SECTOR COUPLING THROUGH DISTRIBUTED POWER-TO-X: A PATHWAY FOR RENEWABLE INTEGRATION IN ELECTROCATALYTIC HYDROGEN PEROXIDE PRODUCTION

Gregor Riha[1]*, Hannah Aster[2]*, Johannes Lindorfer[3]

Content

Decentralized electrochemical hydrogen peroxide (H_2O_2) production based on paired electrolysis offers a novel pathway for sector coupling with further benefits such as decentralized chemical production and flexible load following renewable generation profiles. Hydrogen peroxide is widely used in pulp and paper, wastewater treatment, semiconductor cleaning, and various chemical processes [1], [2], [3], [4], [5], [6].

By 2024, Europe's total demand for hydrogen peroxide amounted to 1.5 million tons. Compared to the global hydrogen peroxide demand (6.55 million tons in 2024), the European market has had a consumption market share of almost 23 % [7], [8]. However, both local and global hydrogen peroxide production currently remains highly centralized and dominated by the fossil-based anthraquinone (AO) process, leading to logistical and safety constraints associated with long-distance transport and bulk storage.

Within the Power2HyPe project, a GIS-based energy and industrial mapping framework was developed to identify optimal deployment sites for decentralized electrochemical H_2O_2 units. The GIS method supports a renewable, sector-coupled H_2O_2 production model by linking electricity price volatility, CO_2 intensity, renewable penetration, and industrial demand. Particular attention is given to the matching between plant operation and variable renewable generation, enabling highly flexible operational modes. These insights provide an essential basis for future techno-economic assessments (TEA), particularly when comparing decentralized electrochemical routes with the incumbent fossil-based AO process.

Methodology

The GIS-based workflow combines spatial datasets for generic renewable electricity supply and industrial location data. Input layers include:

- renewable generation (onshore and offshore wind, PV),
- historical electricity market prices and CO_2 intensities,
- industrial H_2O_2 demand locations for pulp & paper, wastewater treatment, semiconductor cleaning, and chemical processing,
- grid congestion indicators and local renewable curtailment volumes.

Renewable availability and industrial load are spatially correlated to identify zones with high co-benefits for decentralized electrochemical H_2O_2 production in the future. For each suitable industrial site, energy-matching indices were calculated to quantify the ratio of coincident renewable surplus to generic plant electricity demand. This forms the basis for flexible operation windows, realizable load shifting, and integration with power purchase agreement (PPA) based contracting schemes.

The Power2HyPe process model provides mass and energy balances, including downstream processing loads. These parameters are fed into the evaluation to determine the minimum renewable energy coverage required to unlock climate benefits relative to the AO benchmark.

This approach will be extended to two detailed country case studies (Germany and Spain). For 2024, historic electricity prices and hourly CO_2 emission factors from the national electricity mixes will be

[1] Energieinstitut an der Johannes Kepler Universität Linz, Altenberger Straße 69, +4373224685714, riha@energieinstitut-linz.at, https://energieinstitut-linz.at/
[2] Energieinstitut an der Johannes Kepler Universität Linz, Altenberger Straße 69, +4373224685656, aster@energieinstitut-linz.at, https://energieinstitut-linz.at/
[3] Energieinstitut an der Johannes Kepler Universität Linz, Altenberger Straße 69, +4373224685656, lindorfer@energieinstitut-linz.at, https://energieinstitut-linz.at/

integrated into the matching process. Multiple contracting scenarios (day-ahead exposure, fixed-price PPAs, hybrid PPAs, and curtailed-renewable utilization) will be simulated to analyze the cost and environmental performance under realistic operating conditions.

Results

The preliminary results indicate that GIS-driven siting significantly improves the techno-economic feasibility of decentralized H_2O_2 production using local renewable energy supplies. Regions with a high spatial overlap between industrial demand and renewable electricity (e.g., wind-rich northern Germany or solar-rich southern Spain) enable low-cost and low-carbon operations through dynamically adjusted electrolyzer loads.

Areas with high renewable curtailment potential offer additional advantages, as surplus electricity can be converted into H_2O_2, a storable chemical energy carrier. This enables broader energy system integration by linking the electricity sector with distributed chemical production, thereby creating new pathways for utilizing variable renewable resources.

GIS-based filtering shows that many industrial clusters already meet the energy coverage requirements for specific electricity consumption below approximately 10 $kWh/kg_{H_2O_2}$. When consumption increases toward a specific energy consumption of 30 $kWh/kg_{H_2O_2}$, the number of feasible sites decreases, making GIS optimization even more critical.

For the TEA, the GIS analysis strongly influences CAPEX and OPEX expectations, renewable supply profiles, annual full-load-hours, electricity costs, and overall carbon footprint. In addition, the integration of historic market prices and CO_2 intensities allows calculation of dynamic levelized cost of product (LCoP) and product carbon footprint (PCF). Incorporating PPA scenarios further demonstrates how long-term contracting strategies can stabilize costs despite volatile electricity markets.

Overall, the multidisciplinary approach proves essential for determining economically and ecologically viable locations, enabling flexible operation modes to enhance sector coupling, and guiding scale-up strategies for renewable hydrogen peroxide production.

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