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Optimal Wind Farm Repowering under Uncertainty with Hydrogen Hybridization

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ABSTRACT This paper addresses the optimal repowering of existing wind farms by integrating battery storage and green hydrogen production systems to enhance profitability and flexibility under market and resource uncertainty. A two-stage stochastic mixed-integer linear programming model is developed to jointly optimize wind turbine selection, battery sizing, and electrolyzer and hydrogen storage capacities. The model considers uncertainty in electricity prices, wind resource availability, and hydrogen prices through a scenario-based approach, and incorporates physical constraints such as turbine spacing and grid capacity. To ensure computational tractability, a chronological time-period clustering technique and an iterative technology-evaluation algorithm are applied. A case study of a wind farm in Spain demonstrates that hybridization with hydrogen increases expected annual profit by approximately 4%, while batteries remain uneconomical at current costs. Sensitivity analyses reveal that higher hydrogen prices significantly increase investments in electrolyzer capacity and hydrogen storage, highlighting the importance of supportive market conditions for the green hydrogen transition.

INDEX TERMS batteries, hybridization, hydrogen, stochastic programming, wind power

I. INTRODUCTION

A. BACKGROUND AND MOTIVATION

THE global energy transition toward low-carbon systems has driven a profound transformation in how electricity generation infrastructure is planned, operated, and expanded [1]. Within this context, wind energy has emerged as one of the most mature and competitive renewable technologies, playing a central role in reducing greenhouse gas emissions and achieving international climate targets [2].

However, a substantial proportion of the wind power capacity commissioned over the past two decades is now approaching the end of its operational lifetime, thereby giving rise to new technical, economic, and environmental challenges associated with repowering and with the reintegration of these assets into power systems that are becoming increasingly complex and decentralized [3], [4]. End-of-life decision-making must explicitly account for underlying market and resource volatility [5], [6]. Consequently, traditional deterministic approaches are increasingly being replaced by stochastic programming frameworks that more accurately represent the trade-offs among decommissioning, lifetime extension, and full repowering. Recent contributions have established an important economic benchmark by employing stochastic models to support decision-making under uncertainty, in particular through the joint modeling of hourly electricity prices, characterized by seasonality, and stochastic capacity factors [5], [7]. The results of these studies indicate that, when the stochastic evolution of price volatility and annual energy yield is incorporated, full repowering yields a substantially higher net present value than alternatives such as reblading or simple lifetime extension [5], [6].

Beyond purely economic assessments, contemporary re-