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Integration of Variable-rate Industrial Processes with Variable Renewable Energy: A Case Study in H_2-DRI

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Abstract: This study develops a techno-economic optimisation framework for integrating variable renewable energy (VRE) with a hydrogen-based direct reduced iron (H_2-DRI) steelmaking process. A mixed-integer linear program (MILP) couples photovoltaic (PV) and wind generation, hydrogen and pumped-hydro storage, and variable-rate production, accounting for operational thresholds, ramp limits, and shutdown costs. Simulations for Australian sites show that hybrid PV-wind systems with increased operational flexibility reduce the Levelised Cost of Steel (LCOS) by up to 43% compared to inflexible PV-only configurations. Site-specific strategies for resource mix and storage sizing enable significant cost savings while maintaining stable production in steelmaking.

Keywords: *Hydrogen Direct Reduced Iron, Variable Renewable Energy, Techno-Economic Optimisation*

1. INTRODUCTION

The H_2-DRI steelmaking route, comprising a fluidised bed reactor, electric smelting furnace, and basic oxygen furnace, offers a pathway to deep decarbonisation. However, its integration with intermittent VRE sources requires balancing generation overbuild, storage capacity, and process flexibility. Variable-rate production allows output to follow renewable supply, potentially reducing infrastructure costs but introducing operational challenges. This work models the coupled energy-production system, optimising plant operation and energy infrastructure across distinct Australian resource profiles. The aim is to identify cost-optimal configurations and operating strategies that minimise LCOS while ensuring reliable, large-scale steel production under high VRE penetration.

2. METHODOLOGY AND RESULTS

The study models an integrated energy–production system in which a 1.8 Mt/year H_2-DRI plant is supplied by VRE through PV arrays and wind farms as depicted in Figure 1. Energy is delivered via three carriers—electricity, heat, and hydrogen—supported by underground hydrogen storage in salt caverns (99% round-trip efficiency) and pumped-hydro energy storage (PHES, 79% efficiency). Hydrogen is produced using electrolysers operating at 70% efficiency (LHV basis) and combusted in 95%-efficient burners to meet process heat demands. The plant's nominal energy requirements comprise 347 MW of hydrogen to the reactor, 77.5 MW to burners, and 92.3 MW of electricity for other processes, all scaling proportionally with production rate. The energy input requirements were obtained from steady-state simulations results reported by Rahbari et al. (2023).

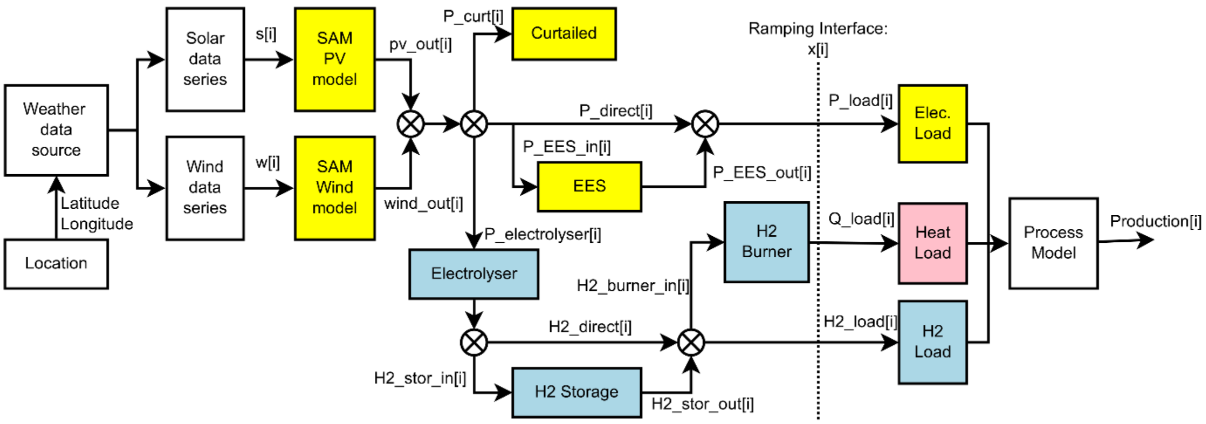


Figure 1. Schematic of the Hydrogen-DRI (H_2-DRI) steelmaking process.

A mixed-integer linear program (MILP) was implemented in Pyomo and solved via the GUROBI solver, following the methodology proposed by Mitra et al. (2012), to optimise system design and operation over an annual horizon.

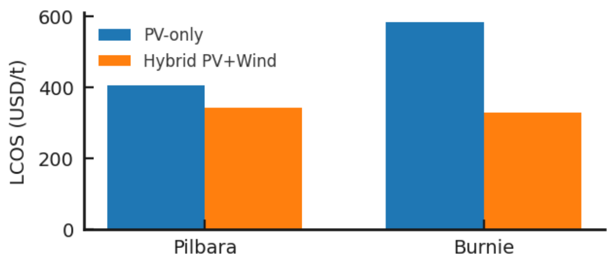
The optimisation minimises the sum of the annualised capital expenditure (CAPEX) and the annual cost of plant associated with shutdown and restarts, expressed as:

$$\min \text{Objective} = \text{CRF} \cdot \text{CAPEX} + C_{\text{annual,cycling}}$$

where CRF is the capital recovery factor, calculated from the plant lifetime and discount rate, and $C_{\text{annual,cycling}}$ is the penalty cost associated with shutdowns and restarts. The optimisation enforced hourly energy balances for electricity, heat, and hydrogen; minimum load thresholds of 90% and 70% of nominal capacity; ramping constraints; and storage capacity limits.

Case studies were conducted for two representative Australian locations: Pilbara and Burnie. Capacity factors between 70% and 100% were explored under cycling penalty levels from zero to 1 million USD per shutdown. The comparison of optimised systems was made using the Levelised Cost of Steel (LCOS), which combines annualised capital and operating costs with achieved steel output, enabling a consistent cost-performance assessment across different capacity factors and operational strategies.

Results indicated that H_2-DRI steelmaking powered by VRE with hybrid PV–wind systems consistently achieved a lower Levelised Cost of Steel (LCOS) than PV-only configurations. In the solar-rich Pilbara region, the hybrid system reached an LCOS of 343.1 USD/t at a 97 % capacity factor, compared with 406.8 USD/t for PV-only at 92 %. In the low-solar, wind-rich Burnie region, the hybrid configuration achieved 328.8 USD/t at a 92 % capacity factor, compared with 582.7 USD/t for PV-only at 70 %. These cost reductions stem from the hybrid system's ability to balance seasonal and short-term variability in renewable output, reducing reliance on oversized hydrogen storage and limiting costly shutdowns. By leveraging complementary wind and solar resources and optimising plant operation within defined flexibility thresholds, the hybrid systems maintained steadier production, minimised weather-driven interruptions, and reduced the capital intensity of generation and storage infrastructure.



Location	Configuration	CF (%)	LCOS (USD/t)
Pilbara	PV-only	92	406.8
Pilbara	PV+Wind	97	343.1
Burnie	PV-only	70	582.7
Burnie	PV+Wind	92	328.8

Figure 2. LCOS comparison for H_2-DRI steelmaking in Pilbara and Burnie using PV-only and hybrid PV–wind VRE systems. The table lists the optimal capacity factors (CF) that achieve the lowest LCOS.

3. CONCLUSION

The results demonstrate that coupling hybrid PV-wind generation with increased operational flexibility enables significant cost reductions and operational resilience for H_2-DRI steelmaking. Location-specific optimisation is critical: solar-rich sites can rely on PV with supplementary wind, while wind-dominated mixes are optimal in low-solar regions. Reducing the minimum operational threshold allows for smaller generation and storage capacities, lowering capital costs without compromising output. The MILP framework provides a robust decision-support tool for balancing CAPEX, storage sizing, and production scheduling, offering a clear pathway to cost-effective decarbonisation of large-scale steel production.

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