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Key technologies of rural integrated energy system with renewable energy as the main body

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Introduction

The sustainability of energy and food supply has become a major concern in the world today. Renewable energy such as photovoltaic and hydrogen energy has developed rapidly in recent years because they do not emit carbon. Zhang et al. put forward a novel method for producing hydrogen energy, which not only reduces the cost of hydrogen energy but also consumes renewable energy (Zhang et al., 2022). The power of photovoltaic power generation may change rapidly with the change in weather, which brings great uncertainty to the operation of power networks (Fu et al., 2020a). When the solar radiation becomes sufficient, photovoltaic power generation surges up like the rising tide; when dark clouds cover the sun, photovoltaic power generation will fade as quickly as the ebb tide. Li et al. established a multi-level energy trading model to deal with the uncertainty of new energy in a market-oriented way (Li et al., 2022). Fu pointed out that statistical machine learning is an effective way to model the random characteristics of photovoltaic power (Fu, 2022a). Rural house roofs and agricultural greenhouse roofs provide a wide range of ground for photovoltaic installation. Given the disadvantages of petroleum agriculture, the application of photovoltaic power generation and hydrogen energy in modern agriculture has become the focus of attention in the field of agricultural energy. Despite the uncertainty in power, photovoltaic generation is an important scheme of a microgrid for remote rural areas far away from the power grid (Habib et al., 2021). In addition, the combination of hydropower and wind power can provide a reliable power supply for villages (Pathak et al., 2019). The combination of greenhouse and photovoltaic is called the agrivoltaics system, which has become a new and potential technology in agricultural energy systems (Riaz et al., 2022). It should be noted that agrometeorology has a direct impact on the agrivoltaics system. Not only the photovoltaic generation but also the crop needs soar radiation (Fu et al., 2020b). Li et al. carried out several sets of simulation experiments, which indicated that greenhouse artificial lighting can consume renewable energy (Li et al., 2021). With the development of agricultural energy and high-energy consumption agriculture in

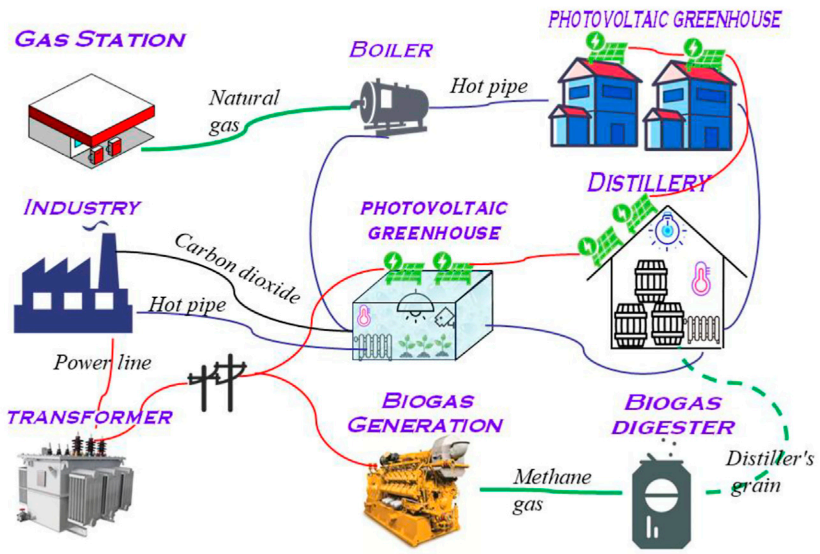

FIGURE 1
Schematic diagram of the rural IES in Qingdao, China.

villages, rural energy systems can have the function of a virtual power plant through load controls (Ju et al., 2022). Rural electrification not only occurs in agricultural planting but also fishery and aquaculture (Long et al., 2022). All-electric digital farms and all-electric digital fishing grounds have become rural-electrification programs, which have laid an engineering foundation for the theory of agricultural energy internet. The essence of agricultural energy internet means the integration of smart agriculture and smart grid in rural areas, and it is the inevitable result of the development of agricultural electrification and agricultural informatization (Fu and Yang, 2022). The fishery energy internet can deeply integrate power big data and fishery breeding so that fishermen can save money and labor (Fu, 2022b). The photovoltaic panel can change the amount of solar radiation on the water surface through angle change to shade the crabs cultured in the fish pond. At the same time, the ground source heat pump can be driven by photovoltaic power generation to adjust the water temperature. Wireless communication technology can improve the operational efficiency and security of the rural integrated energy system (IES) (Zhang, 2022). The deep integration of renewable energy, agriculture, and fishery industries, and the cluster development of the facility agriculture industry have an important effect on the economic operation mode of the rural IES. The requirements of agricultural planting, fishery, and aquaculture for energy quality vary greatly, which brings great challenges to the planning and control of the agricultural energy system.

Key technologies

Composition of rural IES

This paper studies a rural IES in Qingdao, China, as shown in Figure 1. The IES is composed of heat, electricity, and gas sources, which are used in agricultural production to improve energy efficiency, reduce environmental pollution and realize agricultural automatic production. Rural IES contains an ocean of renewable energy, including photovoltaic generation, biogas generation, and natural gas heating. The photovoltaic generation system can be placed on the roofs of villagers' houses, greenhouses, and distillery factories. Wine lees are generated during the fermentation, and they are transported to the biogas digester to supply biogas for power generation. The natural gas is supplied for gas-fired boilers to heat villagers' houses, greenhouses, and distillery factories in winter. The carbon dioxide produced by industry is transported to the greenhouses, and the carbon dioxide supplementation in the greenhouse provides a guarantee for the photosynthesis of crops.

We can realize the development of Shandong rural electrification from two aspects, including the construction of new energy and the transformation of distribution networks. The first way is to encourage the construction of renewable energy sources such as agricultural-photovoltaic complementarity projects and fishery-photovoltaic complementarity projects, which can be achieved through rural collective land shareholding and income sharing mechanisms. The second way is to implement upgrading projects of distribution networks so that each village has a reliable power supply network.

Synergy between agriculture and energy

The synergy between agriculture and energy includes many aspects, such as agricultural energy, agricultural production energy consumption, carbon-rich agriculture, etc. Agricultural biomass resources can be converted into energy, and energy is the escort of the facility's agricultural environment. Energy and agriculture also have carbon sink benefits. Specifically, the synergy technologies of agriculture and energy are as follows. 1) The first is carbon-rich agriculture technology. The use of carbon dioxide emitted from energy production in agricultural production can simultaneously solve the problems of the low-carbon energy systems and carbon dioxide fertilization, thus realizing a virtuous cycle of carbon emission from power generation to agricultural carbon fixation, and promoting the coordinated development of agricultural production and low-carbon energy. 2) The second is energy coupling technology, including agricultural energy and agricultural production energy consumption. On the energy side, agricultural energy includes crop straw power generation, rural biogas, biodiesel, fuel ethanol, etc. The development of agricultural biomass resources not only helps to solve the problem of agricultural waste pollution but also helps to solve the problem of energy shortage and carbon emissions. On the demand side, agricultural production energy consumption refers to the energy used in agriculture equipment working, which consumes energy to maintain the best environment in the greenhouses. The supply of the energy system should meet the agricultural energy demands. 3) The third is spatial coupling technology. The spatial coupling mode of the photovoltaic greenhouse brings about the problem of solar radiation competition between photovoltaic and crops. The coverage ratios of photovoltaic panels can change the greenhouse temperature and lighting. It is necessary to balance the lighting demands for photovoltaic generation and photosynthesis. The synergy between agriculture and energy is based on resource sharing and energy cascade utilization, that is, to use of differentiated space and energy demands to improve energy efficiency and agricultural output. The collaborative technology between agriculture and energy not only solves the single energy problem, but also takes on more responsibilities in the development of green circular agriculture, the comprehensive utilization of crop wastes, the reduction of agricultural non-point source pollution, and the protection of the ecological environment in rural areas.

Complementarity between agriculture and industry

There is a good complementary relationship between agricultural energy consumers and industrial energy consumers. Making good use of this complementary relationship can give full play to the environmental protection of agriculture and the economy of industry, reduce carbon emission and improve the comprehensive utilization efficiency of multiple energy. Specific technologies of the complementarity between agriculture and industry include carbon cycle technology, thermal cycle technology, and renewable energy consumption technology. In terms of the carbon cycle, the food and cash crops in the greenhouse are varieties that absorb carbon dioxide, which can realize the local consumption of industrial carbon dioxide. The biomass waste in the greenhouse can be used for power generation and heat supply, which can compensate for parts of the power and heat demands of the greenhouse, and also produce carbon dioxide as fertilizer. The flue gas discharged from high carbon emission industries can be used to manufacture carbon dioxide fertilizer through the processes of desulfurization, denitration, and carbon dioxide capture. In terms of the thermal cycle, the greenhouse can use industrial waste heat as the heat source for maintaining the thermal environment of the facility's agriculture. Through light-temperature coupling and waste-heat recovery, the energy consumption level of the greenhouse can be greatly reduced, so as to reduce its operation cost. It has positive practical significance for the promotion and application of fully automatic control greenhouses. In terms of renewable energy consumption, facility agricultural load is a unique meteorological sensitive load, which has a certain matching relationship with renewable energy. The high energy consumption and cluster production mode of modern agriculture provides a way for the local large-scale consumption of new energy. In addition, the supplementary lighting and irrigation are time-shifting loads, which can be controlled to consume renewable energy. The differentiated demands of industry and agriculture for energy and carbon dioxide provide an opportunity for the complementarity between industry and agriculture, and the complementary project between industry and agriculture has broad prospects for development in the future.

Applications of biomass energy

Biomass energy is a zero-carbon fuel, which not only has no carbon emission but also can be obtained in local rural areas. There are many feasible ways to develop biomass energy. 1) Each village should build a factory to realize the molding and granulation of dry biomass materials under economically feasible conditions. A large biomass gas station should be built for one million hectares of farmland to handle a large number of wet biomass materials. 2) Large biomass boiler combustion equipment can realize the large-scale consumption of various biomass resources, and then the production cost of biomass gas can be cut and no greater than natural gas. 3) Biomass materials are by-products of rural life and agricultural production, and the treatment of these products needs to avoid emitting carbon dioxide. The traditional methods are returning straw to the field or stacking green manure, resulting in emitting a certain amount of greenhouse gases. Converting biomass materials into biomass gas can avoid the emission of greenhouse gases. 4) Rural cooking, hot water, and heating are the primary energy loads of rural life, and biomass energy can meet the quality needs of rural domestic energy. We use livestock manure and straw as raw materials to ferment biogas and purify it to form biogas. Biogas can be used as boiler fuel or incorporated into the township gas pipe network to provide combustible gas.

Coal-fired power plants consume an ocean of mineral resources, but renewable energy such as wind power, photovoltaic, and biomass energy just needs natural resources such as space and solar radiation. Compared with crowded cities, rural areas have vast and abundant natural resources. Photovoltaic panels can be installed on the roofs of rural houses, greenhouses and livestock facilities, and open spaces. Wind power generation can be installed in rural areas with abundant wind resources. Small hydropower generating units can be installed in rainy mountain villages. The by-products of agriculture, forestry, and animal husbandry can provide rich resources for renewable energy power generation.

Discussion

With the development of modern agricultural industrial parks, energy production and consumption in rural areas show many new characteristics. The high energy consumption mode with high pollution is difficult to meet the needs of economic development in rural areas. There are a lot of renewable energy resources in Chinese villages, and the utilization of rural energy tends to be centralized. However, the utilization of rural energy is often developed and planned independently, leading to a large amount of energy waste, extremely low energy efficiency, and weak overall security and self-healing ability.

The rural revitalization strategy requires the development of renewable energy, which not only conforms to the development trend of China's energy strategy but also helps to reduce energy bills. The development of rural renewable energy should be in accordance with the general requirements of local conditions, policies, multiple-energy complementary, and efficiency. The utilization of green energy such as photovoltaic, biomass, and natural gas is an important part of the rural energy strategy. Specifically, the intensive development of distributed PV can be used as a primary energy source in Chinese villages. Natural gas should completely replace coal, and clean energy heating needs to be fully realized in rural areas.

With respect to power grid planning, the significant difference between the industrial energy system and agricultural energy system is that seasonal changes need to be well-considered and modeled in agricultural power grid planning, while an industrial load is not sensitive to seasons. This electricity demand for industrial products will not change significantly due to the weather, but the energy consumed by crops in different seasons varies greatly as they are very sensitive to weather changes.

Conclusion

In view of the rural modern agricultural park scenario, this paper proposes key technologies for the planning and design, operation control, virtual power plant, etc. of the rural comprehensive energy system with renewable energy as the main body. The key technology development of rural IES needs to fully consider the controllability of the facility's agricultural environment and the physiological characteristics of crops. The uncertainty of renewable energy and seasonal agricultural load should be modeled, and we should put forward a complete set of technical schemes for planning and design, operation control, and virtual power plant in the rural IES. The research on rural IES in this paper provides feasible ideas and schemes for implementing the strategic objectives of carbon peaking and carbon neutralization and promoting the comprehensive development and diversified utilization of rural green energies.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

LS, XG, YL, and ZX were employed by State Grid Shandong Electric Power Company Qingdao Power Supply Company.

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