Centre for Sustainable Subsurface Resources

Robust Constrained Optimization for Emission-Free Reservoir Operation Integrating Wind Power and Hydrogen Storage

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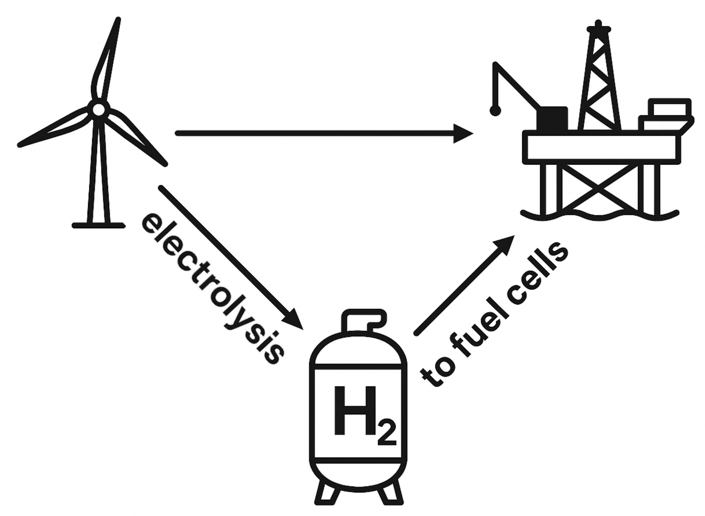
1. Introduction

- Replace gas turbines with **on-site wind power + hydrogen storage**
- Excess wind is stored as hydrogen and later converted back to electricity
- Robust optimization accounts for uncertainty in both geology and wind
- The cost function balances discounted production value against energy-system CAPEX

2. Energy System & Objective



Excess wind power is converted to hydrogen; fuel cells supply power when wind is insufficient.

- Electrolysis: $e_{\mathrm{el}} = 50\ \mathrm{kWh/kg}$ ($\approx 70\%$ efficiency)
- Fuel cell conversion: $e_{\mathrm{fc}} = 33.3\ \mathrm{kWh/kg}$ with $\eta_{\mathrm{fc}} = 50\%$
- 65 control variables: well rates (7 wells $\times$ 9 control steps), wind turbines x_{wt}, and hydrogen storage x_{h2}

Multi-objective NPV:

$$J = \omega_1 \sum_{i=1}^{N_t} \frac{V(t_i)}{(1+d)^{t_i/\tau}} - \omega_2\,\mathrm{CAPEX}, \quad \omega_1 + \omega_2 = 1$$

$\mathrm{CAPEX} = x_{\mathrm{wt}}\, r_{\mathrm{wt}} + x_{\mathrm{h2}}\, r_{\mathrm{h2}}$, and varying ω_2 traces the profit–CAPEX Pareto front.

3. Ensemble-based constrained optimization using an exterior penalty method

The optimization uses an ensemble gradient approximation (EnOpt) over geological and wind realizations. For control vector x, the preconditioned gradient is

$$C\nabla f_k \approx N_e^{-1} \sum_{i=1}^{N_e} \left[J(x_k^i, y^i, w^i) - J(x_k, y^i, w^i) \right] \left[x_k^i - x_k \right].$$

- Samples $\{x_k^i\} \sim \mathcal{N}(x_k, C)$ capture average performance over likely scenarios
- This avoids adjoint equations and naturally propagates uncertainty in geology and wind

Hydrogen feasibility is enforced by an *exterior penalty*:

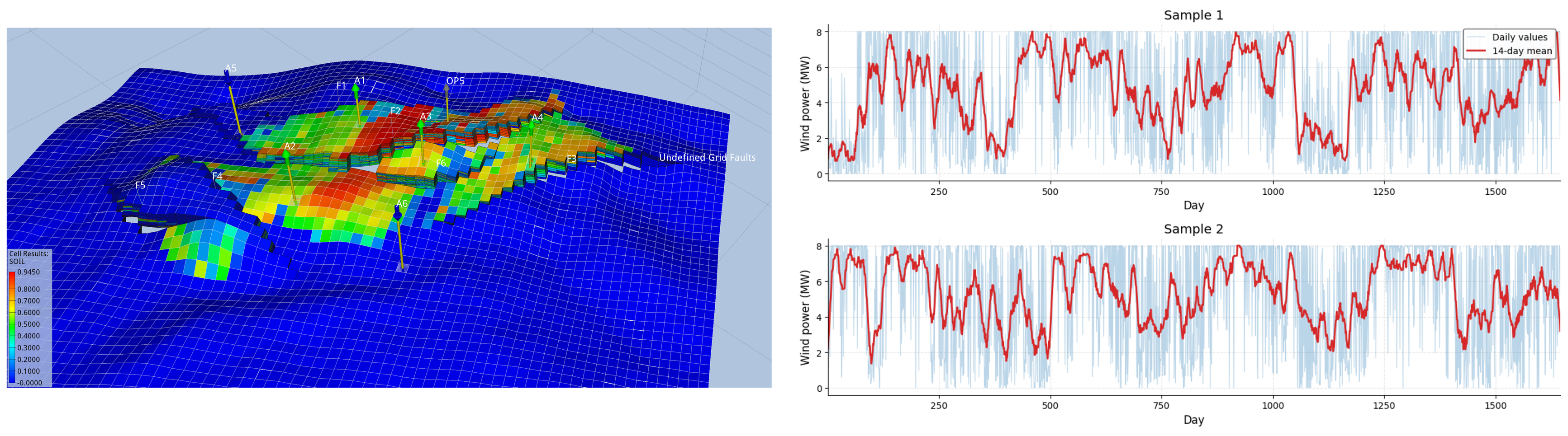
$$\hat{J}(x;\mu_l) = J(x) + \mu_l \big(\min\{h(x), 0\}\big)^2, \qquad \mu_{l+1} = c\,\mu_l,$$

where $h(x)$ is cumulative hydrogen deficiency.

- Ensemble size: $N_e = 50$
- Initial energy design: 35 turbines and 350 t H_2 storage
- Up to 5 outer penalty loops gradually increasing μ_l by a factor of $c = 10$
- Up to 30 inner iterations solving the unconstrained problem for each μ_l using EnOpt
- Wind uncertainty comes from a seasonal autoregressive model fitted to North Sea data

4. Drogon Test Case

The method is demonstrated on the synthetic Drogon reservoir ($\approx 70\,500$ active cells) with five producers, two injectors, and a 4.5-year production horizon. Wind forcing comes from NORA10EI hindcast data near Hywind Tampen and is converted using an 8 MW turbine curve.



Drogon reservoir model (left) and representative wind-power realizations (right).

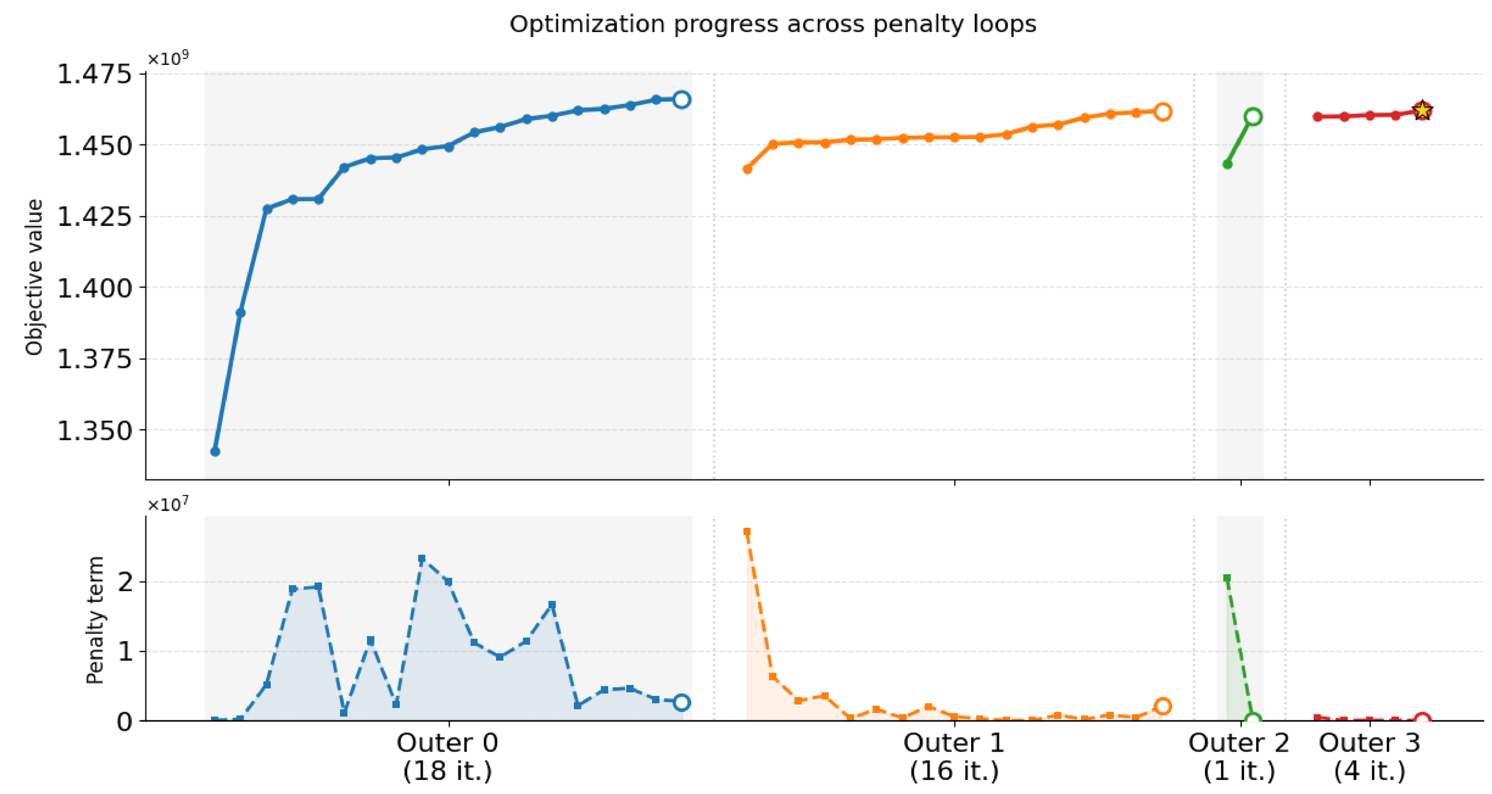
- Maximum platform oil rate: 18 000 m^3/day
- Control updates every six months over the life cycle
- Wind realizations preserve both seasonality and daily variability

Description	Value
Oil price	472 $\$\,m^{-3}$
Gas price	0.4 $\$\,m^{-3}$
Water disposal	37 $\$\,m^{-3}$
Water injection	25 $\$\,m^{-3}$

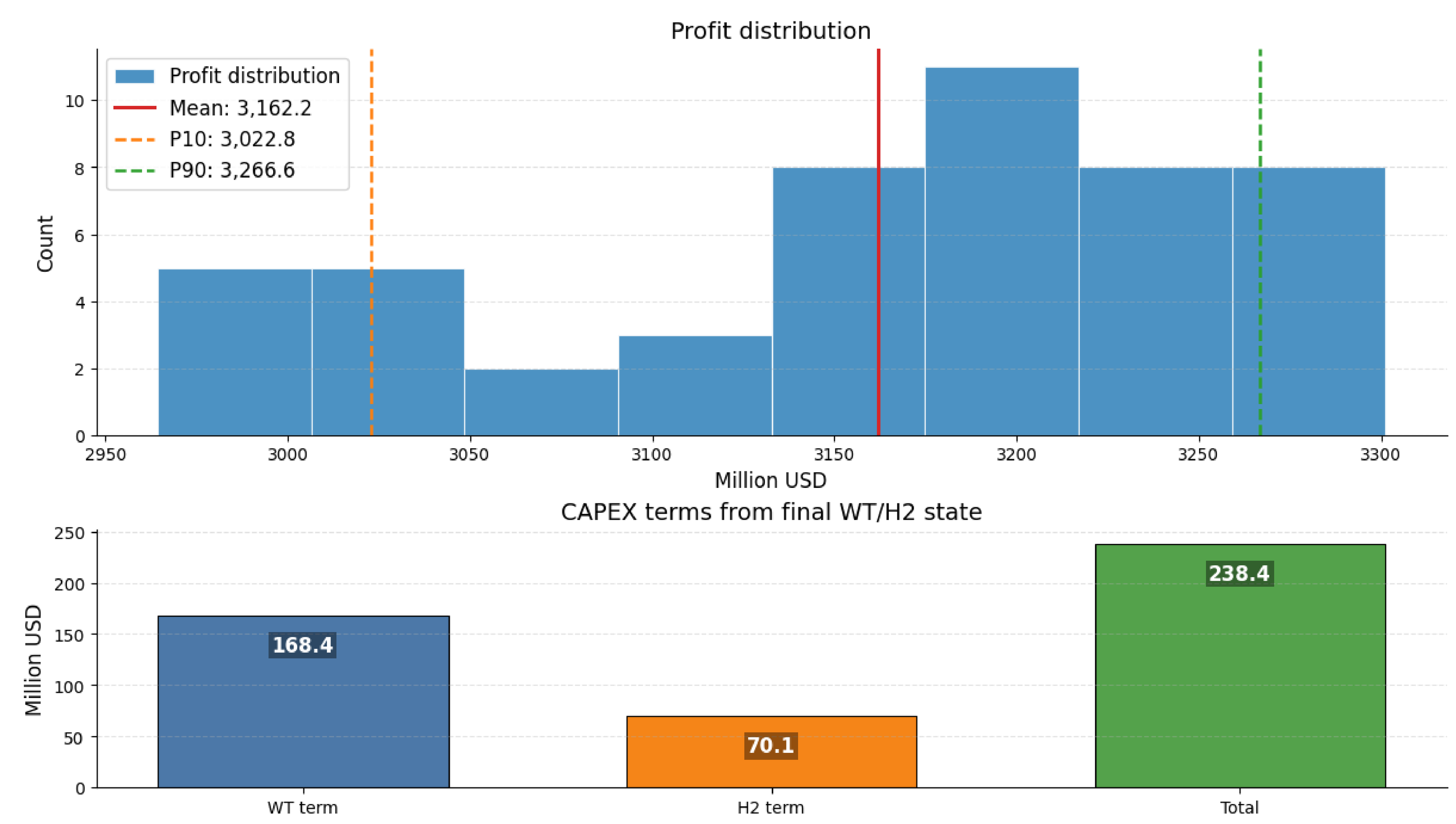
Description	Value
Wind turbine	7.2 M$/turbine
H_2 storage	0.18 M$/tonne
Discount factor	0.08
Life cycle (years)	4.5

5. Results

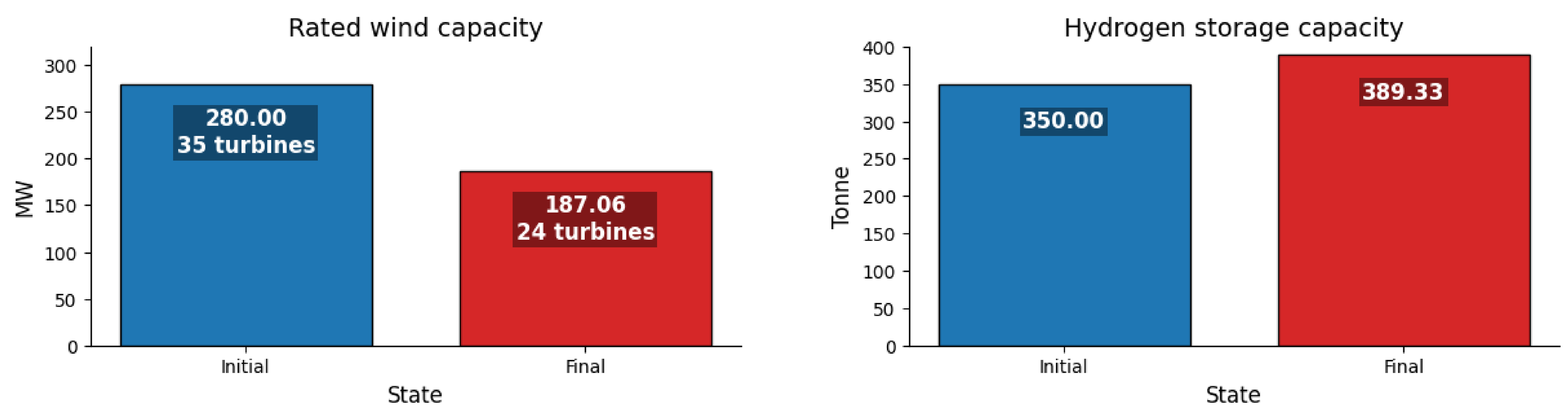
- Base case ($\omega_1 = \omega_2 = 0.5$): convergence after four outer penalty iterations
- Final objective value $\approx 1.46 \times 10^9$, corresponding to about 9% improvement over the initial strategy
- Feasible solutions maintain zero hydrogen deficiency across the sampled realizations



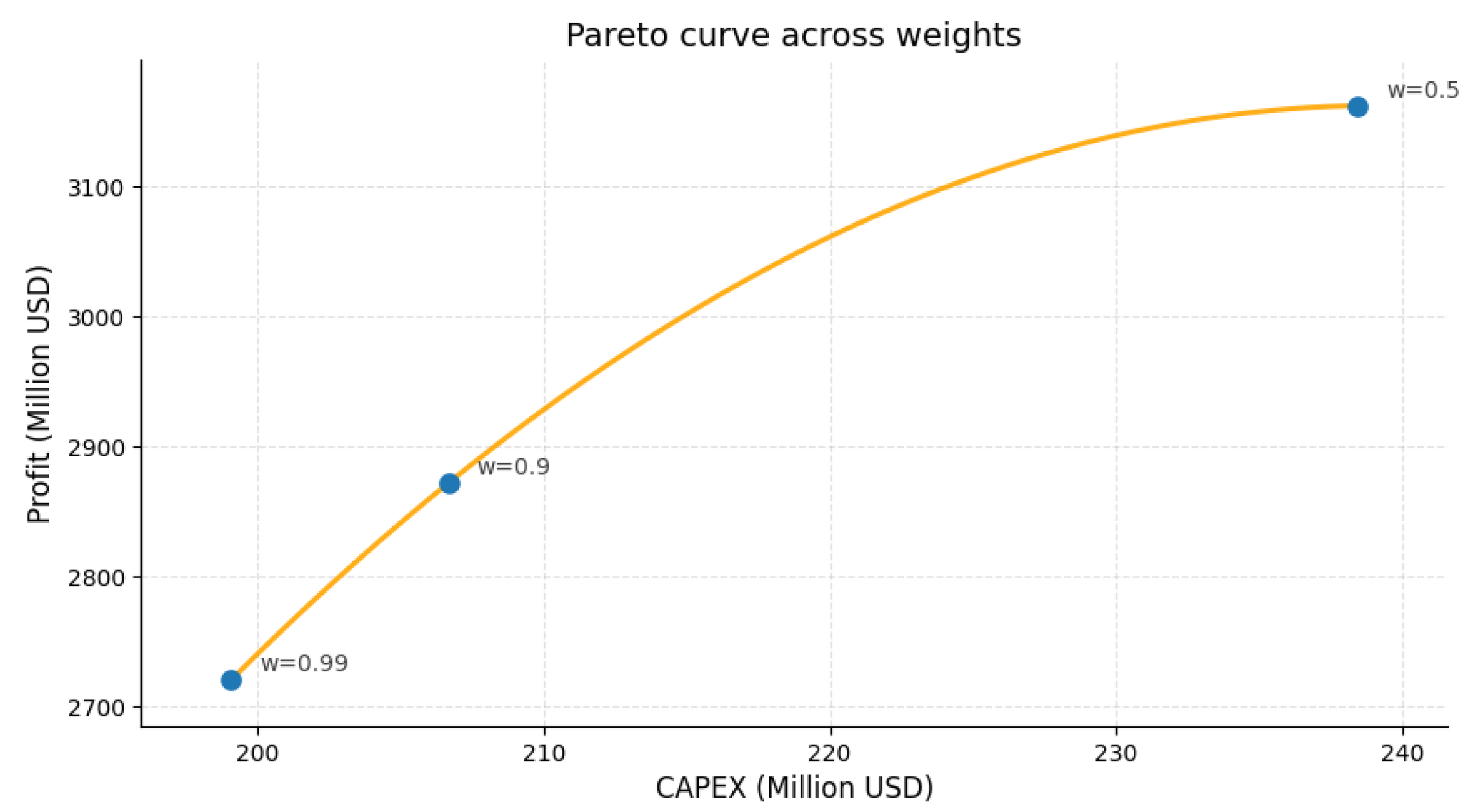
Exterior-penalty iterations. The star marks the best feasible solution with zero penalty.



Profit uncertainty across realizations (top) and CAPEX split for the optimized solution (bottom).



Optimized energy design variables: number of wind turbines (left) and hydrogen-storage capacity (right).



Pareto front obtained by increasing the CAPEX weight from 0.5 to 0.99.

ω_2	Turbines	H_2 storage (ton)	Profit reduction	CAPEX reduction
0.90	21	348	9%	13%
0.99	19	348	14%	17%

6. Key Findings & Future Work

- Robust constrained optimization (EnOpt) can deliver a **fully renewable offshore production strategy** that remains feasible under uncertain wind conditions
- The penalty formulation is essential for maintaining positive hydrogen inventory throughout production
- Future work includes improved economics, larger fields, batteries, and subsurface hydrogen storage
- The method and results will be presented at the ECMOR 26 conference in September

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