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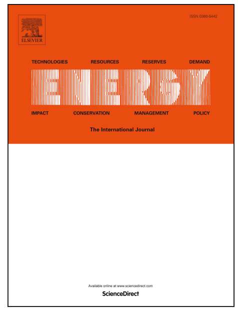

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# Improved Multi-objective Model and Analysis of the Coordinated Operation of a Hydro-wind-photovoltaic System

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**Abstract** The coordinated operation of a hydro-wind-photovoltaic system can mitigate the conflict between power generation and output fluctuations and overcome the bottleneck of new energy development. Because of the lack of available research on the coordination mechanism for analysing the relationship between power generation and output fluctuations, depicting the grid architecture and allocating power curtailment, this study establishes a multi-objective model for the coordinated operation of a hydro-wind-photovoltaic power system. The model seeks to maximize power generation and minimize output fluctuations under the constraints of multilayer architecture of the power network and balanced allocation of power curtailment. In a case study of a prefectural-level power grid in southwest China, three schemes are compared: independent operation with a single objective, coordinated operation with a single objective, and coordinated operation with multiple objectives. The complementary role of hydropower for increasing power generation and mitigating output fluctuations is explored; the effects of coordinated operation on transmission utilization and the hydrological regime are analysed; and the Pareto frontier of power generation and output fluctuations is obtained and the interaction of these factors is discussed. This study refines the model of a hydro-wind-photovoltaic system and investigates the complementary mechanism underlying multi-energy systems.

**Keywords:** hydro-wind-photovoltaic system; coordinated operation; power generation; output fluctuation; complementary mechanism; non-inferior frontier

## 1 Introduction

The uncertainty and limited storability of wind and photovoltaic power cause issues related to output fluctuations and power curtailment, which severely impede the utilization of renewable energy (Acker et al 2012) and decelerate carbon emissions reductions (Zhang et al 2016). The coordinated operation of hydropower with intermittent renewable energy can efficiently solve these problems (Liu et al 2011, Hirth 2016). Modelling and optimizing the coordinated operation of a hydro-wind-photovoltaic system can be used to study the coordination mechanism and provide decision support for regulations (Rani D et al 2010, Singh A 2012).

In recent years, many studies have modelled and optimized the coordinated operation of hydro-wind (Papaefthymiou et al 2014, Pereira et al 2015), hydro-photovoltaic (Tao et al 2015) or hydro-wind-photovoltaic (Schmidt et al 2016) systems. The model objectives usually include the power generation (Wang et al, 2013), economic benefits (Kern et al 2014a), emissions reductions (Azizipanah-Abarghooee et al 2012), water supply (Glasnovic et al 2016), generation costs (Pérez-Díaz et al 2016), power curtailment (Segurado et al 2016), output fluctuations (Destro et al 2016), and flow regime of hydropower discharge (Kern et al 2014b). The first 4 items, middle 2 items and last 2 items reflect the effects of coordinated operation in terms of its benefits, costs and influence, respectively. Because the cost of hydro-wind-photovoltaic systems is low and approximately constant, especially in the short term, most objectives focus on the benefits and influence. Because the primary aim of multi-energy coordination is to increase the power generation and decrease the output fluctuations by regulating hydropower generation, power generation and power fluctuations are the main objectives. The modelling constraints can be divided into three categories: resource type, station type, and grid type (Labadie 2004, Cheng et al 2011, Wu et al 2015). With the rapid development of wind and photovoltaic energy and the lagging construction of the power grid in China (Sun et al 2017), the grid constraints, which include the power framework and transfer capability, have become the dominant restrictions for coordinated operation.

Earlier studies (Jaramillo et al 2004, Pan et al 2008) mostly focused on increasing the power generation profit and mitigating the output fluctuations without considering the relationship between power generation and output fluctuations. Because of the randomness of wind, solar radiation and runoff, as more power is generated, the output fluctuations increase. Thus, there is a trade-off between power generation and output fluctuations. Regulations, such as those associated with dispatching hydropower via a reservoir, could alleviate this competing relationship to some extent. A study on the coordinated operation of pumped storage hydropower and wind power found that this relationship follows a Pareto relevance (Wang et al 2011). However, that study did not consider the resource changes in different seasons, and it used the reciprocal of the deviation to quantify the output fluctuations, which is not ideal for neglecting contoured fluctuations (Wang et al 2016a); moreover, it did not consider the restraint of the transfer capability of the power grid. Based on a review of common methods for characterizing the output fluctuations, a new index that combines both contoured and quantitative features was proposed and verified (Wang et al 2016a, 2016b). In later studies, the constraint

**Highlights:**
►With refined objective functions and constraints, a model for a hydro-wind-photovoltaic power system that considers power generation and output fluctuations is proposed.
►By comparing three schemes, the complementary role of hydropower in the coordination is discussed.
►The Pareto frontier of power generation and output fluctuations is obtained.