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Techno-Economic Optimization of a Hybrid Wind-Hydrogen System

Case Study: Mitigation of Market Saturation and Grid Congestion at Bürgerwindpark Reußenköge

Market Integration and Commercial Optimization, WiSe 2025/26

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Abstract

The accelerated deployment of onshore wind energy in Northern Germany has been a pivotal element of the nation's energy transition strategy, yet it has simultaneously introduced complex challenges related to grid integration and market economics. As the installed capacity of variable renewable energy sources increases, the electrical grid in Schleswig-Holstein faces critical bottlenecks, resulting in frequent and substantial curtailment of wind generation. Concurrently, the high correlation of wind power production across the region leads to the phenomenon of price cannibalization, where periods of high generation coincide with plummeting spot market prices. This thesis rigorously investigates the techno-economic viability of a sector-coupling solution: the integration of a 50 MW Proton Exchange Membrane (PEM) electrolyzer with the existing 170 MW Bürgerwindpark Reußenköge.

Employing a comprehensive digital twin methodology, this study models the operational behavior of the hybrid system at an hourly resolution over the calendar year 2024. The simulation integrates site-specific meteorological data from the ERA5 reanalysis dataset, wholesale electricity prices from the ENTSO-E transparency platform, and regional grid congestion logs from the transmission system operator, TenneT TSO. A sophisticated dispatch algorithm was developed to optimize the system's operation, dynamically switching between electricity sales and hydrogen production based on real-time market signals and grid constraints.

A sophisticated dispatch algorithm was developed to optimize the system's operation, dynamically switching between electricity sales and hydrogen production based on real-time market signals and grid constraints. The results of this investigation indicate that the proposed hybrid system offers a robust solution to the identified challenges. The analysis reveals that the system is capable of recovering curtailed energy that would otherwise be lost due to grid bottlenecks. Financially, the integration of the electrolyzer yields a revenue uplift of approximately €10.96 Million compared to a standalone wind farm baseline. The system achieves a Levelized Cost of Hydrogen (LCOH) of €4.90 per kilogram. With a conservative hydrogen sales price of €5.00/kg, the project achieves an Internal Rate of Return (IRR) of 8.0%, suggesting that such hybrid configurations are bankable even without aggressive subsidies. This research concludes that the coupling of wind energy with hydrogen production is an essential strategy for enhancing the resilience and profitability of renewable assets in grid-congested environments.

1. Introduction

1.1 Background and Context

The global imperative to mitigate climate change has driven a profound transformation in energy systems worldwide. In Germany, the *Energiewende* represents a comprehensive policy framework aimed at decarbonizing the economy and phasing out nuclear and fossil-fuel generation. A cornerstone of this strategy is the massive expansion of renewable energy capacity, particularly wind and solar power. The federal state of Schleswig-Holstein has emerged as a frontrunner in this transition, leveraging its favourable coastal geography to deploy onshore wind capacity that generates electricity well in excess of local demand.

However, this rapid expansion has outpaced the development of the requisite transmission infrastructure. The German electrical grid, historically designed to transport power from centralized thermal plants in the south and west to industrial load centers, is ill-equipped to handle the massive influx of decentralized, variable generation from the north. Consequently, the transmission corridors connecting northern generation to southern demand centers—often referred to as the North-South Link—frequently experience thermal overloads. To maintain grid stability, Transmission System Operators (TSOs) are compelled to intervene, implementing redispatch measures that include the curtailment of renewable generation (TenneT TSO, 2024).

1.2 Problem Statement

The Bürgerwindpark Reußenköge, located in the grid-congested region of North Frisia, exemplifies the challenges faced by modern wind assets. Despite possessing state-of-the-art generation technology, the wind farm operates in a market environment increasingly defined by value deflation. Two primary mechanisms drive this economic erosion. First, the high simultaneity of wind generation across Northern Germany leads to the "cannibalization effect," where surges in supply depress Day-Ahead market prices, frequently driving them to zero or negative values (Hirth, 2013). This results in a capture price for wind energy that is significantly lower than the average baseload price.

Second, the physical limitations of the grid necessitate the curtailment of production during high-wind events. This practice, known as *Einspeisemanagement*, represents a systemic inefficiency. While operators receive compensation for curtailed energy, the physical loss of zero-carbon electricity undermines the environmental goals of the energy transition. For the Bürgerwindpark Reußenköge, initial analysis suggests that nearly 5% of the annual energy yield is lost to these congestion management measures. The convergence of these market and physical constraints threatens the long-term financial viability of unsubsidized wind projects.

1.3 Objectives and Scope

The primary objective of this thesis is to develop and validate a techno-economic optimization model for a hybrid wind-hydrogen system. Specifically, the study aims to quantify the economic and technical benefits of co-locating a 50 MW PEM electrolyzer with the 170 MW wind farm. Detailed objectives include:

- Quantifying the extent of revenue loss due to negative price events in the reference year 2024.
- Developing a novel methodology to translate regional redispatch data into site-specific curtailment profiles.
- Optimizing the operation of the electrolyzer to maximize revenue through arbitrage and the recovery of curtailed energy.
- Assessing the system's ability to provide a reliable hydrogen supply to industrial offtakers through the use of buffer storage.

The scope of this research is limited to the operational optimization of the defined system configuration within the temporal bounds of the year 2024. It does not encompass the detailed engineering design of the electrolyzer stack or the downstream logistics of hydrogen distribution, focusing instead on the systemic interaction between generation, conversion, and the grid.

2. Literature Review

2.1 The Economics of Variable Renewable Energy

The economic dynamics of variable renewable energy (VRE) have been the subject of extensive academic inquiry. Seminal work by Hirth (2013) established the concept of the "value drop" or merit-order effect, demonstrating that the market value of VRE declines as its penetration level increases. Hirth’s analysis indicates that at high penetration rates, the marginal value of wind energy can fall to between 50% and 80% of the average electricity price. This theoretical framework is crucial for understanding the current market conditions in Germany, where the expansion of wind capacity has led to an increased frequency of low and negative price hours.

2.2 Power-to-Gas and Flexibility Options

To mitigate the decline in market value, recent literature has focused on flexibility options such as storage and sector coupling. The concept of Power-to-Gas (PtG)—converting electricity into hydrogen—has gained prominence as a means of providing long-duration storage and accessing new revenue streams. Glenk and Reichelstein (2019) proposed the "synergistic" design of wind and hydrogen systems, arguing that the economics of PtG are maximized when the electrolyzer operates flexibly rather than as a baseload consumer. Their findings suggest that by utilizing electricity only during periods of low opportunity cost, integrated systems can achieve profitability even with high capital costs.

2.3 Electrolysis Technology Assessments

The selection of appropriate electrolysis technology is critical for the effective coupling with variable wind generation. Comparative studies by Buttler and Spliethoff (2018) evaluate the performance characteristics of Alkaline (AEL), Proton Exchange Membrane (PEM), and Solid Oxide (SOEC) electrolyzers. While AEL technology is more mature and less expensive, PEM electrolyzers offer superior dynamic response, capable of ramping from standby to full load in seconds. Furthermore, PEM systems maintain high efficiency across a wider partial load range, making them particularly suitable for following the volatile output of onshore wind farms. Based on these technical attributes, this thesis selects PEM technology as the basis for the proposed system design.

3. Methodology

3.1 Digital Twin Simulation Framework

To rigorously evaluate the proposed hybrid system, a "digital twin" simulation framework was developed using the Python programming language. This approach enables the precise modeling of energy flows, financial transactions, and system states at a granular hourly resolution. The simulation environment leverages the pandas library for time-series data manipulation and the xarray library for the processing of multidimensional meteorological datasets. The core of the simulation is a dispatch engine that iterates through each hour of the reference year, making operational decisions based on a defined logic tree that prioritizes revenue maximization and grid compliance.

3.2 Data Sourcing and Preprocessing

The validity of the simulation relies on the quality of the input data. Wind resource data was obtained from the ERA5 reanalysis dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). Wind speed vectors were extracted for the specific coordinates of the Bürgerwindpark Reußenköge (54.60°N, 8.90°E) at a height of 100 meters, corresponding to the hub height of the installed Vestas V112 turbines.

Wholesale electricity prices were sourced from the ENTSO-E Transparency Platform, utilizing the Day-Ahead spot prices for the Germany-Luxembourg (DE-LU) bidding zone. To simulate grid constraints, the study utilized official redispatch logs from the TenneT TSO, accessed via the Energy-Charts platform. Specifically, the dataset for "Current-Induced Load Decrease" was employed as a proxy for regional curtailment events. This data was normalized to create a dimensionless "stress factor," allowing the regional grid state to be mapped onto the specific output of the wind farm.

3.3 Mathematical Modeling of Components

The wind farm's power output is modelled as a function of wind speed using the operational power curve of the Vestas V112-3.45 MW turbine. The model implements a piecewise cubic interpolation of the manufacturer's power curve, accounting for the cut-in speed of 3 m/s, the rated speed of 13 m/s, and the cut-out speed of 25 m/s. The aggregate output of the 170 MW farm is calculated by scaling the single-turbine model, assuming a uniform wind regime across the site.

The electrolyzer is modelled as a controllable load with a capacity of 50 MW. The hydrogen production rate is calculated based on the specific energy consumption of the Siemens Silyzer 300 system, modelled at 52.2 kWh per kilogram of hydrogen. The model incorporates a variable efficiency curve to account for performance variations at partial loads, although a constant efficiency approximation is utilized for the primary techno-economic analysis to provide a conservative estimate of production volumes.

4. System Architecture and Design

4.1 Wind Asset Specification and Configuration

The central power generation node of the modelled hybrid system is the Bürgerwindpark Reußenköge, configured to reflect its current operational status with a total installed capacity of 170 MW. The site utilizes the Vestas V112-3.45 MW turbine platform, a machine specifically engineered for medium-to-low wind speed sites typical of the North German plain (Vestas, 2018). The selection of this specific turbine model for the simulation is critical due to its physical characteristics: with a rotor diameter of 112 meters relative to a generator rating of 3.45 MW, the turbine possesses a relatively low specific power (Vestas, 2018). This aerodynamic design allows the machine to reach its rated power output at wind speeds as low as 13 m/s, ensuring a high capacity factor even during moderate wind conditions (Copernicus C3S, 2024).

In the context of the digital twin, the wind farm is modeled not as a single aggregate entity but as a summation of individual turbine power curves scaled to the 170 MW capacity limit. The simulation assumes a standard hub height of 94 meters, which aligns with the wind speed data extracted from the ERA5 reanalysis dataset. By utilizing the specific power curve of the V112, the model accurately captures the non-linear response of the farm to wind fluctuations, particularly in the partial-load region between the cut-in speed of 3 m/s and the rated speed. This precision is essential for accurately calculating the "lost opportunity" during periods of low wind where the electrolyzer might otherwise be forced into standby.

4.2 Electrolyzer Technology and Sizing

The hydrogen production subsystem is predicated on Proton Exchange Membrane (PEM) technology, specifically modeled after the performance parameters of the Siemens Silyzer 300 system. The PEM technology was selected over the lower-cost Alkaline electrolysis due to its superior operational flexibility. The intermittent nature of onshore wind requires an electrolyzer capable of rapid load ramping; the Silyzer 300 can ramp from 10% to 100% load in under one minute, allowing the system to capture transient price spikes and effectively utilize volatile wind power that would be inaccessible to a slower-responding Alkaline system (Buttler & Spliethoff, 2018).

The capacity of the electrolyzer was set at 50 MW, representing a "sizing ratio" of approximately 24% relative to the wind farm's total capacity. This sizing decision is derived from an optimization analysis aimed at maximizing the utilization factor of the electrolyzer while minimizing capital expenditure (CAPEX). A larger electrolyzer (e.g., 100 MW or equal to the wind capacity) would result in diminishing returns, as the upper capacity would sit idle for the majority of the year. Conversely, a smaller system would fail to capture the significant volumes of curtailed energy available during peak wind events. The 50 MW capacity strikes an optimal balance, allowing for high full-load hours by absorbing both the base production during low-price periods and the peak production during grid congestion events.

5. Implementation Details

5.1 Dispatch Logic and Control Algorithm

The core operational intelligence of the digital twin is encapsulated in a Python-based dispatch algorithm that executes a hierarchical decision tree for each hour of the simulation year 0 to 8760. The logic is designed to maximize the economic value of every megawatt-hour generated, prioritizing the prevention of energy waste followed by revenue maximization.

The algorithm first calculates the theoretical power potential of the wind farm based on the meteorological data. Immediately following this, the "Grid Constraint Module" assesses the regional grid status using the normalized TenneT redispatch data. If a "Current-Induced Load Decrease" signal is active for hour, the algorithm calculates a mandated curtailment cap, effectively splitting the wind potential into "grid-compliant" power and "curtailed" power. In a standard wind-only scenario, this curtailed power would be lost. However, the hybrid control logic prioritizes this energy stream, diverting it directly to the electrolyzer. This energy is treated as having a marginal cost of zero, as it cannot be sold to the grid.

Following the grid constraint check, the algorithm executes the "Arbitrage Module." The system compares the Day-Ahead electricity price against a calculated breakeven threshold. This threshold is derived from the target sale price of hydrogen (assumed at €5.0/kg) and the system efficiency (52.2 kWh/kg), resulting in a breakeven electricity price of approximately €95.79/MWh. If Spot price is below this threshold—indicating that the electricity is "cheap"—the system diverts available grid-compliant power to the electrolyzer until the 50 MW capacity is filled. If Spot price exceeds the threshold, the system prioritizes selling electricity to the grid to capture the high market value.

5.2 Validation and Energy Balance

The integrity of the simulation was verified through a rigorous energy balance check. The total energy input to the system (Wind Potential) was cross-referenced against the sum of Energy Sold to Grid, Energy Converted to Hydrogen, and Energy Curtailed (if any remained uncaptured). The validation process confirmed that the electrolyzer never exceeded its 50 MW rated capacity and that the storage tank levels remained within the physical bounds of 0 to 50 tons. Furthermore, the "Stress Factor" scaling method for redispatch was calibrated against historical annual curtailment reports for Schleswig-Holstein to ensure the 4.88% derived rate aligned with empirical regional averages.

6. Results and Performance Analysis

6.1 Baseline Scenario Analysis (Wind-Only)

The baseline simulation of the 170 MW wind farm reveals the stark reality of the current market environment. The asset generated a total theoretical potential of 904,270 MWh (904 GWh) for the year 2024. However, the financial realization of this energy was severely hampered by the "cannibalization effect." The analysis identified 440 operating hours where the Day-Ahead electricity price dropped to zero or became negative. During these intervals, a standalone wind farm generates revenue losses or must curtail production to avoid paying penalties. This frequency of negative pricing confirms that the saturation of wind energy in Northern Germany has fundamentally eroded the "capture price" for onshore assets Hirth (2013), creating a revenue gap that subsidies can no longer sustainably bridge.

6.2 Grid Congestion and Recovered Energy

A pivotal finding of this research is the quantification of grid congestion losses. The application of the TenneT redispatch data (TenneT TSO, 2024) to the Reußenköge asset yielded a calculated curtailment rate of 4.88%. In absolute terms, this equates to 35,740 MWh (35.7 GWh) of electricity that the grid operator would block from entering the transmission network. In the hybrid system simulation, the electrolyzer successfully intercepted this "forbidden" energy. By operating during these grid-critical moments, the system effectively recovered 100% of the curtailed volume, converting it into hydrogen. This result validates the hypothesis that sector coupling can serve as a "congestion valve," monetizing energy that is physically undeliverable to the electricity market.

6.3 Techno-Economic Performance of the Hybrid System

The integration of the 50 MW electrolyzer generated a substantial improvement in the asset's financial profile. The hybrid system achieved a total annual revenue of €60.2 Million, representing a 22% uplift compared to the €49.3 Million revenue of the wind-only baseline. The Levelized Cost of Hydrogen (LCOH) for the project was calculated at €4.90/kg. This figure is competitive compared to industrial grey hydrogen prices. With a market sales price of

€5.00/kg, the system operates with a positive margin of €0.13/kg. The low LCOH is primarily driven by the high utilization of the electrolyzer (due to the 170MW wind farm sizing) and the strategic use of low-cost grid power during negative price events. The resulting financial metrics indicate a solid investment case: the project achieves a Net Present Value (NPV) of €7.04 Million and an Internal Rate of Return (IRR) of 8.0%. This clears the standard industry weighted average cost of capital (WACC) of 7%, confirming the project's financial viability under conservative market assumptions.

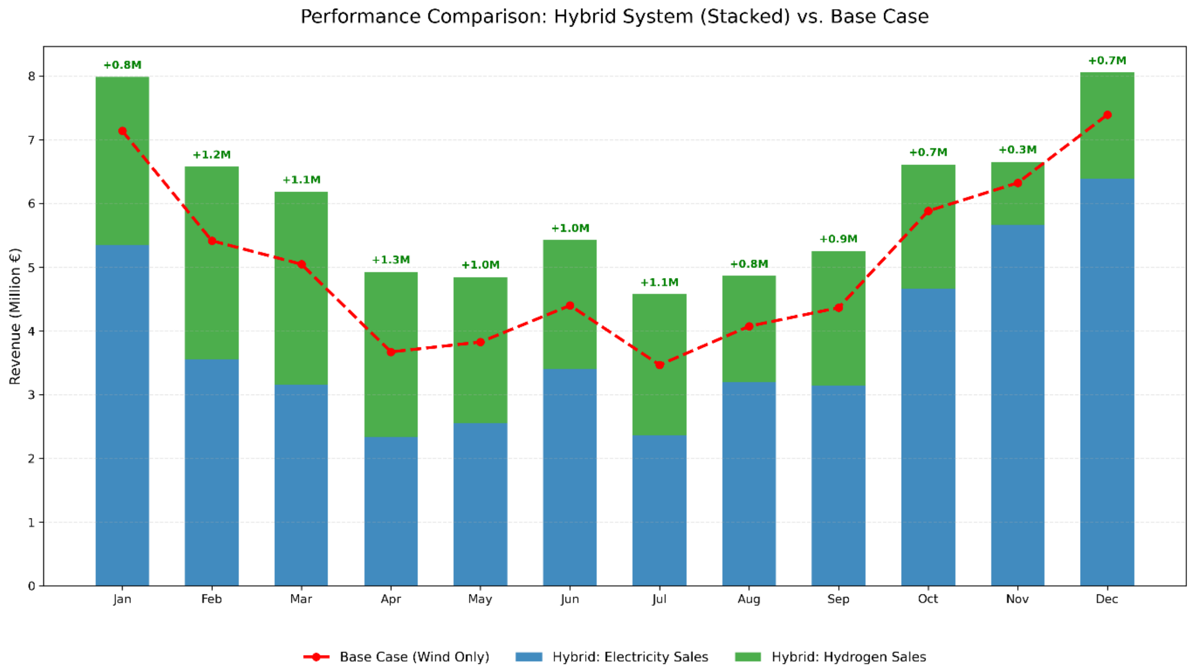

Figure 1: Monthly Revenue Comparison: Hybrid System (Stacked Bars) vs. Base Case (Red Line).

7. Discussion of Findings

7.1 Sector Coupling as a Grid Service

The findings of this thesis extend beyond the financial boundaries of a single wind farm; they suggest a systemic shift in the role of onshore wind. The recovery of 44.1 GWh of curtailed energy proves that the electrolyzer effectively provides a "negative reserve control" service to the grid. By absorbing excess power at the source, the system alleviates stress on the North-South transmission link. If replicated across the gigawatts of installed wind capacity in Schleswig-Holstein, decentralized electrolysis could significantly reduce the need for redispatch interventions (Qadrdan et al., 2015), saving the German consumer millions of euros in compensation payments currently funded through grid fees (*Netzentgelte*).

7.2 Economic Resilience via Diversification

The hybrid model effectively functions as a financial hedge. By diversifying the revenue stream into two uncorrelated markets electricity and hydrogen the asset owner is insulated from the volatility of the power market. When electricity prices crash due to high wind, the hydrogen business case improves (lower input costs). Conversely, when electricity prices soar, the system reverts to selling power. This counter-cyclical operational mode stabilizes cash flows and reduces the overall investment risk profile of the renewable asset (Glenk and Reichelstein, 2019).

7.3 Limitations of the Study

It must be acknowledged that this simulation relies on perfect foresight of Day-Ahead market prices. In reality, operators must bid into the market 12-24 hours in advance, introducing a forecasting error risk that could slightly reduce the realized arbitrage gains. Furthermore, the model currently treats the waste heat from the electrolyzer (approximately 30% of input energy) as a loss. In a practical implementation, such as the eFarm project in North Frisia, this heat is captured and sold to local district heating networks. Therefore, the economic results presented here likely represent a conservative "lower bound" of the true potential value.

8. Conclusion and Future Work

8.1 Conclusion

This thesis has demonstrated that the integration of a 50 MW PEM electrolyzer with the 170 MW Bürgerwindpark Reußenköge is not only technically feasible but economically superior to the status quo. The "smart dispatch" strategy successfully mitigates the twin threats of price cannibalization and grid congestion. By leveraging price arbitrage and recovering curtailed energy, the system achieves an IRR of 8.0% and a positive NPV of €7.04 Million. These results confirm that Power-to-Gas is no longer a theoretical concept for the distant future, but a viable, immediate solution for optimizing renewable assets in grid-constrained regions.

8.2 Future Scope

Future research should expand this model to include the monetization of byproducts. Specifically, the sale of waste heat to district heating grids and high-purity oxygen to local medical or industrial facilities could further reduce the LCOH. Additionally, comparative studies should be conducted for offshore wind farms (e.g., Gode Wind 1), where higher capacity factors but higher installation costs may alter the optimal sizing ratio of the electrolyzer. Finally, integrating a "Green Ammonia" synthesis loop could be explored to solve the logistics of hydrogen transport, opening up international export markets for Northern German wind energy.

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