Decarbonizing Heavy Industry

Electrification and Digital Dynamics: New Business Paradigms

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March 2025
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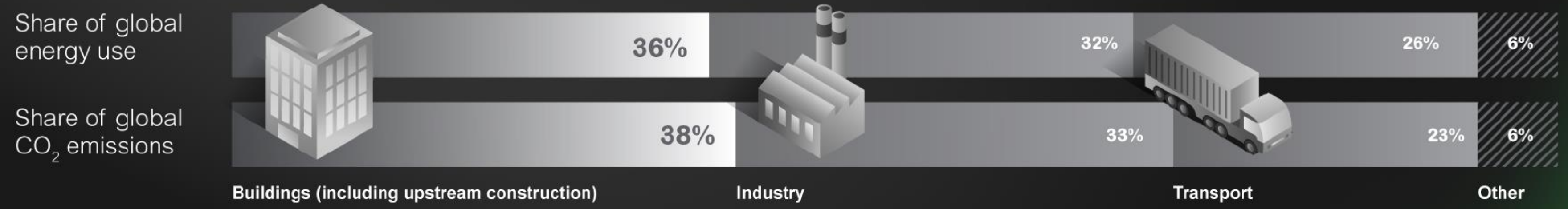
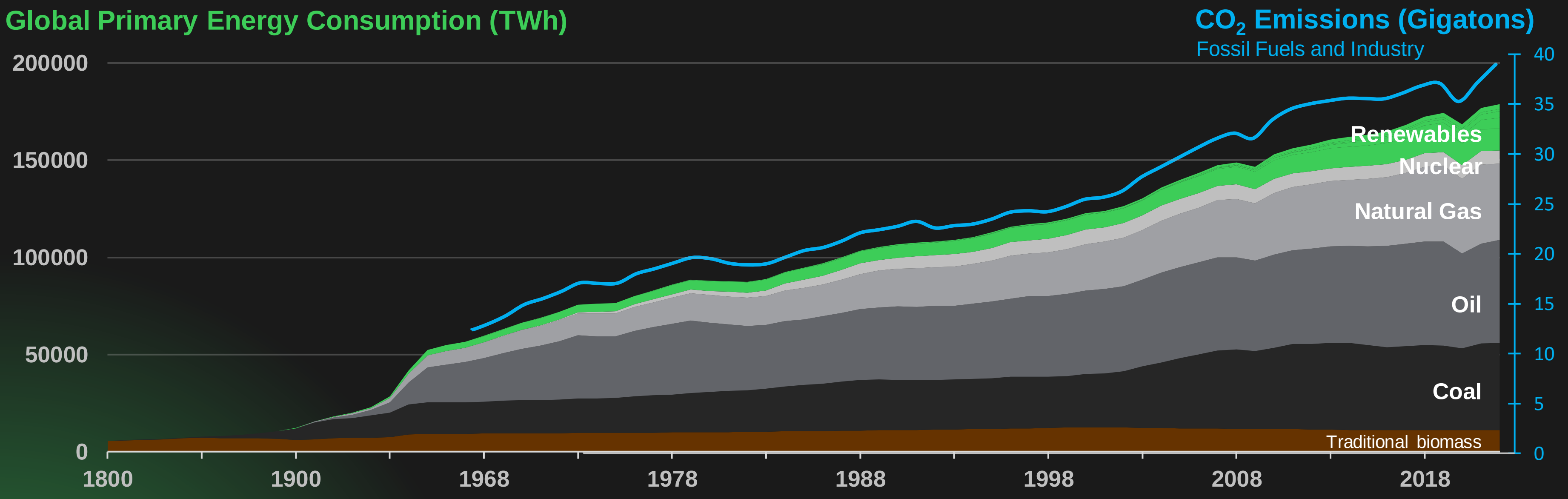
Global Energy Systems Are Coupled With Emissions

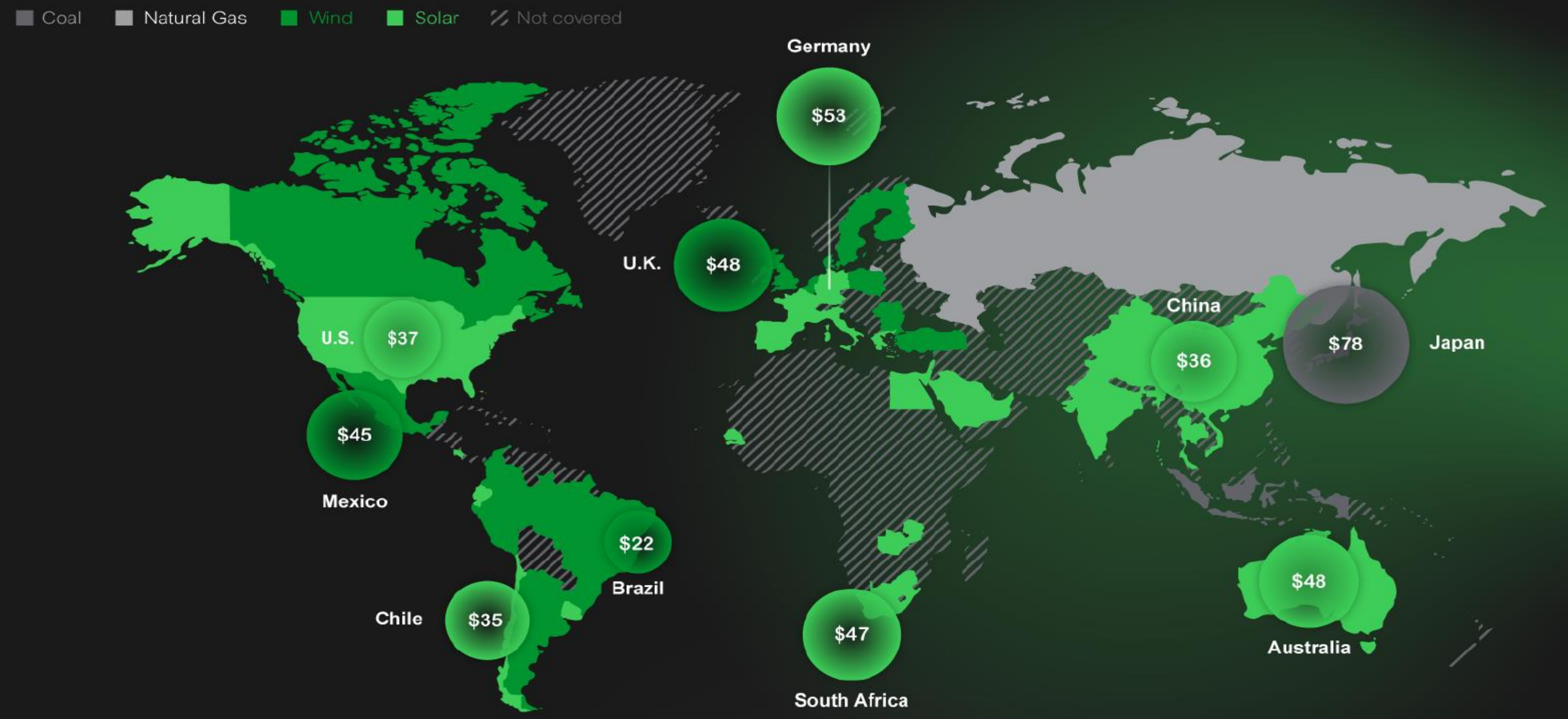




Energy Institute Statistical Review of World Energy; Friedlingstein, P. et.al, Global Carbon Budget 2022, Earth Syst. Sci. Data, 14, 4811-4900

Renewables Least Expensive New Electricity Source for 2/3 of the World

Cheapest source of Bulk Generation. Current LCOEs of New build solar, wind, coal and gas (2021)



Source: BloombergNEF. Note: The map shows the technology with the lowest LCOE for new-build plants in each country where BNEF has data (H1, 2021).
The dollar numbers denote the per-MWh benchmark levelized cost of the cheapest technology. All LCOEs are in nominal terms.
Calculations exclude subsidies, tax-credit or grid connection costs. CCGT is combined-cycle gas turbine.

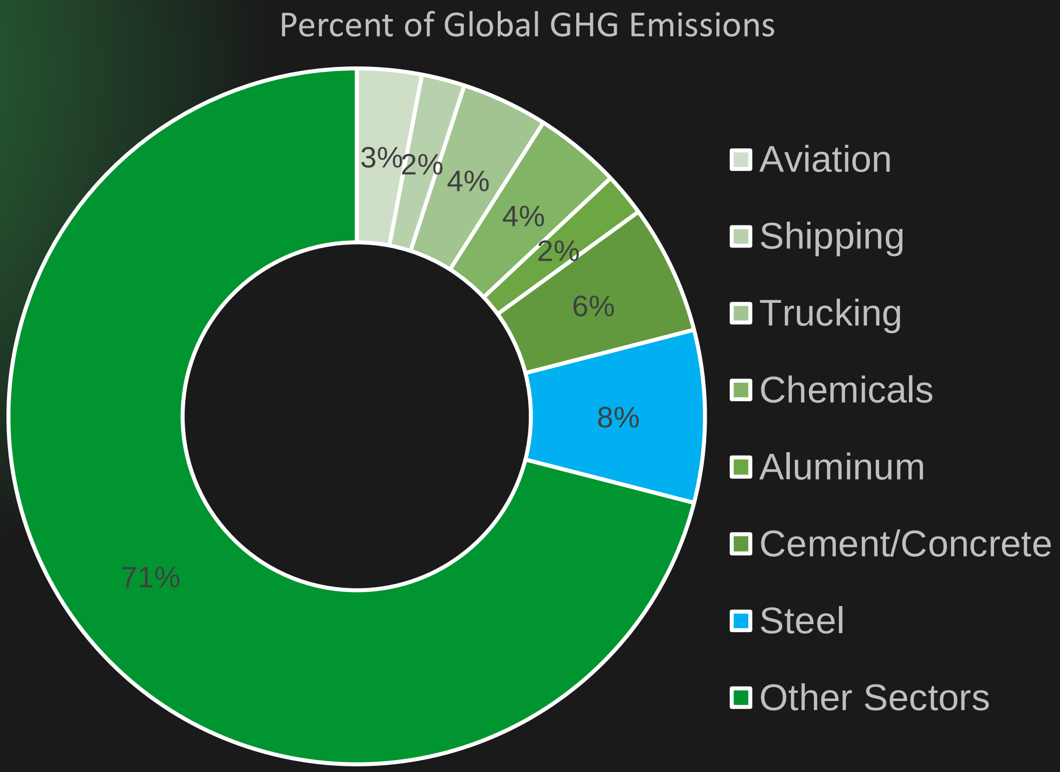
The Industrial Decarbonization Challenge

Heavy industry represents ~30% of global emissions with potential to reach 50%

Demand growth projections by 2050:

- 80% aluminum
- 50% ammonia
- 40% cement
- 30% steel

50% of required emissions reductions need technology not yet at commercial scale



World Economic Forum, How 6 heavy-emitting industries are working to decarbonize, 2024

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How do we tackle the opportunities?

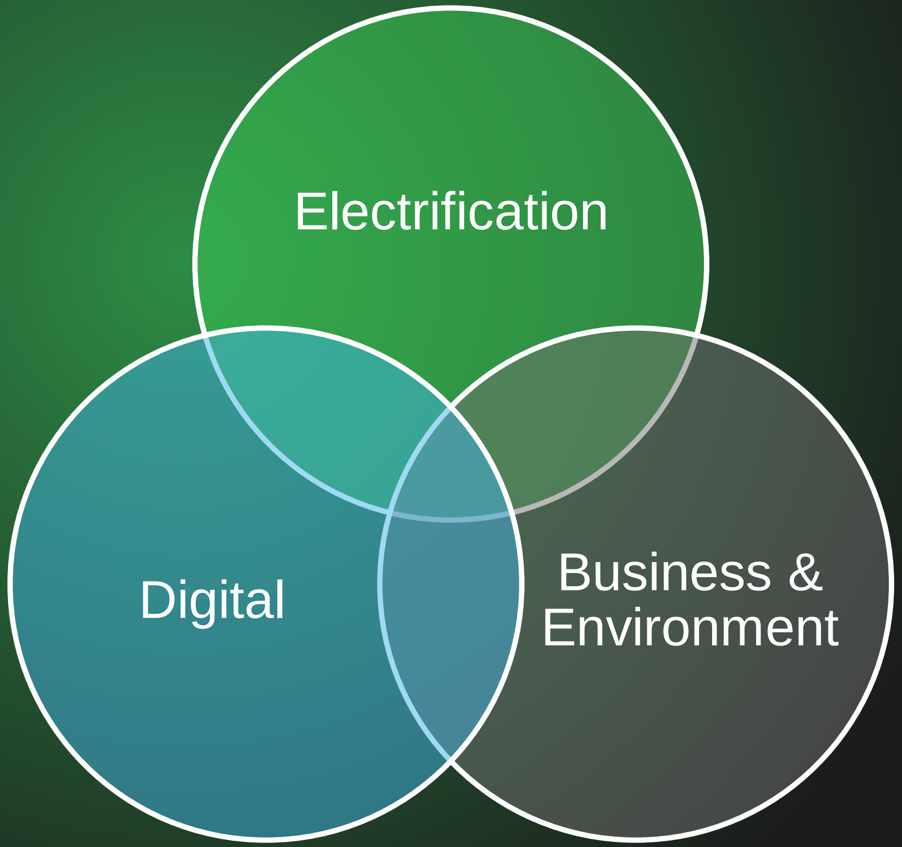
Solutions Approach

Three Pillars for Success

Digital transformation and automation

Electrification and grid integration

Economic and environmental impact assessment (i.e., the new business environment – win/win is a must)

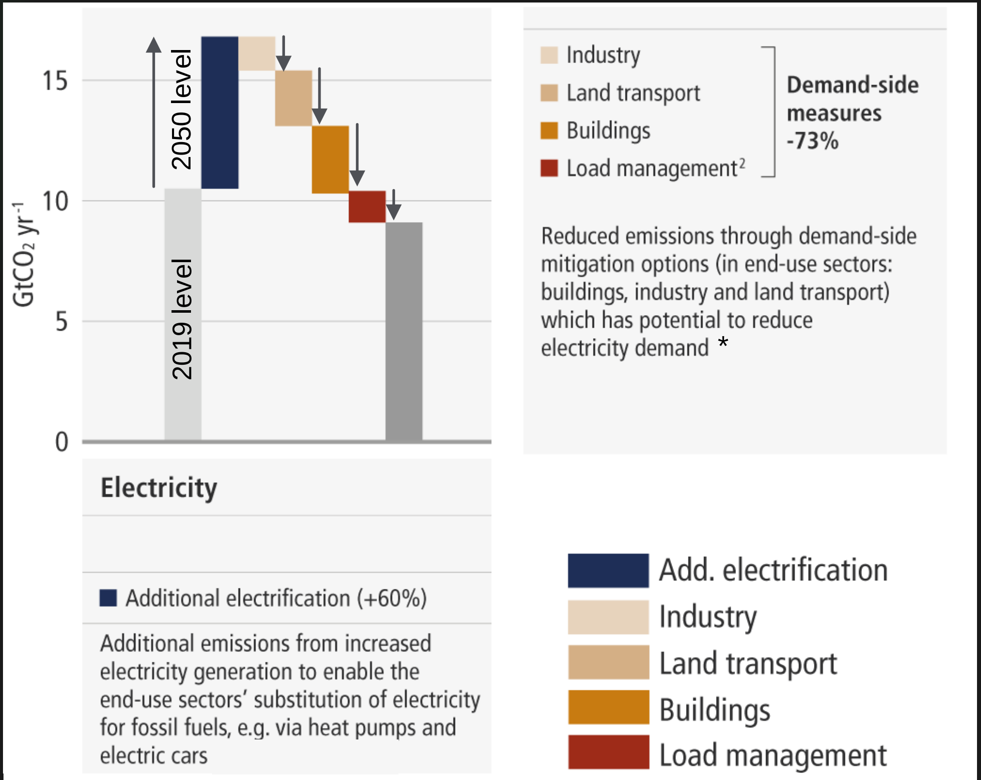


Demand Side is Critical

Demand-side mitigation
Can be achieved through changes in:
- socio-cultural factors
- infrastructure design
- **end-use technology adoption**

Load management
Demand-side **flexibility** that cuts across all sectors can be achieved through incentive design like time of use pricing/monitoring by artificial intelligence, diversification of storage facilities, etc.

Electricity: indicative impacts of change in service demand



**Dependent on variability of the carbon intensity of electric supply*

Source: IPCC, 2022: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change | data to 2050

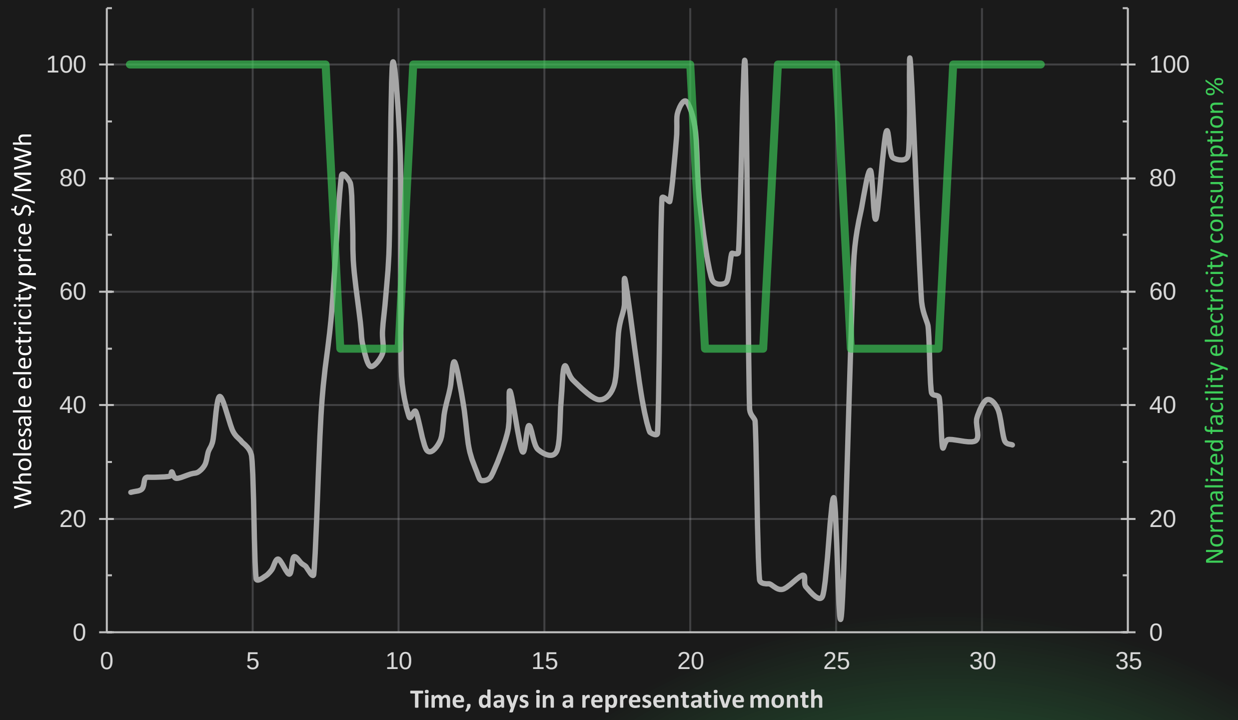
‘Flexibility’ Key Enabler for Smart Energy Consumption

Participation in grid flexibility mechanisms

Demand side management opens new operating and business prospects

Power and process integration leads to new flexibility paradigms for cost, carbon, and scheduling optimization

Example of flexible operation in response to variable electricity prices



SE Sustainability Research Institute; Mallapragada, Dharik S., et al. "Decarbonization of the chemical industry through electrification: Barriers and opportunities." *Joule* 7.1 (2023): 23-41.

SE Approach to Industry E2E Systems – Value Beyond Carbon

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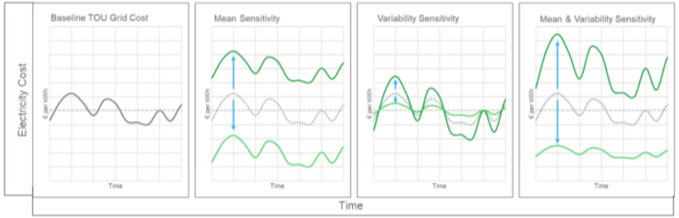
Molecule Flows

Energy Flows
& New Energy Systems

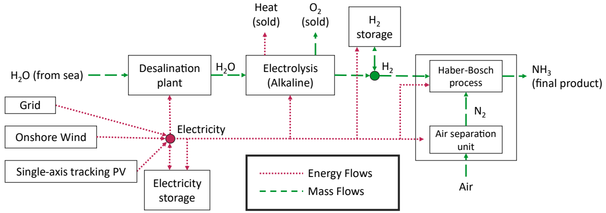
Simultaneously
Optimize Asset Sizing
& Process Operations*

Levelized Cost
of Production
+ Emissions Evaluation

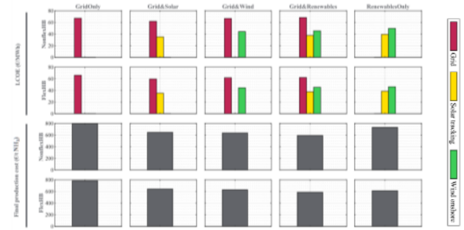
Evaluate Energy Cost Scenarios



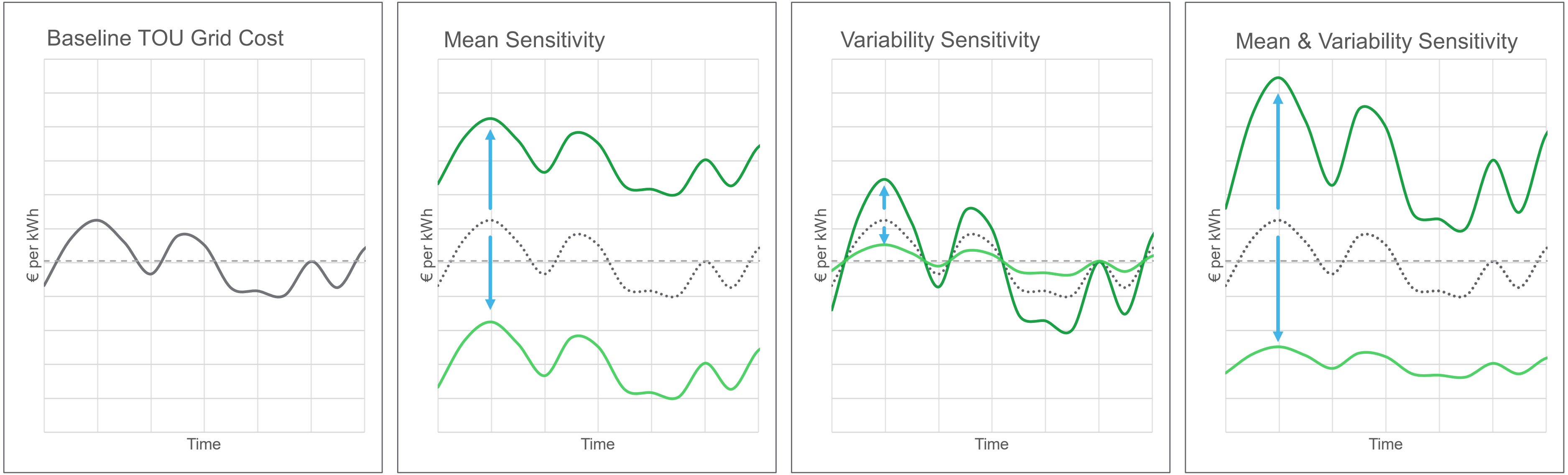
E2E 'Smart' Flexibility



System Optimized to Lower Production Cost

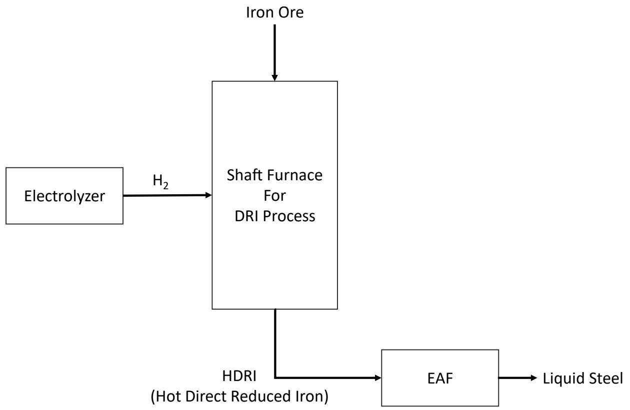


Grid Costs Sensitivity – Modeled Variation as Key Variable

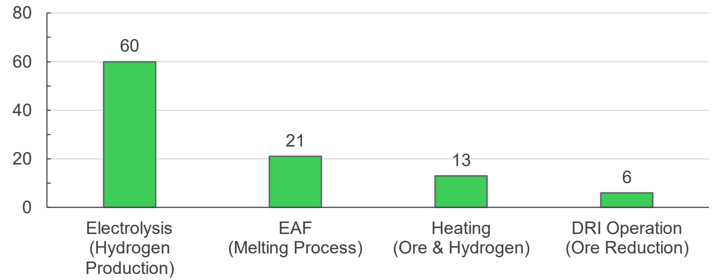


Steel

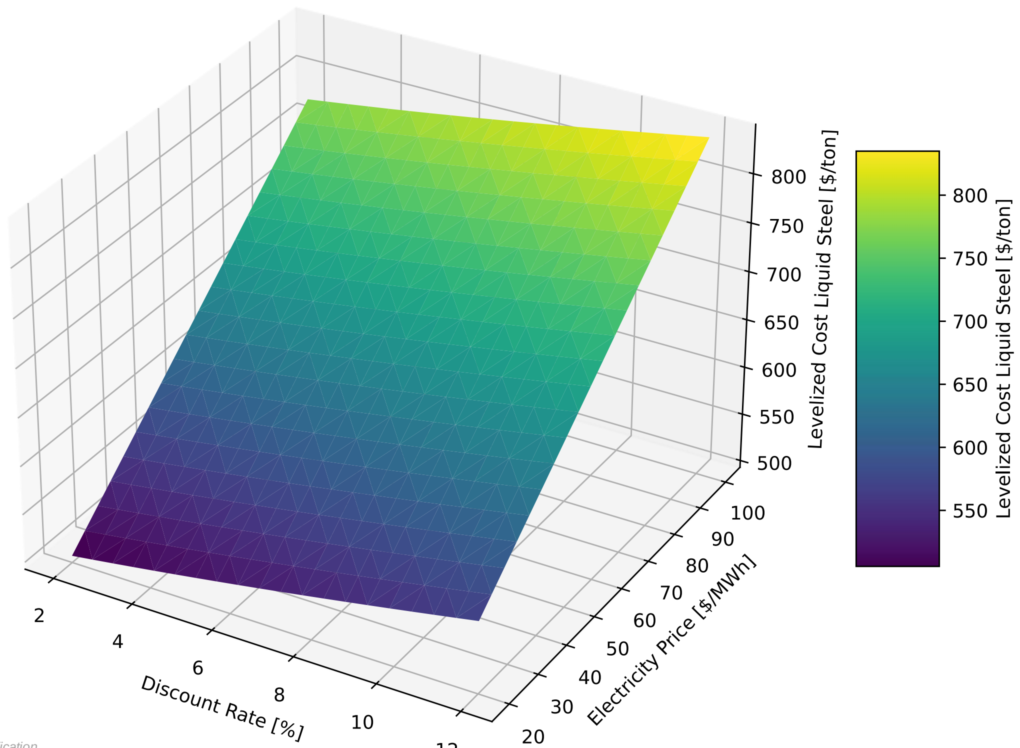
Green Steel Hydrogen Demands Most Electricity in Process



% Electricity Consumption for DRI/EAF Steel Production



Effect of Electricty Price and Discount Rate on DRI/EAF Steel



Source: Kwan, T.A., Roulier, A., 2025, Electrification is a Key Driver in Green Chemical Manufacturing: A Business Case for Process Electrification, The Business Case for Green Chemistry, RSC Books, Royal Society of Chemistry

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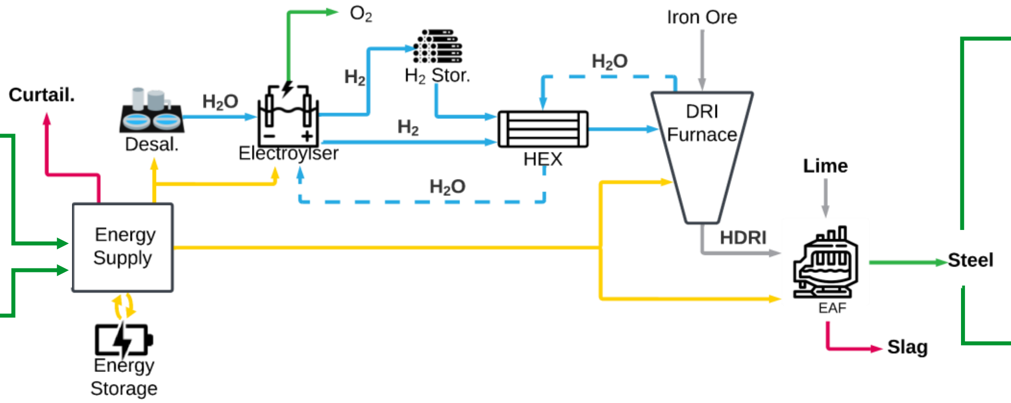
Green Steel Optimization Model

Variables → Green Steel Production Optimization Model (CAPEX and OPEX) → Outputs

Target: Minimize Levelized Cost of Steel (LCOS) Production

Energy Costs from Hourly Spot Prices
- Baseline
- Increased Average
- Increased Volatility
- Increased Average and Volatility

Energy Supply
- Grid Only
- Grid + Onsite Renewables (Semi-islanded)
- Renewables Only (Islanded)



Direct Outputs
- Levelized Cost of Production
- Equipment Sizing
- Hourly Operational Profiles

Calculated Outputs
- Total Investment Costs
- Fixed Costs
- Variable Costs
- Energy Flows
- Material Flows

Fixed Parameters

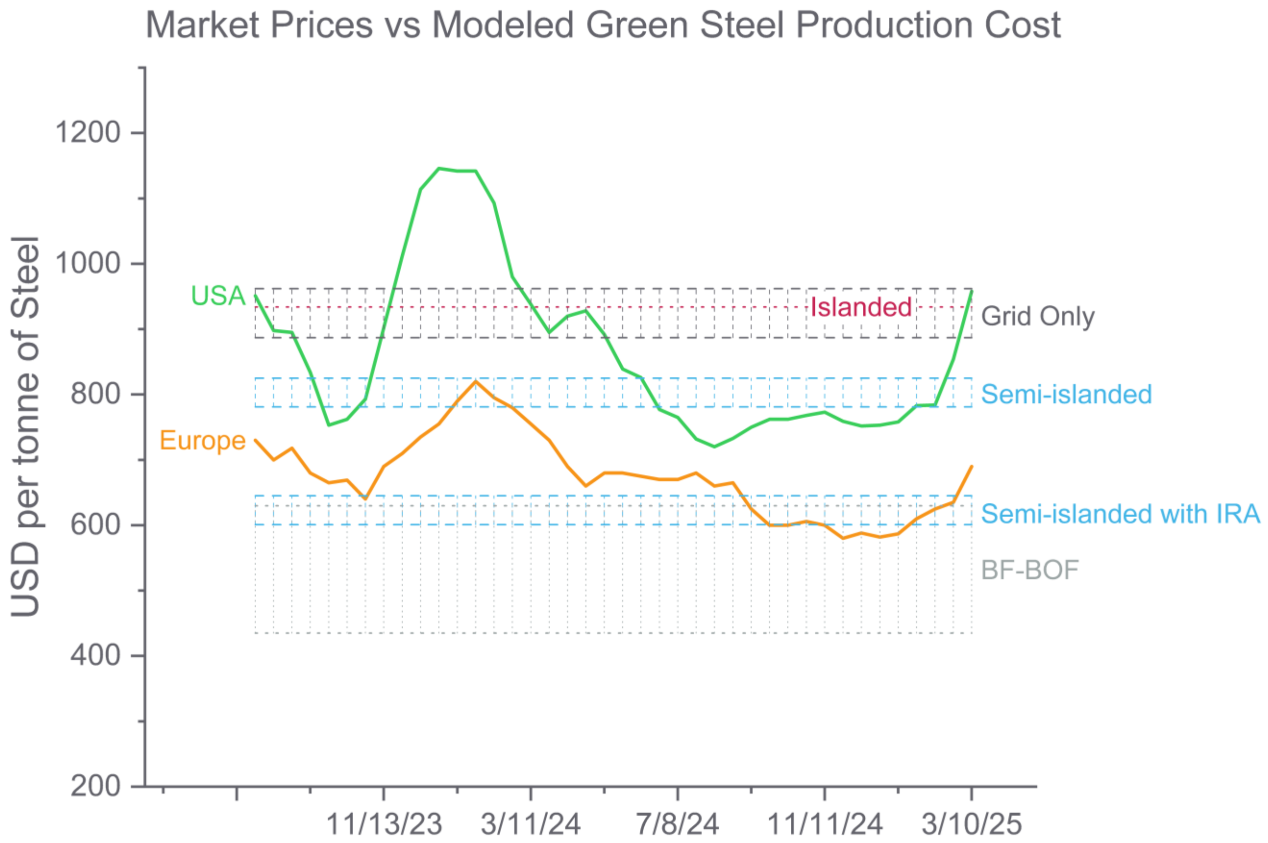
Scheduling (2 Mt steel/year)
Iron Ore and H_2O Composition

Investment Costs per Unit
Stoichiometric Conversion

Material Pricing per Unit
Alkaline Electrolysis (AEC)

Kwan, T.A., 2025, Beyond Grid Dependency: The Technical and Economic Case for New Energy Systems in Green Steel, Schneider Electric Sustainability Research Institute

Green Steel Market Prices vs Production Cost



Key Takeaways

Semi-Islanded Configurations Offer Superior Economics and Emissions Performance

Steel plants that strategically combine grid electricity with onsite renewables can produce greener steel at lower costs than either fully grid-dependent or fully off-grid facilities, offering a practical pathway to cleaner steel production. Optimized hybrid energy systems with partial grid connectivity achieve 12-15% lower levelized steel costs than grid-only alternatives, with LCOS ranging from $781-811/tonne compared to $887-929/tonne, while enabling emissions reductions of 46-84% versus conventional routes.

Higher Capital Investment in Renewable Integration Yields Long-Term Savings

Investing more upfront in renewable energy and hydrogen systems for steel production ultimately saves money by reducing exposure to unpredictable electricity prices and creating opportunities to benefit from price swings in energy markets. While semi-islanded configurations require 60-84% higher initial investment ($4.5-7.9B versus $2.8-4.3B for grid-only systems), this capital premium delivers superior lifecycle economics through operational cost reductions and strategic energy arbitrage during volatile grid pricing periods.

Energy Storage Preferences Challenge Conventional Assumptions

The research reveals that storing energy as hydrogen—which can later be used directly in steel production—makes more economic sense than batteries for most steel plants, creating natural synergies between energy storage and manufacturing needs. Hydrogen consistently emerges as the preferred energy storage medium across optimization scenarios, serving dual purposes as both process input and energy buffer, with battery storage becoming economically viable only under specific high-volatility pricing conditions.

Grid Price Volatility Creates Economic Opportunity

Fluctuating electricity prices, often considered a challenge for industry, can actually benefit steel producers with hybrid energy systems by allowing them to purchase grid power when cheap and use their own renewable energy when prices spike. Counterintuitively, increased grid price volatility consistently reduced overall production costs while driving investment toward expanded energy storage capacity, with the lowest LCOS achieved at the highest volatility scenarios tested.

https://www.se.com/ww/en/insights/sustainability/sustainability-research-institute/