

Modeling Renewable Energy Output Characteristics for Mobile Agricultural Scenarios and Multi-source Complementary Configuration Optimization

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Abstract

Agricultural mobile scenarios have dispersed energy loads that fluctuate with seasons and operational cycles. The intermittency and volatility of a single renewable energy source make it difficult to independently sustain a continuous and reliable power supply. This paper accordingly constructs output characteristic models for three power sources: photovoltaic, wind, and biomass. It further forms a multi-objective optimization model for multi-source complementary capacity configuration. This model balances annualized cost, power supply reliability, and renewable energy utilization. It obtains Pareto-optimal solutions with a non-dominated sorting genetic algorithm. Taking an agricultural demonstration area as a case, the multi-source complementary configuration raises power supply reliability by about 9.00 percentage points. It lowers annualized cost by about 14.00% compared with a single photovoltaic scheme. It also markedly smooths output fluctuations.

Keywords

Renewable energy, Output characteristic modeling, Multi-source complementarity, Capacity configuration optimization

Introduction

Mobile irrigation units, mobile field machinery, unmanned field platforms, cold-chain transport vehicles, and scattered greenhouses together form mobile electricity-use scenarios. These loads are numerous and widely distributed. The energy-consuming equipment is spread across fields and is highly mobile in space. It fluctuates sharply over time with seasons and farming rhythms. It is often located at the end of the grid or in remote areas. There, the supply radius is long, the terminal voltage is low, and reliability is persistently poor. Agricultural areas, in contrast, generally abound in solar, wind, and biomass resources. Developing these renewable sources locally and consuming them nearby can resolve the energy supply difficulty of agricultural mobile scenarios. It can also promote a green and low-carbon transformation of agriculture [1].

The output of renewable energy is governed by meteorological and resource conditions. It is markedly intermittent and volatile. Photovoltaic output concentrates in the daytime and changes abruptly with

wind speed and cloud cover. Wind output fluctuates irregularly. Biomass generation is constrained by the seasonal supply of feedstock. Its output is adjustable yet hard to stabilize. A single energy source can neither smooth its own fluctuations nor match the variable load profile of agricultural mobile scenarios. The supply system must either deploy large-scale storage or accept a high risk of load loss. Both paths drive up costs considerably [2].

Faced with the mismatch between output fluctuation and load, multi-source complementarity offers a way out. Wind, solar, and biomass are naturally complementary in time and space. Leveraging this complementarity together with energy storage and optimized scheduling can improve the continuity and economy of power supply. This can be achieved without markedly enlarging storage capacity. Hybrid systems such as wind-solar and wind-solar-biomass complementarity have been widely used in remote-area power supply and microgrid construction [3].

Agriculture has seen considerable exploration. Approaches to integrating renewable energy and agricultural production include agrivoltaics, photovoltaic greenhouses, and mobile photovoltaic panels. Existing work, however, has not adequately characterized the output features of agricultural mobile scenarios. Output characteristic modeling and capacity configuration optimization are mostly treated in isolation. They lack a framework that connects the two.

This paper therefore proposes, for agricultural mobile scenarios, a method combining output characteristic modeling with multi-source complementary configuration optimization. It builds output characteristic models for photovoltaic, wind, and biomass and defines a complementarity metric. It constructs a multi-source complementary configuration optimization model targeting economy, reliability, and utilization. It verifies the method through a case study.

Related work

Renewable energy utilization in agricultural scenarios

The integration of renewable energy and agriculture has a long history. It has recently formed several crossover directions, such as photovoltaic agriculture and agrivoltaics. Land-use optimization of agrivoltaic systems has been examined. These systems serve both power generation and crop growth. Photovoltaics and agriculture can share land and reinforce each other. Chinese photovoltaic agricultural greenhouses have been taken as the object. The economic and social benefits of the photovoltaic-plus-greenhouse model have been evaluated. Crop price is the most sensitive factor affecting economic benefit. A dynamic agrivoltaic system combining mobile photovoltaic panels with food crops has been proposed. Steerable panels improve total land output. Existing work focuses mainly on generation or economy. It pays insufficient attention to the output fluctuation and supply reliability specific to agricultural mobile scenarios [4].

Modeling and forecasting of renewable energy output characteristics

Output characteristic modeling underpins system planning and operation. Photovoltaic output forecasting methods have been reviewed. Output forecasting is crucial to the planning and dispatch of photovoltaic plants. Artificial intelligence (AI) methods have become

mainstream owing to their ability to capture nonlinear and complex structures. Photovoltaic output relates to solar radiation, temperature, and module characteristics. Wind output depends on the wind-speed-power curve. Biomass generation is constrained by feedstock calorific value and unit load rate [5].

Capacity configuration optimization of hybrid renewable energy systems

The capacity configuration of hybrid renewable energy systems has long drawn attention. Previous research reviewed the planning, configuration, modeling, and optimization techniques for off-grid hybrid renewable energy systems. It noted that combinations of wind, solar, and biomass can effectively support reliable supply in remote areas. Other work surveyed the capacity configuration and optimization methods of wind-solar complementary systems. It stressed the need to balance supply reliability against system cost. Existing work, however, mostly targets generic off-grid scenarios. It neither incorporates the load characteristics of agricultural mobile scenarios nor treats output complementarity as an explicit constraint or objective.

Measurement of multi-source complementarity

The essence of multi-source complementarity is to exploit the temporal misalignment of different energy outputs. Previous work systematically reviewed the concept, metrics, and applications of renewable energy complementarity. It gave a unified definition of the complementarity index. Other work proposed a mathematical metric of wind-solar output complementarity for hydro-solar-wind hybrid systems. It incorporated this metric into capacity configuration and scheduling optimization models. A case in China verified its guiding value [6,7].

Research gap

Surveying the existing research, output characteristic modeling, complementarity measurement, and capacity configuration optimization are mostly handled in isolation. Systematic work oriented to agricultural mobile scenarios is even scarcer. The mobility and volatility of loads in agricultural mobile scenarios impose special requirements on configuration schemes. To bridge this gap, this paper develops a complete method that connects output characteristic modeling with multi-source complementary configuration optimization [8].

Method

Overall framework

The proposed method consists of three parts: output characteristic modeling, multi-source complementarity measurement, and configuration optimization. Output characteristic modeling characterizes the time-series

output of photovoltaic, wind, and biomass sources.

Complementarity measurement quantifies the degree of output complementarity among multiple sources. Configuration optimization solves, on this basis, for the optimal capacity combination that meets economy, reliability, and utilization requirements.

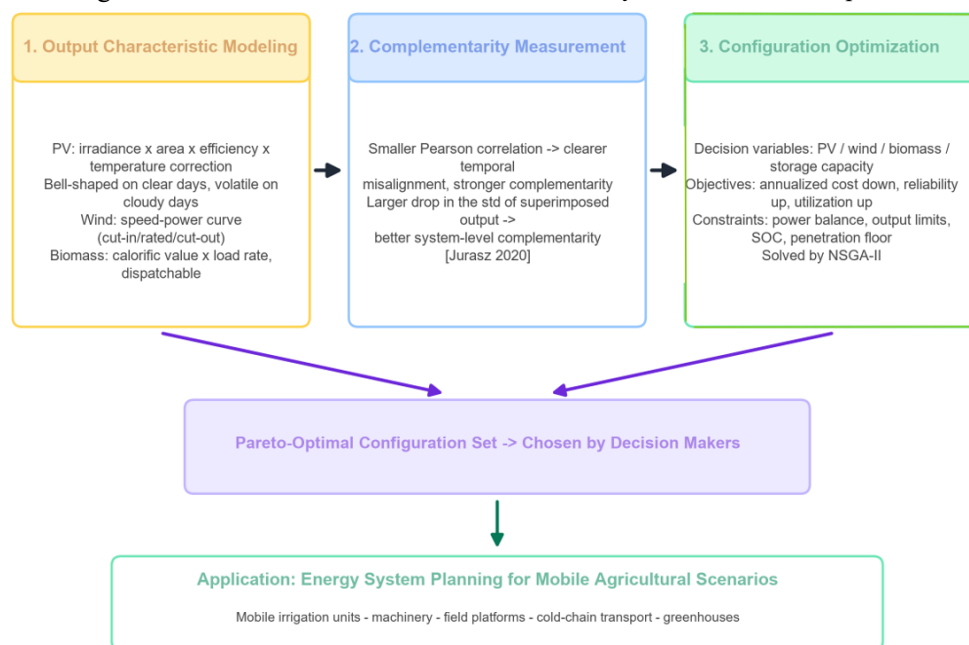


Figure 1. Overall framework of output characteristic modeling and multi-source complementary configuration optimization.

Modeling of renewable energy output characteristics

Photovoltaic output depends on horizontal solar radiation and temperature. According to the photovoltaic module output model, the output at time t is determined by solar irradiance, module area, photoelectric conversion efficiency, and a temperature correction coefficient. On clear days, the output curve is bell-shaped with a peak around noon. On cloudy or overcast days, it fluctuates at high frequency with cloud cover. Wind output is described by the wind-speed-power curve: It grows with the cube of wind speed between cut-in and rated speed, holds rated power up to cut-out speed, and stops beyond it. Biomass unit output is constrained by feedstock calorific value and unit load rate, yet it is highly dispatchable [9].

Measurement of multi-source complementarity

Following established ideas, the reciprocal of the correlation between wind and solar output, or a variant of it, is taken as the complementarity index. A system-level complementarity metric is also defined. The smaller the Pearson correlation coefficient between two output series, the more evident the temporal

misalignment. The stronger the complementarity becomes. The more the standard deviation of the superimposed output falls below that of a single source, the better the system-level complementarity [10].

Multi-source complementary configuration optimization model

Taking the capacities of photovoltaic, wind, biomass units, and energy storage as decision variables, a three-objective optimization model is built. It aims to minimize the annualized system cost while maximizing power supply reliability and renewable energy utilization. Constraints include the power balance at any time period and upper and lower limits on each source's output. They also include the state of charge and capacity ceiling of storage. A minimum requirement on renewable energy penetration is also included [11].

Solution algorithm

An elitist non-dominated sorting genetic algorithm solves the multi-objective model. It encodes decision variables to generate an initial population. A new population is produced through selection, crossover, and mutation. Parents and offspring are merged, and

individuals are partitioned into fronts via fast non-dominated sorting. Elite individuals are retained by crowding distance to preserve diversity. A set of Pareto-optimal schemes is obtained after iteration reaches the termination condition.

Case study and experiments

Experimental setup

An agricultural demonstration area is taken as the case. Hourly solar radiation, wind speed, and agricultural mobile load data are collected for a typical year. The loads cover irrigation, mobile field machinery, and greenhouse climate control. Three comparison schemes are set up: single photovoltaic, wind-solar complementarity, and wind-solar-biomass-storage multi-source complementarity.

Annualized cost, power supply reliability, and renewable energy utilization serve as evaluation indicators. Source and storage parameters are set to typical values used in practice.

Analysis of output characteristics and complementarity

The output characteristic modeling results show that photovoltaic output concentrates in the daytime. Wind output is relatively dispersed between day and night. Biomass units can supplement output during peak-load hours. Wind and solar output exhibit evident temporal complementarity. Their superposition markedly reduces fluctuation. Adding biomass and storage further smooths the system output curve. The multi-source complementary configuration effectively suppresses output fluctuation. It correspondingly lightens the system's dependence on storage.

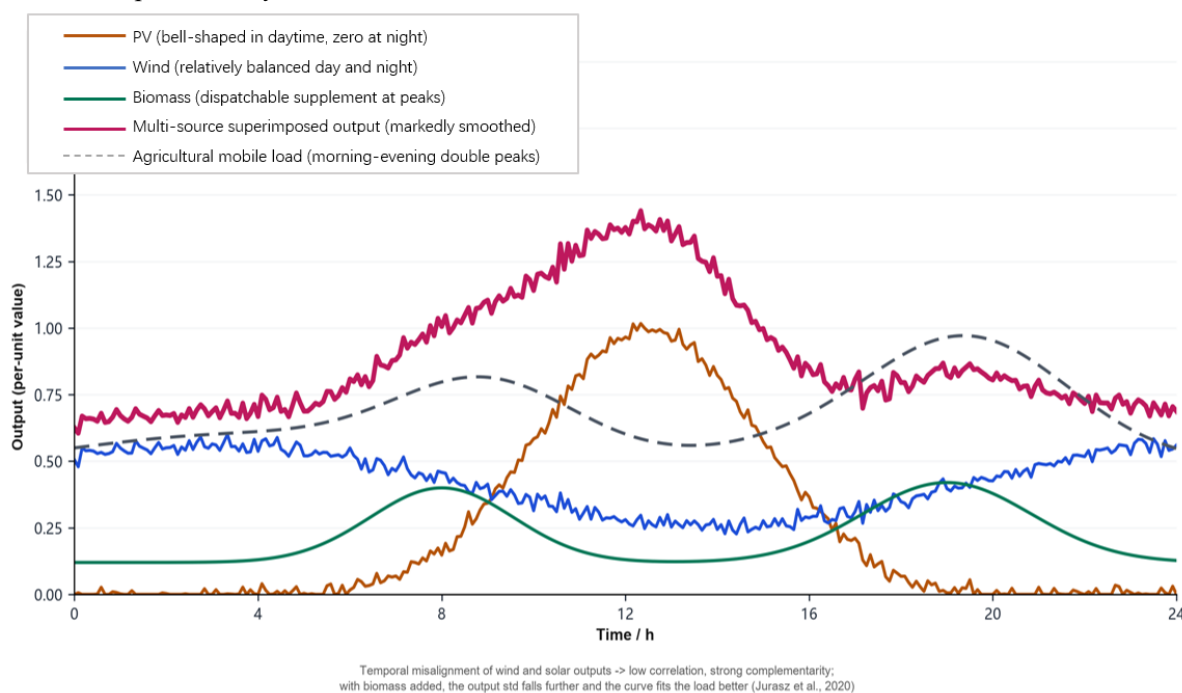


Figure 2. Output characteristics of three power sources and the smoothing effect of multi-source complementarity on a typical day (schematic diagram).

Configuration optimization results

The configuration optimization results show that the multi-source complementary scheme raises power supply reliability by 9.00 percentage points and lowers annualized cost by 14.00% relative to the single photovoltaic scheme. Renewable energy utilization remains relatively stable. The Pareto front reveals the trade-off between economy and reliability, and decision makers can choose a configuration accordingly. Overall, the wind-solar-biomass-storage scheme strikes an effective balance among economy, reliability, and cleanliness.

Discussion

The proposed method performs well in agricultural mobile scenarios, but several issues warrant attention. The output characteristic model depends on the spatiotemporal resolution of meteorological data. Sparse observation stations in agricultural areas may impair modeling accuracy. The choice of complementarity metric also affects the optimization results. The spatial mobility of loads makes supply demand more uncertain. Robust optimization or stochastic programming could be introduced to capture this in future work.

The case data in this paper are illustrative values and must be replaced by actual observations and re-verified before formal application. In real deployment, multi-source complementary systems also face engineering constraints such as equipment selection, grid-connection policies, and operation and maintenance management.

Conclusion

To address the unreliability and large fluctuation of a single renewable power supply in agricultural mobile scenarios, this paper proposes a complete method. It combines output characteristic modeling with multi-source complementary configuration optimization. It constructs output characteristic models for photovoltaic, wind, and biomass. It also builds a multi-source complementarity metric. A multi-source complementary configuration optimization model is built, targeting economy, reliability, and utilization. A case study verifies the effectiveness of the method. Future work will focus on refined modeling of mobile-load uncertainty and validation in larger-scale scenarios.

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Conflicts of Interest

The author declares no conflict of interest.

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