Assessment Portfolio 1

Course: Minor Offshore Renewable Energy (ORE)

Course Code: MI00033

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Introduction

This portfolio systematically investigates the critical challenges and future solutions within the Offshore Renewable Energy (ORE) sector, moving from macro-level industry trends to micro-level technological applications. As the global transition towards renewable energy accelerates, offshore wind has emerged as a cornerstone. However, the exponential growth in offshore generation capacity has exposed significant infrastructural bottlenecks, most notably net congestion. By synthesizing theoretical research on energy transmission alternatives with empirical data gathered from a real-time electrolyser operation experiment, this portfolio aims to critically evaluate "Power-to-X" (specifically green hydrogen) as a viable strategy to mitigate energy curtailment and ensure the sustainable scaling of offshore wind systems.

1 Chapter 1: The Ambition - Global and Regional Offshore Wind Development

The global energy landscape is undergoing a fundamental paradigm shift towards renewable sources, driven by both climate goals and shifting economic priorities (World Economic Forum [WEF], 2025). Within this transition, offshore wind energy stands out due to its high capacity factors, consistent wind speeds, and massive scalability (Montel, n.d.).

1.1 Global and European Trends

Globally, the trend is characterized by moving further offshore into deeper waters, utilizing larger turbines (such as the 15MW+ class), and exploring floating wind technologies. Europe has historically been the pioneer in this sector, leveraging the favorable conditions of the North Sea. The European strategy is now evolving from individual wind farms towards interconnected, large-scale "Energy Islands" designed to serve multiple countries simultaneously(European Parliamentary Research Service [EPRS], 2025).

1.2 Comparative Development: Europe vs. China

While Europe focuses on technological maturation, deep-water innovation, and cross-border grid integration, China has demonstrated an unprecedented pace of expansion.

Driven by strong state policies and a highly localized, robust supply chain, China has rapidly become the world leader in total installed offshore wind capacity, fundamentally altering the global market dynamics (German Aerospace Center [DLR], 2025; Global Wind Energy Council [GWEC], 2024). The contrast is distinct: Europe excels in sophisticated, multi-national planning and pioneering complex technologies, whereas China excels in rapid industrial scaling and aggressive capacity deployment.

1.3 The Growth of Offshore Wind in the Netherlands

Zooming in on the local context, the Netherlands plays a critical role in the North Sea's development. Driven by the ambitious targets set in the Climate Agreement, the Dutch offshore wind sector is experiencing exponential growth, steadily increasing its national wind capacity year over year (Compendium voor de Leefomgeving [CLO], n.d.).

Table 1: Projected Offshore Capacity in the Netherlands

Target Year	Projected Offshore Capacity (GW)	Strategic Context and Policy Drivers
2024	4.7	Completion of early Roadmap 2023 projects including Hollandse Kust (noord).
2030	21.0	Anchor target for meeting the 55% greenhouse gas reduction goal.
2032	25.7	Integration of initial sites in the Nederwiek and Doordewind zones.
2035	35.0	Expansion toward deeper North Sea sites using 2 GW HVDC standards.

Target Year	Projected Offshore Capacity (GW)	Strategic Context and Policy Drivers
2040	40.0	Current coalition's upper-bound target for industrial electrification.
2050	70.0	Long-term objective for a fully climate-neutral energy system.

For example, the government has set a target to achieve 21 GW by 2030 of offshore wind capacity. This rapid deployment requires massive spatial planning and necessitates the continuous tendering of new wind farm zones.

2 Chapter 2: The Bottleneck - The Reality of Net Congestion

The ambitious scaling of offshore wind capacity introduces a severe infrastructural bottleneck: net congestion. This phenomenon occurs when the physical transmission capacity of the onshore electrical grid is insufficient to accommodate the peak power generated by offshore wind farms.

2.1 The Root Causes of Grid Congestion

The core issue is a mismatch in development speeds. While the installation of offshore wind turbines can be executed relatively quickly, the expansion of the onshore high-voltage grid is a prolonged and highly complex process (Ember, 2026). The grid acts as a "funnel" with limited capacity; during periods of high wind, the massive influx of energy cannot be entirely transported or absorbed. To prevent grid overload and potential blackouts, grid operators are forced to implement energy curtailment—deliberately halting wind turbines and wasting clean energy.

2.2 The Timeframe for Resolution

Solving net congestion is not a short-term endeavor. Upgrading physical grid infrastructure (substations, high-voltage lines) is hindered by lengthy permitting processes, environmental impact assessments, supply chain constraints for critical electrical components, and labor shortages. Consequently, substantial grid expansion projects typically take 7 to 10 years, or even longer, to complete (VDMA, 2025). Because upgrading the electrical grid cannot keep pace with offshore wind development in the short-to-medium term, the industry is forced to look beyond traditional electron transmission.

3 Chapter 3: Navigating the Bottleneck - Transmission Alternatives

Given the long timeframe required to solve onshore grid congestion, relying solely on traditional electrical transmission is becoming increasingly unsustainable. The industry must evaluate alternative methods to transport offshore energy to land.

3.1 Traditional High-Voltage Cables (The Current Baseline)

Currently, the standard industry practice—as observed in standard offshore tender documents and major infrastructure projects (such as those executed by marine contractors like Boskalis)—relies on High-Voltage Alternating Current (HVAC) or High-Voltage Direct Current (HVDC) cables.

Table 2: Pros & Nons of HVAC and HVDC

Alternatives	**High Voltage Alternating Current**	**High Voltage Direct Current**
Working principle	Using standard AC submarine cables, the electrical energy collected by the offshore substation is directly transmitted to the land power grid.	The massive offshore converter station converts alternating current (AC) into direct current (DC), which is then transmitted over long distances via DC submarine cables. Once on land, the DC power is converted back to AC and fed into the power grid.
Pros	1.Most traditional transmission method.	1. Long-distance, low-loss: Suitable for long-distance (>80 km)

	2.Good economic efficiency for short distances (usually less than 50-80 kilometers). 3.The size and cost of an offshore substation are relatively small.	2. No capacitor limitation 3. Grid stability: Helps isolate faults and improve the stability of the grid-connected system.
Cons	1.Long-distance transmission results in significant losses Capacitive effect: 2.Submarine cables generate reactive power, which becomes more severe over longer distances, requiring the installation of expensive compensation equipment. 3.Not suitable for large-scale wind power projects in deep-sea areas.	1. Offshore and land-based converter stations are extremely expensive to build. 2. The project is extremely challenging 3. Short-distance uneconomical

3.2 Power-to-X: Offshore Green Hydrogen Production

To bypass the electrical grid entirely, a promising alternative is "Power-to-X," specifically converting electrical energy into green hydrogen via electrolysis either offshore or at the landing point.

Pros: Hydrogen can be transported to shore using pipelines, which can carry significantly more energy at a fraction of the cost of electrical cables over long distances. Moreover, it acts as a "pressure valve" for the grid; by absorbing peak power during high wind periods, it eliminates curtailment and provides a form of energy storage.

Cons: The primary drawbacks are the high initial CAPEX for electrolyser systems and the energy conversion losses inherent in the electrolysis process.

3.3 The Need for Empirical Validation

The theoretical advantage of using hydrogen to bypass grid congestion is clear, but its viability heavily depends on the operational efficiency of the electrolysers when subjected to the variable power output typical of renewable energy sources. This necessitates a micro-level investigation into electrolyser performance under dynamic load conditions.

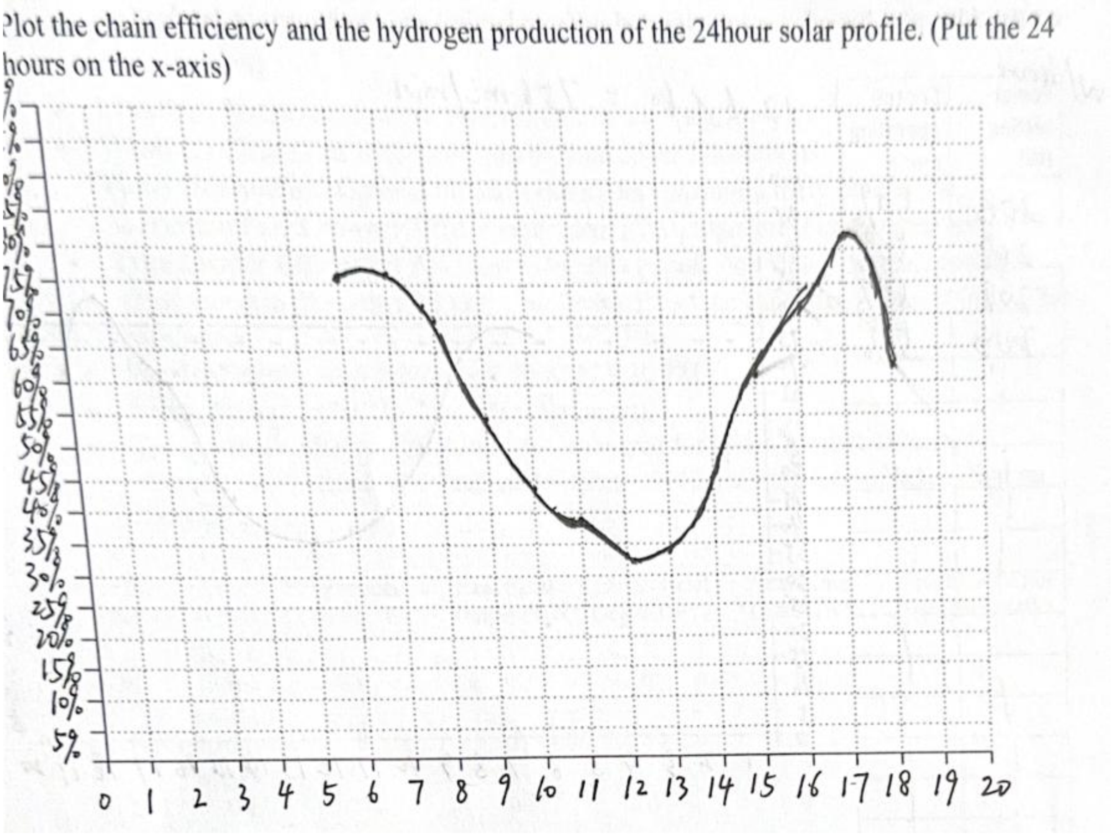
4 Chapter 4: The Empirical Evidence - Simulating Congestion and Solutions

To validate the theoretical "Power-to-X" solution proposed in Chapter 3, a real-time operation experiment of a PEM electrolyser was conducted. The experiment utilized a 24-hour solar power production profile to simulate the highly variable and intermittent nature of offshore renewable energy generation. The core objective was to analyze the chain efficiency of the system under varying load conditions and evaluate the impact of a Battery Energy Storage System (BESS).

4.1 The Efficiency Paradox: Direct Connection and Curtailment

Initial baseline testing revealed a critical operational paradox when the electrolyser was directly subjected to the unbuffered renewable energy profile. The gathered empirical data (illustrated by the black curve in the system efficiency graph) demonstrates that during peak energy generation hours (analogous to extreme offshore wind conditions or solar noon), the electrolyser is forced into maximum load operation.

This maximum capacity operation leads to significantly higher thermal losses and potential energy curtailment, causing the overall chain efficiency to plummet to approximately 38%.



Plot the chain efficiency and the hydrogen production of the 24hour solar profile. (Put the 24 hours on the x-axis)

Figure 1: 24-Hour Chain Efficiency and Hydrogen Production

Conversely, the electrolyser demonstrated its highest electrochemical conversion efficiency during partial load conditions (morning and late afternoon). This proves that directly coupling a highly volatile energy source to an electrolyser is fundamentally inefficient and mirrors the macro-level net congestion problem: the system simply cannot efficiently process the peak influx of power.

4.2 BESS as the Ultimate System Enabler

To resolve this efficiency paradox, a simulated BESS with a capacity of approximately 3000 Wh and a roundtrip efficiency of 90% was integrated into the model.

4.2.1 Mathematical Derivation of BESS Capacity

To determine the optimal battery capacity, we assume a constant electrolyser working power (P_{target}) of 200W with the BESS installed.

Based on the 24-hour solar production profile (Figure 2), the total energy generated when the net input exceeds 200W is 2522.5Wh. This excess energy is directed to the BESS. The total daily energy generation is 5257Wh. Therefore, the energy directly consumed by the electrolyser (bypassing the battery) is calculated as:

$$E_{direct} = 5257 - 2522.5 = 2734.5Wh$$

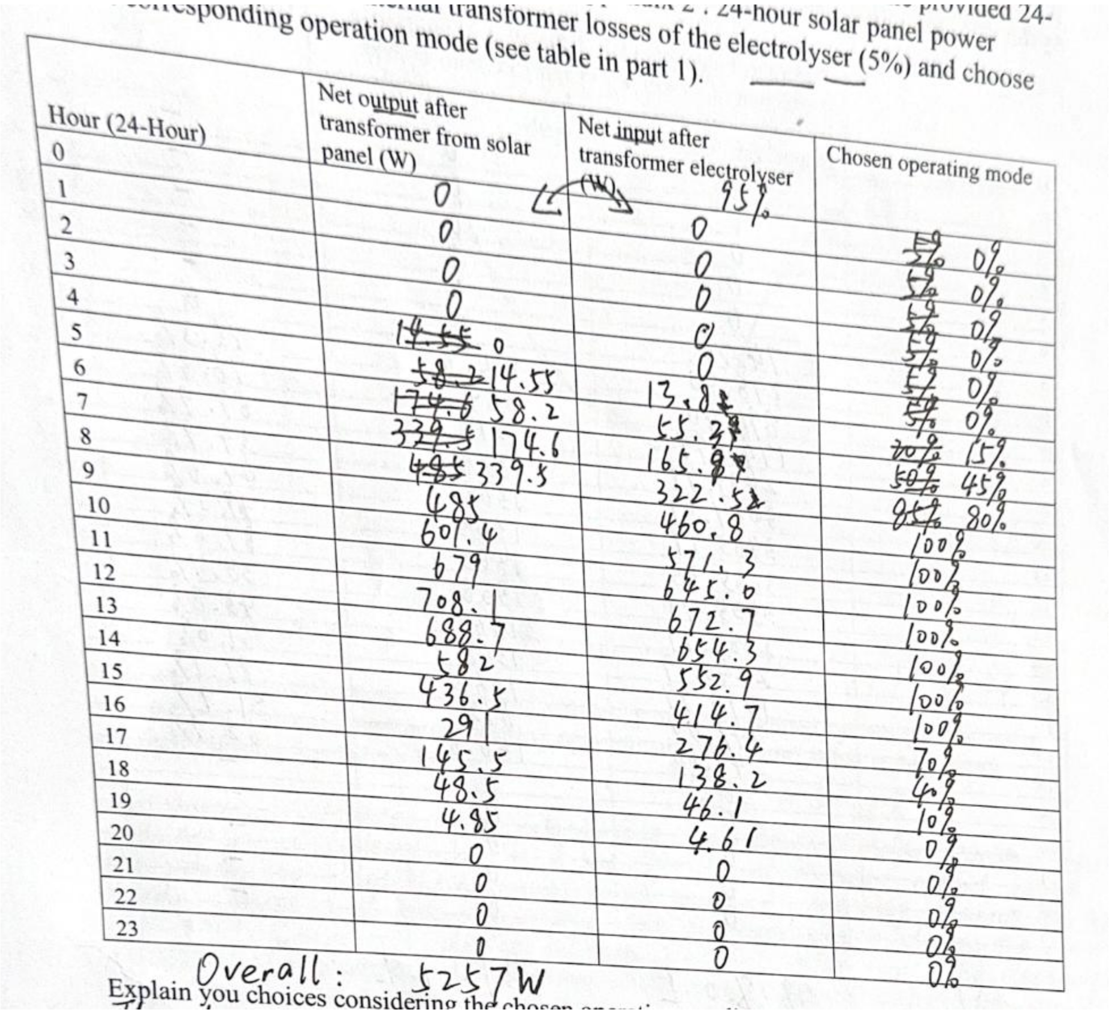
Factoring in a battery roundtrip efficiency of 90%, the total practical energy consumed by the system over 24 hours is:

$$E_{actual} = (2522.5 \times 0.9) + 2734.5 = 5004.75Wh$$

This yields an average hourly power consumption of:

$$P_{avg} = \frac{5004.75}{24} \approx 208W$$

Consequently, the required minimum battery capacity must exceed the direct consumption threshold, making a 3000Wh BESS an optimal choice to ensure continuous operation at an actual constant load of approximately 208W.



transformer losses of the electrolyser (5%) and choose
24-hour solar panel power
provided 24-
rresponding operation mode (see table in part 1).

Hour (24-Hour)	Net output after transformer from solar panel (W)	Net input after transformer electrolyser (W) 95%	Chosen operating mode
0	0	0	~~5%~~ 0%
1	0	0	~~5%~~ 0%
2	0	0	~~5%~~ 0%
3	0	0	~~5%~~ 0%
4	~~14.55~~ 0	0	~~5%~~ 0%
5	~~58.2~~ 14.55	13.8	~~5%~~ 0%
6	~~174.6~~ 58.2	55.3	~~20%~~ 15%
7	~~339.5~~ 174.6	165.8	~~50%~~ 45%
8	~~485~~ 339.5	322.5	~~85%~~ 80%
9	485	460.8	100%
10	601.4	571.3	100%
11	679	645.0	100%
12	708.1	672.7	100%
13	688.7	654.3	100%
14	582	552.9	100%
15	436.5	414.7	100%
16	291	276.4	70%
17	145.5	138.2	40%
18	48.5	46.1	10%
19	4.85	4.61	0%
20	0	0	0%
21	0	0	0%
22	0	0	0%
23	0	0	0%

Overall : 5257W

Explain you choices considering th

Figure 2: 24-Hour Net Input After Transformer

The results, as depicted by the red and green flat lines in the graph, are transformative.

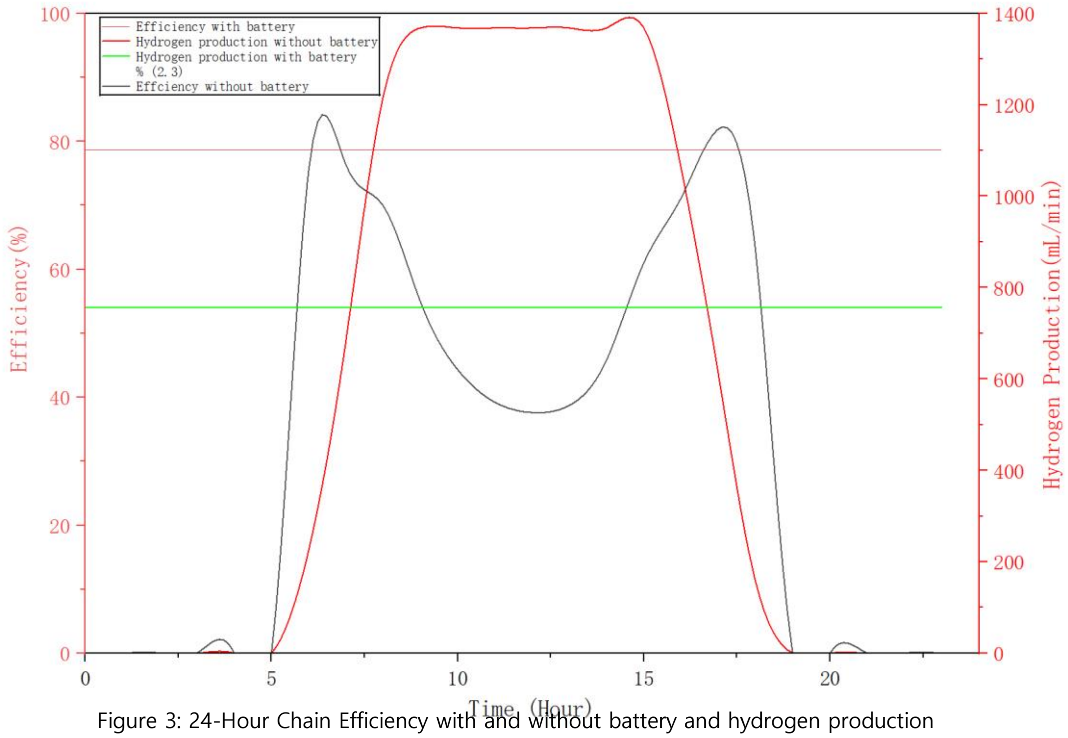


Figure 3: 24-Hour Chain Efficiency with and without battery and hydrogen production

The battery acts as a critical buffer, absorbing the excess energy generated during peak hours that would otherwise be curtailed. By storing this peak energy, the BESS enables the electrolyser to operate at an optimal, constant partial load (e.g., 50% capacity at roughly 208W) 24 hours a day. Consequently, the volatile efficiency curve is replaced by a stable, high-efficiency flatline at approximately 78%, and hydrogen production becomes a continuous, predictable output.

4.3 Bridging the Lab to the North Sea

These micro-level empirical findings have profound macro-level implications for the offshore wind sector. They mathematically prove that future offshore green hydrogen platforms cannot simply consist of wind turbines and electrolysers. To bypass onshore net congestion economically and maximize the yield of green hydrogen, these offshore systems must inherently integrate large-scale energy storage (BESS) to smooth the power curve prior to hydrolysis.

5 Chapter 5: Synthesis & Reflection

This portfolio has navigated the complex landscape of the Offshore Renewable Energy sector, transitioning from global strategic ambitions to micro-level electrochemical data. The initial investigation into the exponential growth of offshore wind in the Netherlands highlighted a severe bottleneck: the physical limitations of the onshore electrical grid.

While current major infrastructure tenders—such as those analyzed in concurrent Boskalis projects—still rely heavily on traditional HVAC/HVDC cabling, this research critically evaluated the long-term sustainability of that approach. By systematically investigating the "Power-to-X" alternative, it became evident that offshore green hydrogen production offers a viable pathway to circumvent grid congestion.

However, the empirical evidence gathered during the real-time electrolyser experiment added a crucial layer of nuance to this theoretical solution. The data unequivocally demonstrated that hydrogen production is only an efficient solution if the volatility of the renewable energy source is mitigated. The necessity of integrating a BESS to maintain partial-load efficiency in electrolysers serves as a vital engineering constraint for future offshore design.

Ultimately, this study underscores that overcoming net congestion requires a holistic, multi-disciplinary approach. It is not merely about generating more power or laying thicker cables; it is about intelligently managing energy flows, combining generation (turbines), conversion (electrolysers), and buffering (BESS) into a cohesive, optimized system. This rigorous alignment of macro-industry challenges with micro-experimental validation has profoundly deepened my understanding of the genuine engineering complexities driving the energy transition.

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