Research on Collaborative Operation Modes of Hydropower and Wind-Photovoltaic Renewable Energy

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Abstract Global decarbonization is pushing large amounts of wind and solar power onto the grid. Their output is naturally volatile, and that volatility disturbs system stability. Hydropower has flexible regulation and can respond quickly. That is why it has become a reliable partner for absorbing the uncertainty of renewable output.This paper reviews the ways hydropower and wind-PV have been coordinated, drawing on the domestic and international literature. For each approach it compares the scenarios that fit, the gains achieved, and the limits. Four main paths come out of the studies: stochastic optimization based on physical models, flexibility resource expansion, multi-agent benefit compensation, and macroscopic regional competition.The paper does not stop at listing these technologies. It sets up a four-level framework that runs from technical scheduling, through physical flexibility and benefit coordination, to regional governance. Each path is matched against the concrete scenarios it targets and the range it can cover. The aim is to give planners and schedulers of large clean energy bases a theoretical reference they can draw on.

Keywords Hydro-Wind-PV complementarity; Collaborative approaches; Uncertainty optimization; Benefit compensation

1. Introduction

Wind and PV power now fill a large share of the grid, and that has made system operation harder. Their output is random and intermittent. Brought in on their own, they often weaken grid security and stability. Studies show that coupling highly regulated hydropower with VRE into a Hydro-Wind-PV system is an urgent, realistic need in the energy sector [1]. Getting such a system to run optimally over the long term is still difficult. Long-term inflow stays uncertain, short-term VRE stays random, and the stochastic scenario methods in use today give no clear physical interpretation [1].

Technical scheduling is not the only difficulty. At the macro level, the problems grow. Cross-regional diffusion of wind and PV does not always bring synergy. The two can fight for grid access and market share, and the relationship can swing between predator-prey and mutualistic patterns [2]. Figuring out scientifically sound collaborative operation modes matters a lot for renewable energy accommodation. This paper groups these modes and compares them, with a brief look at how domestic and international collaborative development methods differ. The core task is to show which constraints each mode answers, which scenarios it suits, and how the modes work together.

2. Classification of Collaborative Approaches

Existing literature suggests that current collaborative operations can be grouped into four approaches, sitting at the technical, physical, economic, and governance levels. The progression runs from algorithmic optimization, to physical expansion, to economic compensation, and finally to macroscopic coordination. Each step reflects a fuller understanding of what system integration involves.

2.1 Collaborative Scheduling Based on Physical Stochastic Optimization

Uncertainty makes scheduling hard, so researchers came up with a physically-based stochastic scenario modeling approach for coordinating hydropower and VRE efficiently. The core idea is straightforward: scenario probabilities come straight from how often weather conditions actually occur. A hierarchical optimization framework is built to couple long-term and short-term operations, chasing two goals at once—maximize long-term power generation, minimize short-term average scheduling deviations [1].

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The approach answers short-term weather uncertainty through hierarchical stochastic optimization. Its weak spots are computational complexity and the need for reliability assessment.

Because practical use demands solid reliability checks, multivariate stochastic simulation was used to generate long-series hydro-wind-PV data, and a medium-to-long-term stochastic optimal scheduling model was built with stochastic dynamic programming [3]. The results show complementary operation does improve system reliability, though reliability falls as the total installed capacity of wind and PV grows. In this study, a relatively optimal complementary reliability appears when the installed capacity ratio of PV to wind is 3:7, and the system reacts far more strongly to total installed capacity than to this ratio [3]. The approach answers medium-to-long-term uncertainties with multivariate stochastic simulation and dynamic programming. The 3:7 ratio and the reliability findings are context-dependent—they hold for this study, not as universal laws.

Uncertainty does not stop at scheduling. It carries through the whole system, and that pushes expansion planning to a higher standard. A source-grid-load-storage coordinated expansion model based on stochastic programming was put forward for this. The model has a wide reach: demand response entities, converter stations, DC transmission systems, and cascade hydropower stations. Energy storage is brought in to smooth intermittency, which improves renewable energy accommodation from the planning side [5]. Set the three studies next to each other and the division is clear. Reference [1] handles short-term weather uncertainty. Reference [3] deals with medium-to-long-term reliability. Reference [5] works on source-grid-load-storage expansion planning. They also share one common weakness—heavy computational complexity and a strong dependence on specific scenario settings.

2.2 Collaborative Pathway Based on Flexibility Resource Expansion

Algorithmic optimization and storage planning help renewable integration, but their reach stops at the physical flexibility of the existing infrastructure. Flexibility resources also include storage and demand response. This paper takes PSPS as a representative case. PSPS here is a typical example, not a stand-in for all flexibility resources. Expanding system flexibility resources becomes another vital collaborative pathway on its own.

Research has looked into building pumped storage power stations (PSPS) among cascade reservoirs to add flexibility to multi-energy complementary clean energy bases [4]. The approach does strengthen regulation capacity. It also complicates the hydraulic and electrical connections between upper and lower reservoirs, which brings new uncertainties to power generation. To support high-quality power supply, the research explored the complementary characteristics under different PSPS construction types and located efficient operation intervals for giant cascade reservoirs [4]. The pathway answers renewable uncertainty by strengthening physical regulation. Its limits are connection complexities and geography. This physical expansion gives the later collaborative operations a solid regulatory foundation.

2.3 Collaborative Pathway Based on Multi-Agent Benefit Compensation

Physical feasibility alone is not enough to make things run smoothly. Collaborative operation usually pulls in several power generation entities, and where they meet, conflicts of interest show up. Hydropower pays an opportunity cost to provide regulation services. Wind and PV, in turn, gain accommodation benefits. Without compensation, nobody has much reason to keep collaborating, so the work comes down to quantifying contributions and paying for the benefits. Wind and PV are stochastic, and they need adjustable hydropower to be accommodated by the grid. That makes the multi-agent benefit coordination among entities more intense. This mechanism deals with collaborative feasibility when the benefit distribution is uneven.

A study took the Yalong River large-scale clean energy base as a case to tackle this economic barrier. It set up a day-ahead scheduling model and sorted out the profit-loss relationships of different entities, using a contribution quantification model and compensation mechanisms to balance interests through economic means [6]. Compensation resolves the interest conflicts. It leans heavily on accurate quantification and market policies, though. This mechanism helps close the gap between technical scheduling and practical implementation.

2.4 Extended Governance Perspective: Regional Coopetition

Technology diffusion and regional competition sit above scheduling and PSPS. They are treated here as a higher-level collaborative governance perspective, not as an equivalent operation approach. This section is a macroscopic supplementary view, then, not a fourth parallel to the earlier technical, physical, and economic approaches. Move beyond a single energy base and the spatial dynamics of technology diffusion add another layer of complexity. Seen from a macroscopic regional angle, collaboration runs through physical scheduling, and it runs just as clearly through the competition dynamics of technology diffusion.

An improved Lotka-Volterra model was used to study how wind and PV technologies co-diffuse across regions in China. The results were telling: PV diffuses significantly faster than wind, and both feel scale-restrictive effects [2]. Their diffusion trajectories keep switching between predator-prey and mutualistic patterns. The mutualistic pattern showed up only in Southwest China. Spatial spillover effects add more color. Wind power deployment

picks up positive synergies from neighboring regions. PV technology, by contrast, is more often held back by peer competition [2].

The macroscopic view gets a further complement from the environment. Renewable energy plants look green and clean, but they still leave a negative footprint. A comprehensive review based on SWOT analysis pointed out that large-scale renewable deployment needs careful environmental assessment, and that assessment should be folded into regional planning [7]. This pathway answers regional coordination and environmental externalities. It offers a higher-level governance perspective.

3. Comparative Analysis of Collaborative Approaches

3.1 Comparison of Pathway Characteristics and Applicable Scenarios

The first three approaches are the core collaborative operation pathways. The fourth one offers an extended governance perspective.

The physical stochastic optimization approach [1,3,5] is about handling technical uncertainty. It solves long-short-term nested scheduling problems with mathematical modeling and algorithms. This approach fits basins where inflow and wind-PV output swing sharply and power quality requirements run high. The 3:7 capacity ratio finding [3] shows how capacity ratios can shift reliability under one specific system configuration. It is not meant to be a general engineering parameter.

The flexibility resource expansion approach [4] focuses on physical regulation capability. PSPS is configured among cascade reservoirs, and system regulation capacity rises at the root. It suits large hydropower bases that have conditions for cascade reservoir development. New risks from complex hydro-electric coupling still need to be watched.

The multi-agent benefit compensation approach [6] moves into economic mechanism design. The first two deal with technical and physical constraints. When a clean energy base has multiple investors, pure technical optimization cannot stir up much willingness to collaborate. This approach evens out the uneven benefit distribution through contribution quantification and compensation. It fits highly marketized power systems.

The regional competition perspective [2] belongs to macroscopic planning. It brings out the nonlinear character of wind and PV spatial diffusion, and it pushes policymakers to think about inter-regional homogeneous competition and spatial synergy effects. Add the global environmental angle [7], and collaborative pathway design has to fold in environmental SWOT analysis to stay sustainable over the long run.

3.2 Brief Comparison of Domestic and International Collaborative Development Methods

This review only covers a limited set of literature, and the studies in it lean toward different things. Some stress engineering optimization, some market mechanisms, some regional governance. When it comes to collaborative development methods, international research got to market mechanisms and cross-regional spatial synergy earlier. The Lotka-Volterra model is used there to break down competitive and mutualistic relationships between renewable technologies, with an eye on spatial spillover effects and the diffusion patterns that free market competition brings [2]. Systematic comparison work has also been done on comprehensive environmental impact assessments [7]. These differences reflect the varying focuses of the literature in this review. They are not strict systematic divergences. A small literature sample, no matter which side it comes from, cannot stand in for all international or domestic research.

Domestic research, by contrast, leans on the engineering practice of large-scale clean energy bases and cascade reservoirs. The focus falls on building medium-to-long-term stochastic optimal scheduling models [3], drawing out cascade reservoir PSPS flexibility [4], and designing benefit compensation mechanisms among the entities inside a base [6]. Part of these differing emphases probably comes from differences in energy-system structure and market design. The sample is too small to support a cross-country conclusion, though.

Both sides have strengths. Future collaborative operation calls for a deep blend of physical scheduling optimization, market mechanism design, and macroscopic regional planning. Studies on the engineering side give useful insight into physical scheduling and flexibility construction. Studies on the institutional side bring in market mechanisms and cross-regional coordination. Put the two together, and a comprehensive collaborative framework can take shape, one that bridges technical feasibility and economic viability.

4. Conclusion

Running hydropower together with wind and PV is a core piece of building new-type power systems. This paper has gone through four collaborative approaches, each sitting at a different level: technical, physical, economic, and governance. They are physical stochastic optimization, flexibility resource expansion, multi-agent benefit compensation, and a macroscopic governance view of regional cooperation.

Comparing them shows that no single approach can handle the full complexity of real operation. Stochastic optimization is good at absorbing uncertainty. PSPS expansion lays a physical regulatory foundation. Benefit compensation balances the interests of multiple parties.

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Regional competition analysis supplies a macroscopic planning view.

Look at the domestic and international methods side by side, and the next step becomes clear: future research should break down the walls between technology, economics, and spatial planning, and look for a comprehensive framework that brings several pathways together. That is how high-proportion renewable energy gets better support for high-quality development.

Collaborative operation is a multi-level stacked problem. One technique, no matter how good, is not enough. It takes an organic mix of physical flexibility, economic incentives, and governance coordination.

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