developed by simulating the foraging behavior of birds. It's generally considered a type of swarm intelligence (SI), and it can be incorporated into multiagent optimization system (MAOS) [84–86].

Table 3: Optimization algorithm feature table.

Arithmetic	Advantage	Deficiency
ABC	Solve multi-variable function optimization problem	The calculation speed is slow in the later stages of optimization
GA	When solving complex combinatorial optimization problems, compared with some conventional optimization algorithms, better optimization results can be obtained faster	(1) Non-standard coding and inaccurate representation of coding (2) A single genetic algorithm coding cannot fully express the constraints of the optimization problem. One way to consider constraints is to use thresholds for infeasible solutions, which inevitably increase the computation time (3) The efficiency of the genetic algorithm is usually lower than that of other traditional optimization methods (4) Genetic algorithm is prone to premature convergence (5) There is no effective quantitative analysis method for the accuracy, feasibility and computational complexity of the genetic algorithm
PSO	The advantage of evolutionary computing is that it can deal with some things those traditional methods cannot. The calculated LCOE is the minimum [101]	(1) The performance is not particularly good on some problems (2) Coding of network weights and selection of genetic operators are sometimes troublesome

The above optimization algorithms have slightly different economic effects. When scholars like Shakti Singh predicted the minimum LCOE value in the optimization of island micro-grid such as rural multi-energy storage systems, they compared the complete optimization results of the ABC algorithm, HOMER and PSO in case studies. The results show that the ABC algorithm can predict the minimum ASC (annual system cost) of the system with the minimum LCOE. In addition, the ABC algorithm has better performance in calculation time and results compared with particle swarm optimization. Moreover, the performance of the two algorithms is better than the HOMER algorithm.

3.3.2 Objective function

NPC represents the life cycle cost of the system. The calculation method of total NPC is to sum up the total discounted cash flow of each year within the project life cycle. Based on HOMER software, the minimum NPC is taken as the main objective function, which is a very common economic research method in multi-energy energy storage systems. After completing the system optimization, another economic parameter COE is introduced on the basis of the lowest NPC, and the value of COE can be calculated by dividing the total annual cost by the power. The COE of the whole system is minimized to analyze the economic feasibility of the system according to real cases. The options for multi-energy systems are being optimized. The intention of the objective function is to reduce the COE. In the equation, the design process of the hybrid system is put forward, and the partial group optimization method is used to solve it:

$$M_{\text{Toal annual}} = M_{\text{AIC}} + M_{\text{O \& M}}\,. \tag{9}$$

Energy cost is measured by unit electricity cost or constant price of unit energy. Minimize the calculation formula [88]:

$$\text{COE} = \frac{\text{IR} + \text{C}_{\text{O \& M}}}{\text{P}_{\text{AE}}}, \tag{10}$$

where I is the initial project investment cost, R is the coefficient of recovery of equal amount of funds, $\text{C}_{o\ \&\ M}$ is the operation and maintenance cost, and P_{AE} is the annual generating capacity of unit.

The concept of annualized system cost (ASC) is introduced [89]. When all constraints and parameters are satisfied, the minimum ASC, that is, the minimum sum of the total annualized costs of each component is considered to obtain the best result. The total ASC of each component can be expressed as the annual cost of any component, which can be calculated by a factor called the capacity recovery factor (CRF). The objective function is to impose a minimum value on several constraint sets.

By minimizing the net present cost (NPC) of the system, the optimal size of the components used in the system is deduced with the minimum LCOE, and the optimal configuration is selected according to LCOE and reliability [101]. LCOE is the average price of energy (useful) generated by the system per kilowatt hour, and the minimum ASC of the system can be predicted by minimizing LCOE:

$$\text{LOCE} = \frac{\text{ASC(USD/year)}}{\text{Toal useful energy served (kWh/year)}}\,. \tag{11}$$

3.3.3 Optimization performance

A typical village near Pongalur and Manit is cited here as the examples. By comparing the life cycle costs of different hybrid systems and single independent systems, it is determined that the most economical hybrid combination with the lowest life cycle cost is solar energy/(wind energy + biomass) = 1/(0.25 + 0.75) [91]. The economy of solar-biomass hybrid power generation system in northern Cameroon is analyzed [102, 103]. The concentrated solar energy (CSP) technology of parabolic trough collector (PTC), linear Fresnel reflector (LFR) and solar tower (ST) is studied. They are hybridised with biomass-fired (BF) technology. The exergy damage of solar field (PTC-BF accounts for 86.3%, ST-BF accounts for 92.2%, and LFR-BF accounts for 85.4%) is the main cause of the whole damage [93]. The hybrid system with LFR-BF accounting for 85.4% is the most cost-effective system. The hybrid system with ST-BF accounting for 92.2% is the least cost-effective. The lower the proportion is, the more cost-effective of the system will be [94]. The details are shown in Figs. 4 and 5.

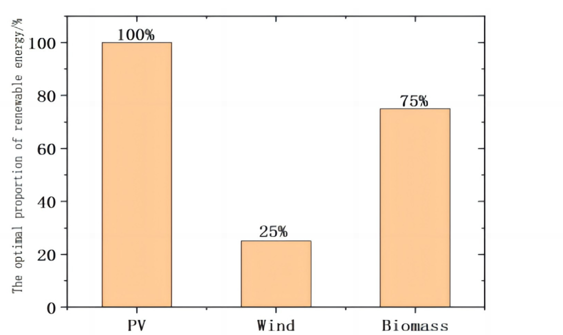

Figure 4: Optimal ratio of solar energy, wind energy and biomass energy [91, 92].

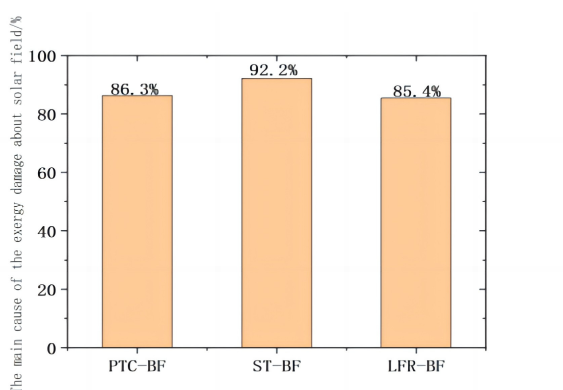

Figure 5: The main cause of the exergy damage about solar field [93].

3.4 Economic feasibility study of multi-energy complementary energy storage system

With the decrease in solar thermal cost and the continuous increase of raw materials, fossil fuels and land prices, hybrid power plants have become an increasingly attractive choice [104]. The decrease in solar energy supply means an increase of system operation cost (an increase of biomass consumption). The use of solar energy is very important, and wind energy is a pioneer industry in the field of RES [105]. The hybrid system is introduced as a reliable alternative to improve the traditional wind power plant, and a reliable wind power plant is designed by mixing with biomass energy [106]. In a hybrid system with insufficient solar energy, biomass energy is an effective component. The NPC and COE of each system through economic analysis of multi-energy systems in various places are shown in Table 4.

For a small village in Egypt, a solar photovoltaic/wind/biomass hybrid system can significantly reduce NPC. In rural India, wind-biomass gasifier systems have very low energy costs and operating costs compared to wind-diesel systems. The energy system supplying power to the northern islands near the Bay of Bengal in Bangladesh has also improved economically. Moreover, the hybrid energy system in Bangladesh will also be applicable to other countries with similar environments and other conditions, such as Malaysia, Australia, Singapore and other regions with great potential. In addition, there are energy systems in Pakistan, Australia and other places that are used to supply local electricity, all of which have cost advantages [102].

Take a solar-biomass hybrid system in India as a case. Compared with the single biomass system, the hybrid system can save 29% of biomass and land, which indicated that the hybrid power station is an attractive and beneficial choice. In addition, compared with single energy system, the annual average energy efficiency and primary energy-saving rate of the solar-biomass hybrid system are 25.18% and 94.98%, respectively, reducing carbon emission by about 2961.85 tons per year. Besides, for a multi-generation system using solar energy and biomass, the energy efficiency and exergy efficiency of the whole system are 91.0% and 34.9% respectively. In China, the biomass-solar hybrid power system is especially suitable for the northwest rural areas where the economic development is relatively slow, yet the solar energy and biomass resources are quite abundant.

Table 4: Regional energy system economic index table.

Ref. (year)	Research area	System energy	Optimization objective	Optimization algorithms or platforms	Installed capacity	NPC (USD)	COE (USD/ kWh)	Economic feasibility	
[49] (2020)	A village in western China	Solar – wind – biomass	Minimize the NPC	HOMER	P V 104 kW WT 30 kW BG 50 kW Battery 331 kWh Converter 99 kW	587013	0.201	PV/wind/BG/ battery more economically viable than grid expansion	yes
[48] (2020)	A village in Fars Province, Iran	Solar – wind – biomass	Minimize the NPC	HOMER	BG 150 kW PV 80.7 kW	904513	0.128	The development of the project will save up to 8444 USD.	yes
[36] (2016)	Egyptian village	Solar – wind – biomass	Minimization of cost	HOMER	PV 150 kW WT 20 kW BG 100 kW	5772		It provides a cheap source of electricity for the area	yes
[5] (2014)	In rural India	Wind-biomass gasifier system	Minimum net present value	HOMER	BG 150 kW WT 100 kW Converter 100 kW		0.078	Compared to the wind-diesel system, the energy cost and operating costs are very low	yes
[23] (2017)	The remote area of Bwani	Solar – wind – biomass	Minimize the COE	GA, PSO			0.2393		yes
[24] (2018)	Kallar Kahar, near Chakwal, Punjab province, Pakistan	Solar – wind – biomass		HOMER		$180.2 \cdot 10^6$		Energy costs are lower	yes
[1] (2017)	The northern island of Bangladesh of the Bay of Bengal	Photovoltaic – wind – biomass – diesel		HOMER		160626	0.431	Can reduce the NPC	yes

Table 4 [cont.]

Ref. (year)	Research area	System energy	Optimization objective	Optimization algorithms or platforms	Installed capacity	NPC (USD)	COE (USD/ kWh)	Economic feasibility	
[95] (2018)	The remote area of Punjab (Multan) in southern Pakistan	Photovoltaic – wind – biomass – diesel		HOMER			0.06	Pakistan has abundant renewable energy resources that could be used to reduce dependence on fossil fuels	yes
[49] (2020)	A village in western China	Solar – wind – biomass	Minimize the NPC	HOMER	PV 104 kW WT 30 kW BG 50 kW Battery 331 kWh Converter 99 kW	587013	0.201	PV/wind /BG/battery more economically viable than grid expansion	yes
[48] (2020)	A village in Fars Province, Iran	Solar – wind – biomass	Minimize the NPC	HOMER	BG 150 kW PV 80.7 kW	904513	0.128	The development of the project will save up to 8444 USD	yes
[36] (2016)	Egyptian village	Solar – wind – biomass	minimization of cost	HOMER	PV 150 kW WT 20 kW BG 100 kW	5772		It provides a cheap source of electricity for the area	yes
[5] (2014)	In rural India	Wind – biomass gasifier system	Minimum net present value	HOMER	BG 150 kW WT 100 kW Converter 100 kW		0.078	Compared to the wind-diesel system, the energy cost and operating costs are very low	yes
[23] (2017)	The remote area of Bwani	Solar – wind – biomass	Minimize the COE	GA, PSO			0.2393		yes

BG – biomass generation, WT – wind turbine, PV – photovoltaic.

3.5 Summary

Some cost economic parameters, analysis platforms, economic research methods and various algorithms are taked the references such as NPC and COE. Firstly, they optimize the multi-energy complementary energy storage system economically to make the cost as low as possible. Secondly, the feasibility of different energy systems in various regions are analyzed. By comparing the economic parameters, it can be known that the multi-energy complementary energy storage system is feasible to supply power to various regions. Such as Australia, small villages in Egypt, rural India, northern islands near the Bay of Bengal in Bangladesh, etc. Therefore, the renewable hybrid energy system is more efficient and cost-effective than the single renewable energy system and it also helps to overcome the defects of the single system. Renewable hybrid energy storage systems will be applied in more places and will present a greater potential.

Renewable energy mainly includes wind energy, solar energy and biomass energy. The resources, climates and economic conditions are different in all regions, so the hybrid systems are different. For example, in China, the northwest rural areas are rich in solar energy and biomass resources, so the hybrid system of solar energy and biomass is suitable. However some areas, which are rich in wind energy and solar energy resources, are also suitable to another system. According to a large number of researches, the cost of energy system will be reduced substantially by using the hybrid renewable energy complementary system, and at the same time, the power output is more stable.

4 The direction of future research

4.1 Optimization system

The need for wind energy and biomass or anything else on top of current PV is only based on the discrepancy between the solar generation curve and grid demand curve. The discrepancy results from the diurnal cycle and weather factors. To solve this problem, we need to find a more appropriate optimization algorithm.

Biomass is essentially similar as fossil-fueled generation in terms of electricity dispatchability characteristics. The only difference, though, is its renewability. But the carbon issue needs to be considered as a dominating factor. For example, In-situ burning of straw not only wastes a lot of resources and energy but also pollutes the environment.

The research of straw utilization technology and the development of energy products have become the urgent problems in the fields of agriculture, energy and environment, which are great significant to ensure national energy security, sustainable development of national economy and environmental protection.

The hybrid wind-PV complementary system is indeed a trend, but there are better ideas than simply adding them together. The essential question lies in 'complementarity'. Therefore, it is particularly important to analyze the types of wind energy resources that significantly complement solar PV in future studies.

In addition, wind resource characterization is the key work of economic analysis and optimization.

In this paper, the analysis of multi-energy complementary hybrid energy storage system comes from many aspects. On the basis of ensuring the stability of the power system, the system is made to be more economic. However, consideration of environmental factors is also essential.

With the further development of remote rural areas in China, the pattern and scale of power demand of various users will also change accordingly, which is worthy of further analysis. In addition, it is necessary to find new alternative and renewable biofuels and explore a better energy combination. In order to increase the penetration of renewable energy in the energy structure and reduce the power generation cost of renewable energy system, it is important to explore detailed sensitivity analysis to consider the changes of technology cost and energy supply. The influence of biomass price on system cost and the way for better usage of renewable energy are also the fields we need to study in the future.

4.2 Cost model

There should be more comprehensive and realistic cost models for economic optimization. The labor costs related to solar photovoltaic, wind turbines and biomass plants vary according to cases and countries, and the operation and maintenance costs vary. Economic analysis often ignores spillover costs, such as land value. The land use of a multi-energy complementary system is an essential practical factor to consider the potential investment. Suppose the photovoltaic project covers a large area, once the 'land use tax' and 'farmland occupation tax' are levied, the benefit of the project will be significantly reduced or even fail to meet the expectations. Therefore, the attribute of project land is becoming an important factor that affects an investment decision.

4.3 Complementary effect

Identical to any fossil fuel-based generations, biomass electricity has essentially no dispatchability limitation apart from the ones in its renewability. The remaining questions thus are purely on techno-economics which must include the add-on costs associated with its carbon emissions. Wind energy, on the other hand, has its dispatchability issues due to the intermittency. Therefore, optimizations in any practical multi-energy complementary systems ultimately rely on how complementary it is between solar and wind power generations within such systems.

Wind resource distributes more sensitively to geographic conditions and locations than solar irradiation. This brings a substantial challenge in seeking a general conclusion in optimizations of the solar-wind-biomass integration concepts. Nearly all the work reviewed in this paper is case-specific and sometimes seems contradictory to each other. However, a generalized guideline of complementary systems may be 'peak-offset' sought by looking into temporal distributions of the two renewable forms about that of the power demand, provided that wind speeds also exhibit sensible statistical patterns with time.

Almost all of the work reviewed in this paper is case-specific, and they sometimes seem to contradict each other. However, a generalized guideline of complementary systems may be 'peak-offset'. It is sought by looking into temporal distributions of the two renewable forms about that of the power demand.

Taking Australia as an example, a common statistical trend is seen in wind speed variations with the time in a day in different coastal regions. A preliminary study of 1-minute wind data is done by the University of Queensland. The date is measured by multiple weather stations of the Australian Bureau of Meteorology for over ten years. It is revealed that the peaks of wind speed generally occur between 15:00 and 17:00 (local time) of a day, which is 3–5 hours lagging the solar peak at noon. These stations are all located in densely populated urban areas along the coastal lines and have their wind sensors installed on 10–12 m-tall weather masts.The measured data represents a micro-scale observation of the wind speeds at lower altitudes, and mainly focus on the range of 5–20 km/h.

A solar-wind integration concept was thus proposed to incorporate solar PV with small-scale low-altitude vertical axis wind turbines as an isolated grid system. Increasing the proportion of wind turbines in this type of grid system reduces the required battery capacity because the peak of the wind generation curve is much closer to that of the demand. The trade-off to this is the rise in capital costs as small-scale wind turbines are generally more expensive than PV in terms of dollars per watt actual capacity. The optimal point sits somewhere between the two ends (100% PV and 100% wind). For instance, the study analyzed the LCOEs for a 2.5 MW-equivalent isolated complementary micro community grid in Canterbury and NSW (New South Wales) with different solar-to-wind ratios, shown in Table 5.

Table 5: LCOE (USD/MWh) of the off-grid power system with solar or wind energy.

The proportion of wind energy (in MW)	LCOE (10 years)	LCOE (20 years)
0% (pure solar PV)	331	270
20%	330	255
40%	334	244
60%	346	240
80%	368	245
100% (pure wind turbines)	402	261

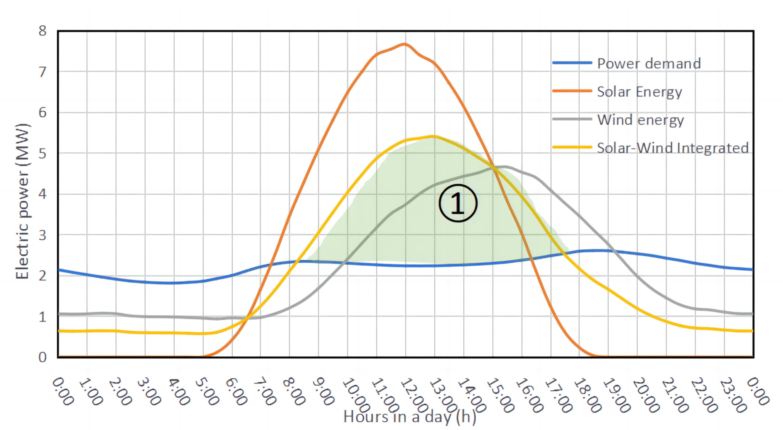

Figure 6: Power supply by pure solar PV, pure wind turbines, and integrated solar-wind (60% wind) in comparison with the grid demand over the 24 hours of a day. The area of enclosure (1) indicates the minimum amount of energy storage required for the integrated solar-wind grid system.

The example demonstrates how to offset the peaks of solar and wind. And the temporal demand curves influenced decision makings in planning, designs, and optimizations are also demonstrated. Of course, these all require true dynamics of the three components to suggest the importance of reliable data collection.

5 Conclusions

Hybrid energy system can increase the grid's reliability while reducing the dependence on energy storage. The result shows that the hybrid multi-energy system has more obvious economic advantages than the single energy system. Regarding energy ratio, the energy storage system with complementary hybrid energy has an economic advantage. Based on optimization, NPC or COE of energy systems in various regions are obtained through financial analysis. Through comparison, it can be known that applying hybrid renewable energy systems in these regions is feasible. It can be seen that the renewable energy system has excellent development potential, which is worthy of further research.

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