

Optimal Wind Farm Repowering under Uncertainty with Hydrogen Hybridization

KEYWORDS

Wind Repowering · Green Hydrogen · Stochastic Programming · MILP · Battery · Electrolyzer

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INTRODUCTION & MOTIVATION

Context: A large share of wind capacity from the past two decades is approaching end-of-life, requiring repowering decisions under market and resource uncertainty. The global energy transition demands advanced frameworks that jointly account for wind resource variability, electricity market volatility, and hydrogen price uncertainty.

Literature Gap: This work is the first to jointly address stochastic optimization of wind farm repowering with simultaneous sizing of battery and hydrogen systems under market and resource uncertainty — combining all six critical dimensions: repowering, batteries, hydrogen, uncertainty, joint investment, and stochastic MILP formulation.

OBJECTIVE

Develop a two-stage stochastic MILP to jointly optimize wind turbine technology, battery storage, electrolyzer, and H₂ storage capacity to maximize expected annual profit under uncertainty in electricity prices, H₂ prices, and wind availability. The model considers physical constraints (turbine spacing, grid capacity) and uses scenario reduction and time-period clustering for computational tractability.

METHODOLOGY

- **Stage 1:** Turbine selection, battery sizing, electrolyzer & H₂ storage capacities (first-stage decisions)
- **Stage 2:** Hourly dispatch under 10 reduced scenarios representing electricity price, wind speed & H₂ price variability
- **Uncertainty:** 500 scenarios generated from 2008–2023 historical data; reduced via fast-forward selection algorithm
- **Clustering:** Chronological Time-Period Clustering (CTPC): 8,760h compressed to 1,000 representative periods
- **Algorithm:** Iterative procedure: one turbine type evaluated per iteration; best solution retained across all runs
- **Solver:** CPLEX 12.6.3 · HPE ProLiant DL560 Gen11 · 4x18-core 2.2 GHz · 512 GB RAM · 3.2 h/iteration

CASE STUDY: La Plata, Toledo, Spain

- 30 × 850 kW turbines (25.5 MW total)
- Avg. wind speed: **6.5 m/s** Budget: **€60 M**
- Turbines: Repower 2MW · Enercon 2.3MW · Nordex 2.5MW · Vestas 3MW
- PEM electrolyzer: 800 €/kW · 50 kWh/kg-H₂
- H₂ storage: 300 €/kg Avg. H₂ price: **4 €/kg** (range 3–8.3 €/kg)

TWO-STAGE DECISION FRAMEWORK

STAGE 1: Investment

Turbine · Battery
Electrolyzer · H₂ cap.

STAGE 2: Operation

Dispatch · H₂ sales
10 scenarios

Uncertainties: Electricity price · H₂ price · Wind speed

STOCHASTIC VALUE ANALYSIS

Case	Value of Stochastic Solution, VSS (%)	Expected Value of Perfect Information, EVPI (%)
BAU (with H ₂)	6%	46%
No H ₂	1%	31%

Stochastic modeling is significantly more valuable when H₂ hybridization is considered (VSS=6% vs. 1% without H₂). The EVPI of 46% for the BAU case further confirms that uncertainty plays a critical role in investment decisions for hybrid wind–hydrogen systems

MAIN RESULTS: BAU vs No H₂

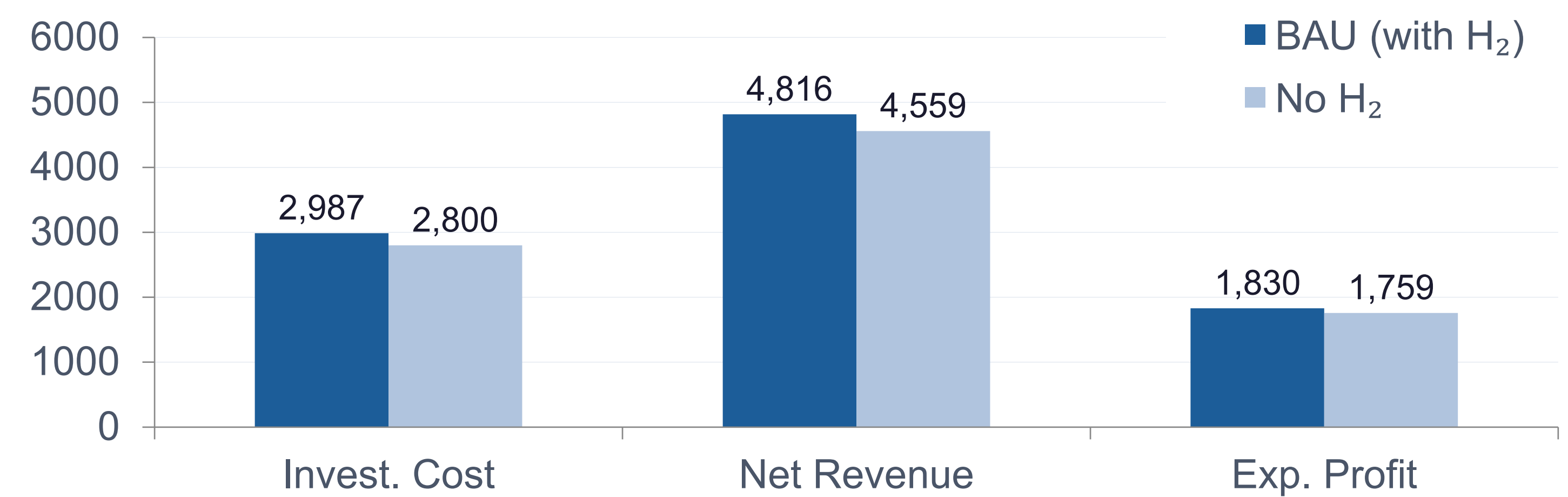
+4%
Expected Annual Profit
(BAU vs No H₂)

2.3 MW
Optimal Turbine
(BAU case)

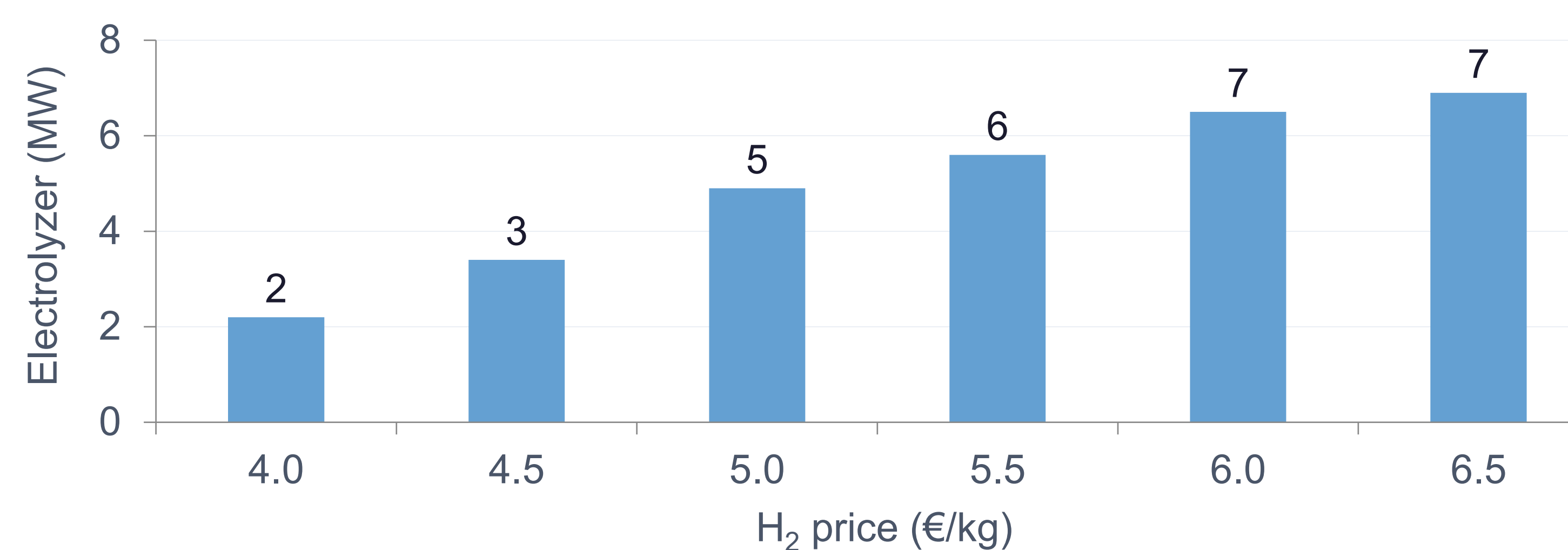
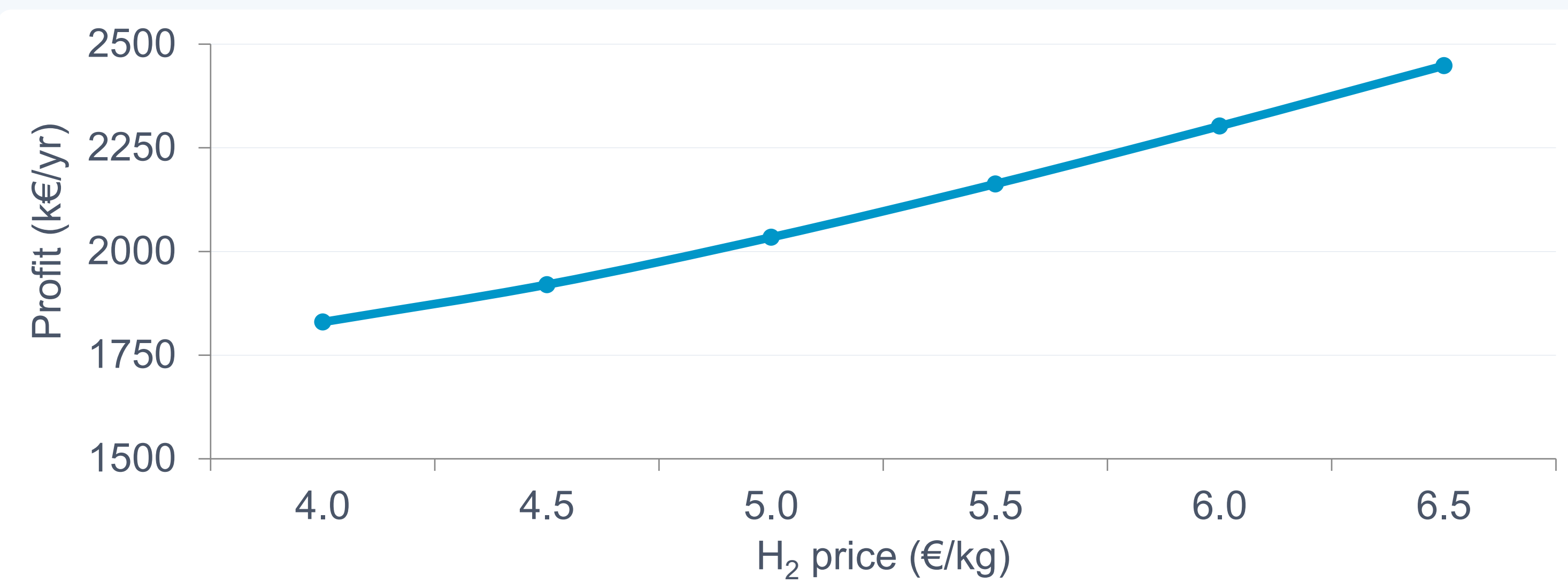
2.2 MW
Electrolyzer
Capacity (PEM)

3.8 t
H₂ Storage
Capacity

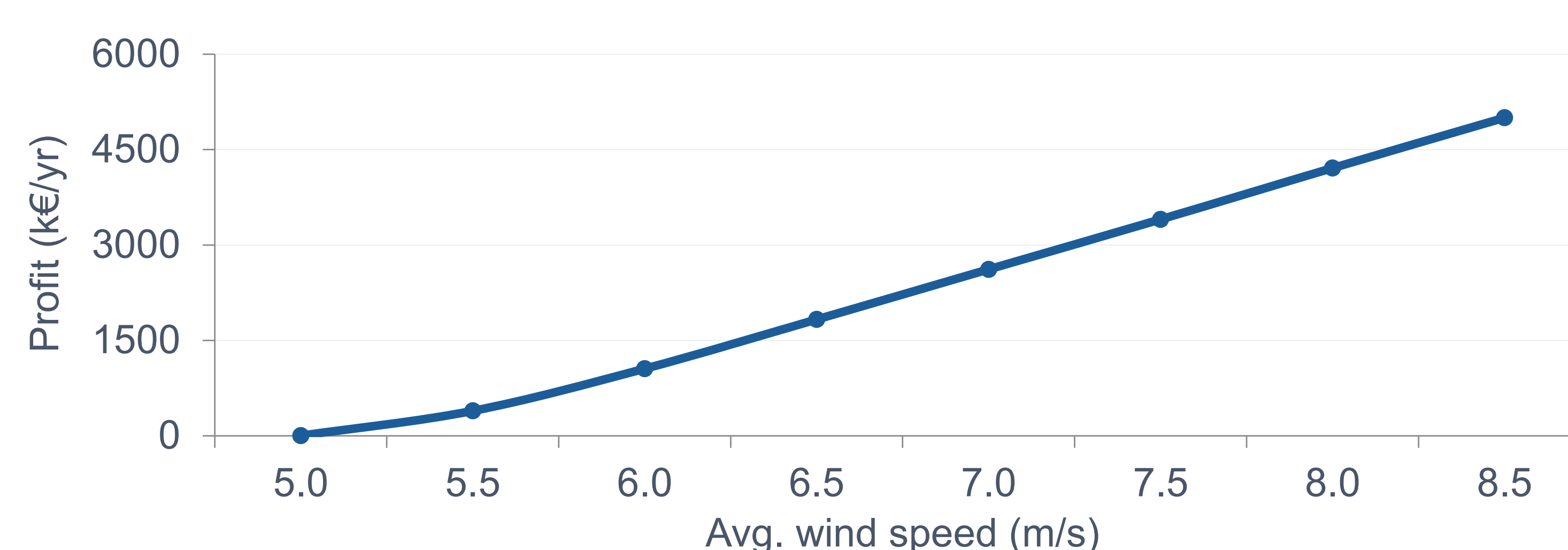
Investment & Profit Comparison (k€/year)



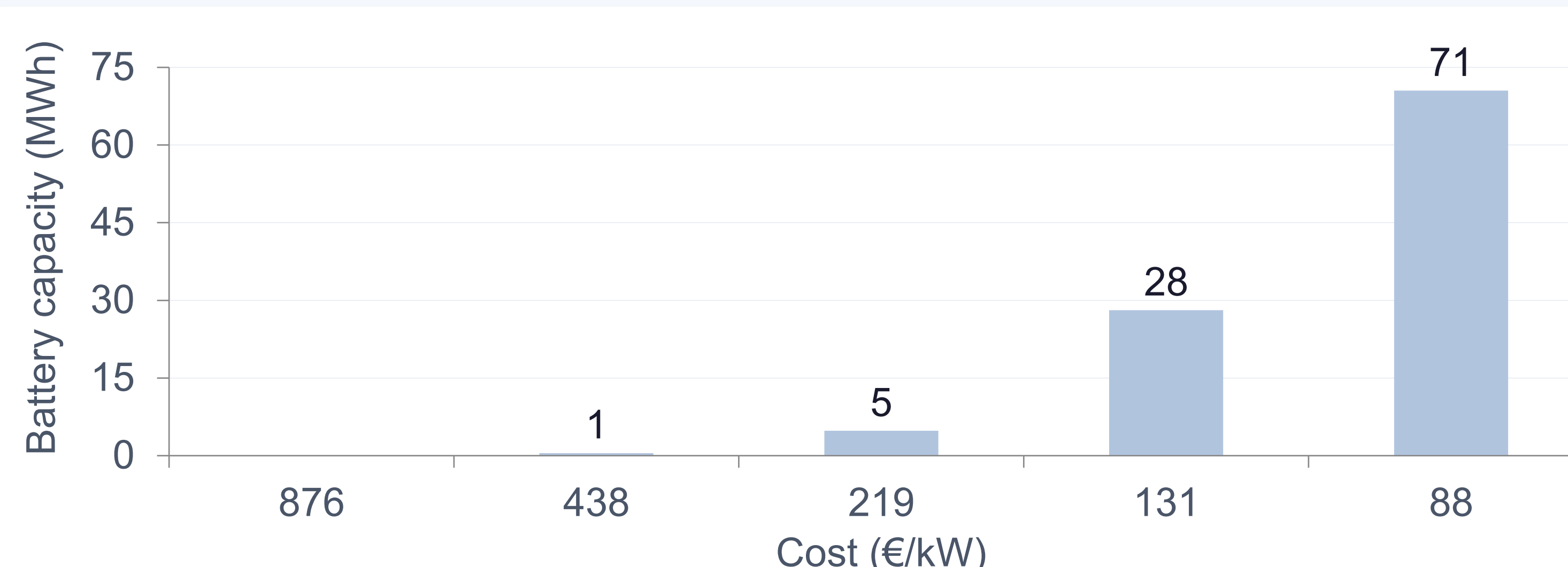
H₂ Price Sensitivity



Wind Speed Sensitivity: Annual Profit (k€/year)



Battery Cost Sensitivity: Li-Ion 4h Installed (MWh)



CONCLUSIONS Hydrogen hybridization raises annual profit ~4% vs. wind-only repowering.

Batteries remain uneconomical at current costs (>75% cost reduction needed). Stochastic modeling yields VSS=6% (BAU) vs. 1% (No H₂). Higher H₂ prices scale up electrolyzer investment; higher grid capacity reduces it. Wind speed is the dominant driver of total profitability.