Project Title: Techno-Economic Optimization of a Hybrid Wind-Hydrogen System

Case Study: Bürgerwindpark Reußenköge (Schleswig-Holstein, Germany)

Section 1: The Problem (Why are we doing this?)

Northern Germany is the "wind capital" of Europe. However, the rapid expansion of wind farms has outpaced the construction of power lines (grid expansion) needed to transport this electricity to the industrial south.

The Twin Challenges:

1. **Price Cannibalization (Economic Failure):**
    - ***Concept:*** **When the wind blows in the North, *everyone* generates power at the same time. This oversupply crashes the market price.**
    - ***Data Evidence:*** **Your model identified 426 hours in 2024 where electricity prices were zero or negative.**
    - ***Impact:*** **The wind farm generates power but earns no money (or pays a penalty) during these hours.**
2. **Grid Congestion (Physical Failure):**
    - ***Concept:*** **The cables facing south get clogged (like a traffic jam). The Grid Operator (TenneT) forces wind farms to turn off to prevent blackouts. This is called Curtailment (or *Einspeisemanagement*).**
    - ***Data Evidence:*** **Your Redispatch analysis showed a 4.88% curtailment rate, meaning nearly 5% of the farm's potential energy is wasted.**

The Research Question:

"Can we solve both problems by placing a 50 MW Hydrogen Electrolyzer directly at the wind farm to 'soak up' this cheap and wasted electricity?"

Section 2: The "Digital Twin" (How we modeled it)

To answer the question, we built a computer simulation (a Digital Twin) of the real site using Python.

2.1 The Assets (The Hardware)

We modeled two specific machines:

1. **The Wind Farm (210 MW):**
    - ***Turbine:*** **Vestas V112-3.45 MW.**
    - ***Characteristics:*** **A "stiff" machine that needs 13 m/s wind to reach full power. It represents the current status of the Reußenköge park.**
2. **The Electrolyzer (50 MW):**

    - *Model:* Siemens Silyzer 300 (PEM Technology).
    - *Efficiency:* 52.2 kWh/kg. (Calculated from the spec sheet: 17.5 MW input / 335 kg output).
    - *Role:* It acts as a "flexible load." It can turn on when power is cheap and turn off when power is expensive.

2.2 The Data (The Inputs)

We used real hourly data for the year 2024:

- Wind Speed: From ERA5 (Copernicus) satellites. We extracted wind speeds at 100m height for the exact GPS coordinates (54.60°N, 8.90°E).
- Electricity Prices: From ENTSO-E. The "Day-Ahead Spot Price" for Germany (DE-LU zone).
- Grid Blocking: From TenneT TSO. We downloaded "Redispatch" logs to see exactly when the grid was clogged.

Section 3: The Operational Logic (The "Brain" of the Model)

This is the core Python code where the decision-making happens. We compared two scenarios.

Scenario A: Base Case (Wind Only)

- *Logic:* The wind turbine generates power. It sells 100% of it to the grid at whatever the current market price is.
- *The Flaw:* If the price is -€10, the farm loses money. If the grid is clogged, the farm shuts down and earns nothing.

Scenario B: Hybrid Case (The Solution)

- *Logic:* We implemented a "Smart Dispatch" algorithm. For every hour of the year ($t=1$ to 8784), the model asks:
    - Is the Grid Price High? (> €128/MWh): Sell electricity to the grid! (Make €€€).
    - Is the Grid Price Low? (< €128/MWh): Turn on the Electrolyzer! Make Hydrogen instead.
    - Is the Grid Clogged? (Curtailment): The grid says "Stop," but we divert that "forbidden" energy into the Electrolyzer.

Section 4: The Results (What we found)

4.1 Financial Performance

- Revenue Uplift: The Hybrid system earned roughly 26% more revenue than the Base Case.
- Payback Period: The extra profit pays off the cost of the Electrolyzer in 4.2 years. This is an excellent investment return.

- **LCOH (Cost of Hydrogen): We produced hydrogen for €5.06/kg. Since the market price is ~€6.70/kg, we have a profit margin of €1.64 for every kilo.**

4.2 Physical Performance

- **Hydrogen Production: The system produced roughly 6,300 tons of green hydrogen.**
- **Waste Recovery: The most impressive engineering result. The model captured 44.1 GWh of energy that the grid would have curtailed.**
  - ***Interpretation:* We turned "waste" into 845 tons of hydrogen (worth €5.6 Million).**

Section 5: System Reliability (Storage)

The Challenge: Industrial customers (like steel mills) need hydrogen 24/7. But the wind doesn't blow 24/7.

The Solution:

We simulated a Hydrogen Storage Tank to act as a buffer.

- ***Tank Size:* 50 Tons.**
- ***Demand:* Constant 700 kg/hour.**
- ***Result:* This tank size guarantees 95.8% reliability.**
- ***Optimization:* We proved that building a bigger tank (e.g., 100 tons) is a waste of money because it only adds 1-2% reliability.**

Section 6: Conclusion (The Verdict)

Your project proves that Green Hydrogen is not just a fuel—it is a financial tool.

For an onshore wind farm in Northern Germany, an electrolyzer acts like an "economic battery." It allows the farm to:

1. **Escape negative prices.**
2. **Bypass grid bottlenecks.**
3. **Unlock a massive new revenue stream (€20M+ per year).**

Final Recommendation: The Bürgerwindpark Reußenköge should proceed with the installation of the 50 MW Electrolyzer system immediately.