PtX Feasibility

REACTRF-22-0054
Feasibility study for
Power-to-X production on Bornholm

Business Case

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1. EXECUTIVE SUMMARY

Bornholm, the picturesque Danish Island in the Baltic Sea, is poised to undergo a transformative journey from being known as the "Sunshine Island" to becoming a thriving Energy Island. Denmark's ambitious plans to establish 3 GW of renewable energy capacity by 2030, accompanied by a commitment to reducing CO2 emissions by 70%, are driving the adoption of Power-to-X (PtX) technology used to produce so-called e-fuels, which are fuels, based on hydrogen, which can replace fossil fuels. PtX holds the key to realizing these ambitions, with DKK 1.25 billion public funding allocated for PtX projects to achieve an electrolysis capacity of 4 to 6 GW by 2030.

The initiative, REACTRF-22-0054 project, titled "Feasibility Study for Power-to-X Production on Bornholm," is a collaborative effort involving participants from various sectors, funded by The European Regional Development Fund and the Danish Board of Business Development.

Denmark's strong commitment to renewable energy and PtX technologies aligns well with national and European sustainability goals, positioning Bornholm as a prime candidate for PtX development in relation to the establishment for Energy Island Bornholm. However, geopolitical risks necessitate diligent risk assessment strategies. Job creation and innovative funding mechanisms offer financial viability, but continuous collaboration with regulatory authorities is essential for project stability.

Bornholm's strategic location, renewable energy potential, and government support create a favorable environment for PtX development. However, uncertainties in production costs, technology advancements, and market conditions require meticulous risk management and diversification of energy sources. To enhance feasibility, optimizing technology choices, diversifying product offerings, and collaborating with government bodies are recommended.

Community involvement and acceptance are pivotal. Transparent processes, ownership models, and cultural preservation are essential for building trust. Leveraging PtX's employment opportunities and partnering with local educational institutions can bridge skill gaps. Educational efforts and terrorism risk assessment are vital for garnering support and ensuring safety.

Cost optimization, advanced technologies, and efficient supply chain management are critical for economic viability. Careful planning for wind power variability, water source utilization, infrastructure, and operational efficiency are essential. PtX production can meet increasing demand for alternative fuels in the local industry and heavy transportation.

E-fuels from PtX offer environmental benefits by minimizing air pollution and greenhouse gas emissions. Transitioning sectors like transportation and industry to cleaner energy alternatives is an opportunity. Strict environmental screening and monitoring are required to mitigate potential pollution. Efficient land utilization and adherence to safety protocols are crucial.

The regulatory landscape in Denmark and Europe supports PtX projects. Government initiatives, funding mechanisms, and streamlined regulatory processes are positive signs. However, environmental and sustainability regulations, definitions of e-fuels, and market complexities may require careful navigation. Land usage and long-term sustainability considerations are also important.

In conclusion, Bornholm's transformation into an Energy Island through PtX technology is a promising endeavor. While challenges exist, with careful planning, risk management, and collaboration, Bornholm can emerge as a beacon of sustainable energy production, contributing significantly to Denmark's green energy ambitions and the global fight against climate change.

2. INTRODUCTION

Bornholm is a small Danish Island located in the Baltic Sea, southeast of Copenhagen, and closer to Sweden and Poland than mainland Denmark. Affectionately known as the "Sunshine Island", Bornholm is widely known for its smoked herring, high-quality arts and crafts, and beautiful nature. The island has a long history as a military and political center in the Baltic Sea, dating back to the famous Vikings.

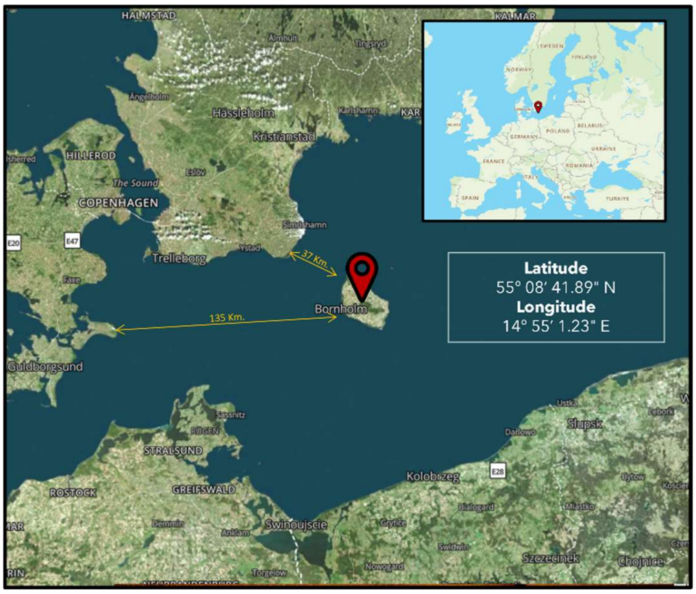


Figure 1. You are here - Bornholm location.

The nearest Danish coast is Møns Klint, 135 km away, and the shortest distance to Sweden is 37 km. The island has a total area of approximately 588 km² and has 158 km of coastline.

Now, Sunshine Island is set to become an Energy Island. Denmark has ambitious plans to establish at least 3 GW of renewable energy capacity by 2030 and is committed to reducing CO2 emissions by 70% 2030[1]. Power-to-X (PtX) technology is a pivotal piece of this plan. The Danish government has launched an impressive subsidy scheme to advance this positive trajectory, allocating DKK 1.25 billion (EUR 161 million) to support PtX projects[2] to achieve an electrolysis capacity of 4 to 6 GW by 2030[3].

The transformation could turn Bornholm into a thriving hub for renewable energy production. However, a crucial question remains: How can this remarkable goal be achieved?

The initiative, REACTRF-22-0054 project, titled "Feasibility Study for Power-to-X Production on Bornholm," is a collaborative effort involving participants from various sectors, including companies, academia, and local authorities. Bornholm's scenic landscapes and strategic location provide an ideal setting for this pioneering effort to assess the viability of PtX production and address uncertainties surrounding its establishment. REACTRF22-0054 is a project funded by The European Regional Development Fund and the Danish Board of Business Development[4].

The project's primary objective is to comprehensively evaluate the feasibility of Power-to-X production in Bornholm. PtX technology harnesses renewable energy sources like wind or solar power to convert electricity into various energy carriers, such as hydrogen and derivates like ammonia and methanol'. These are also known as e-fuels, which could be used locally for industry and heavy road transportation as well as in Bornholm Bunker Hub, which is the vision of transforming Bornholm and Port of Roenne into a green gas station for some of the +60.000 vessels which every year pass close by Bornholm. This can significantly contribute to decarbonizing maritime transportation.

The feasibility study on Bornholm encompasses crucial aspects of Power-to-X production, including manufacturing processes, economic viability, and the potential integration of electrical systems and district heating networks on and throughout the Baltic Sea region. The project will extensively analyze potential energy sources, innovative technologies, product options, and off-takers, explicitly focusing on integrating green hydrogen into Bornholm's energy system. The successful execution of this study relies on collaboration among companies, academia, and local authorities.

3. POWER-TO-X IN A NUTSHELL

3.1. Definition

Power-to-X (PtX) refers to a collection of technologies and processes that convert electricity into various energy carriers, products, and raw materials. It is a term used to describe different ways of generating energy from electricity, including power-to-gas, power-to-liquid, power-to-fuel, power-to-chemicals, and power-to-heat.[5] [6] [7]

3.2. PtX technologies and applications

Power-to-X technologies can be categorized based on the form of energy they produce[8]:

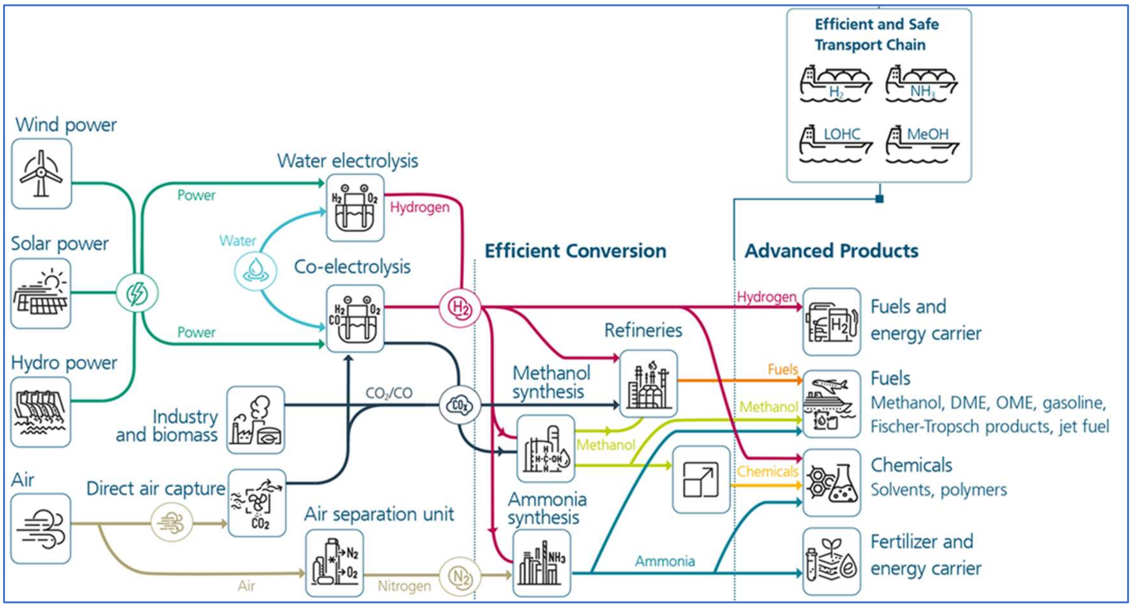


Figure 2. PtX Processes and products. Fraunhofer ISE©

- Power-to-Gas: This process involves converting electricity into hydrogen or methane gas. The produced gases can be used as a renewable energy source, stored for later use, or injected into the natural gas grid.

- Power-to-Liquid: Power-to-Liquid technologies convert electricity into liquid fuels such as synthetic diesel, kerosene, or methanol. These fuels can be used in transportation, replacing fossil fuels with carbon-neutral alternatives.

- Power-to-Fuel: Power-to-Fuel technologies produce various fuels, including hydrogen, ammonia, and synthetic natural gas. These fuels can be used in sectors that are difficult to decarbonize, such as aviation and heavy industry.

- Power-to-Chemicals: Power-to-Chemicals processes convert electricity into chemical compounds that can be used in various industries. This includes producing raw materials for plastics, fertilizers, and other chemical products.

- Power-to-Heat: Power-to-Heat technologies use electrical energy directly as a power source for heating purposes. This can include heating buildings, water, or industrial processes.

3.3. Primary Types of Electrolysis Technologies

Different electrolysis methods produce hydrogen, which can be further processed into various energy carriers or chemicals, including methane, synthesis gas, liquid fuels, or electricity. The specific selection of an electrolysis technology depends on factors like efficiency, cost, scalability, and the intended application of the Power-to-X system. The primary types of electrolysis applied in Power-to-X (PTX) applications are[9,10,11,16] :

- Alkaline Water Electrolysis (AEL/AEC): This method employs an alkaline electrolyte solution, typically potassium hydroxide (KOH), to separate water into hydrogen and oxygen. It stands as one of the oldest and most well-established electrolysis technologies.
- Proton Exchange Membrane (PEM) Electrolysis: PEM electrolysis uses a solid polymer membrane as the electrolyte, enabling selective transport of protons. This technology operates at lower temperatures and responds faster than alkaline water electrolysis.
- Solid Oxide Electrolysis Cell (SOEC): SOEC functions at high temperatures and uses a solid ceramic electrolyte, like yttria-stabilized zirconia (YSZ), to split water into hydrogen and oxygen. It can also operate in reverse mode, known as a solid oxide fuel cell (SOFC), which produces hydrogen-generated electricity.

	AEL	PEM	SOEL
Pros	— Established technology — Plants with the highest nominal output (>100MW) — Lowest investment costs (1000€/kW) and long lifetime — Does not require critical raw materials	— Hydrogen with highest purity — Good dynamic properties and high load gradient: good for fluctuating RES — Cold start in only 15 min	— Highest efficiency (80%) — Suitable for co-electrolysis : direct synthesis gas generation
Cons	— Vulnerability to impurities in the product gases — Relatively long cold start time (50 min)	— Electrodes made of precious metals — Higher investment costs (2000 €/kW)	— Currently still under development (only pilot plants so far) — Highest investment costs (2500 €/kW) — Highest cold start time (several hours)

Source: Water electrolysis explained – the basis for most Power-to-X processes[11]

Figure 3. Comparing the different electrolysis technologies.

3.4. Debating PtX Technologies

3.4.1. Advantages

Power-to-X (PTX) technologies offer several advantages, including:

- Flexibility: Power-to-X technologies provide flexibility in using renewable energy sources. Power-to-hydrogen, power-to-ammonia, and power-to-methane enable power generators to store their excess energy for later use, reducing curtailment of power generation during periods of surplus production.

- Decarbonization: Power-to-X technologies offer carbon-neutral alternatives to replace fossil fuels in sectors that are challenging to decarbonize, such as transportation, heating, and industrial processes[12]. By utilizing renewable electricity, Power-to-X processes can produce energy carriers and products with significantly reduced carbon emissions, contributing to climate change mitigation[13]
- Energy Storage: Power-to-X provides a means to store excess renewable energy, ensuring a more reliable and stable energy supply[14]. Excess renewable energy can be converted into energy carriers or

stored in the form of gases or liquids for later use, reducing curtailment of power generation during periods of surplus production[12].

- Sector Integration: Power-to-X technologies enable the integration of renewable energy into sectors traditionally relying on fossil fuels, facilitating the transition to a more sustainable energy system[13]. Power-to-X solutions can facilitate the integration of variable renewable energy into traditional power grids by balancing demand and supply[12]

- Economic Benefits: Power-to-X technologies offer potential economic benefits, notably for companies[14]. Producing synthetic fuels and other products through Power-to-X technologies can create new markets and jobs, contributing to economic growth and development.

3.4.2. Disadvantages

The challenges associated with Power-to-X technologies are being addressed with ongoing research and development to improve efficiency and cost-effectiveness. Some of the challenges found in literature are:

- Energy Loss: During the conversion processes involved in Power-to-X technologies, such as electrolysis, methanation, and storage, a significant amount of energy is lost[15]. Producing synthetic fuels or other energy carriers through Power-to-X requires large amounts of renewable energy. After electrolysis, only about 67-81% of the point remains, and only about 54-65% is left14 after methanation. This energy loss reduces the overall efficiency of the process.

- Material Degradation and Low Stability: Power-to-X technologies face challenges related to material degradation and low stability, which prevent them from reaching large-scale implementation[16]. The fast degradation of materials used in these technologies can limit their lifespan and increase maintenance requirements.

- Production Process Complexity: Producing synthetic fuels and other products through Power-to-X technologies can be laborious and complex[17]. It involves multiple conversion steps and requires careful control and optimization of various parameters. This complexity can increase the cost and time needed for production.

- Lower Efficiency Compared to Direct Electricity Use: Power-to-X technologies are generally less efficient than direct electricity use[17]. The conversion of electricity into energy carriers or products involves additional steps and energy losses, reducing the overall efficiency of the process. Immediate use of electricity can often be more efficient for specific applications.

3.5. Is it safe?

Hydrogen production through water electrolysis is a well-established process that has been utilized for many years. This method has been successfully scaled up and applied across various industries, with proven success both in Denmark and globally.

Similarly, the production of Ammonia, Methanol, and the utilization of carbon dioxide (CO2) as a feedstock for fuel and chemical production are not new concepts. However, there is an ongoing and active effort to optimize PtX technologies by enhancing efficiency, reducing costs, and ensuring safety. Innovations in catalysts, materials, and process integration are being explored to improve the overall viability and feasibility of these technologies.

As with any industry, it is crucial to have proper safety protocols and risk assessments in place to ensure secure operations. Existing regulations and safety protocols cover critical stages of the process, such as handling, production, storage, and transportation.

Risk assessments play a vital role in the successful implementation of power-to-x projects. They identify and mitigate potential risks, establish a solid foundation for project success, reduce rework costs, ensure compliance with regulations, and help evaluate suitable security partners and protocols. Given the complexity of energy projects and the involvement of multiple stakeholders, conducting thorough risk assessments is essential to proactively address vulnerabilities and achieve project objectives, ultimately contributing to the overall success and sustainability of power-to-x initiatives.

3.6. Power-to-X in Denmark

On July 20, 2023, Denmark initiated the world's inaugural Power-to-X tender, inviting proposals for related projects[18, 19]. The application deadline is September 1, 2023. The Danish government's objective is to elevate renewable energy, transforming Denmark into a green energy net exporter by 2030**Error! Bookmark not defined.**. This includes allocating funds for Power-to-X facilities. The tender's goal is to bolster PtX production, cutting expenses tied to green hydrogen, using a market-driven approach for efficient and significant hydrogen output.

Furthermore, a consensus within the political majority has been reached to establish a PtX task force. This group aims to facilitate collaboration among governmental bodies, foster dialogues with the sector and municipalities, and address regulatory and legislative obstacles to establish Danish utilities.

Several pilot projects have been conducted in Denmark to understand the requirements for making large-scale and cost-efficient hydrogen production possible (Table 1). These projects paved the way for Power-to-X projects that have been recently announced[20,] boasting electrolysis capacities from 1 GW up to 3 GW, sourced entirely from renewable energies and producing hydrogen, ammonia, and e-fuels.

Table 1. Power to X in production. Source: Brint i tal.

Projekt	Projekttype	Forbrugskapacitet (MW)	Produktionskapacitet (MW)	Status	Partnere
Biogas Holsted	Produktion		0.01	I drift	Nature Energy, SDU, DTU, Biogas Clean
Brande Hydrogen (v. Flø)	Produktion	0.40	0.40	I drift	Siemens Gamesa Renewable Energy, Everfuel, Green Hydrogen Systems
HFC-Marine (Ballard Test Lab)	Produktion	0.00	0.00	I drift	Ballard Power Systems Europe, Odense Maritime Technology, Hvide Sande Shipyard, Aarhus Universitet, MARLOG, Strandmøllen
HyBalance	Produktion		1.20	I drift	Air Liquide, Copenhagen Hydrogen Network, Hydrogenics, Centrica, Hydrogen Valley, LBST, Energinet, Akzo Nobel, Sintex
Power2Met	Produktion		0.30	I drift	Green Hydrogen Systems, Reintegrate, Aalborg University, Hydrogen Valley, E.ON
Strandmøllen Ejby	Produktion	0.50	0.50	I drift	Strandmøllen

	Project	Electrolysis capacity	Energy sources	Products
1	Ørsted and Skovgaard Energy	Up to 3 GW	Onshore wind and solar cells – eventually offshore wind	Hydrogen, e-methanol, e-kerosene (jet fuel)
2	Megaton, GreenGo	2 GW	Onshore wind, offshore wind, solar cells	Green ammonia, e-methanol
3	Green Fuels for Denmark	1.3 GW	Offshore wind energy	Hydrogen, e-methanol, e-kerosene (jet fuel)
4	HØST, CIP	1 GW	Wind turbines, solar cells	Green ammonia
5	H2 Energy	1 GW	Offshore wind energy	Hydrogen
6	Green Hydrogen Hub	1GW	Wind and Solar	Hydrogen
7	HySynergy	1GW	Wind and Solar	Hydrogen

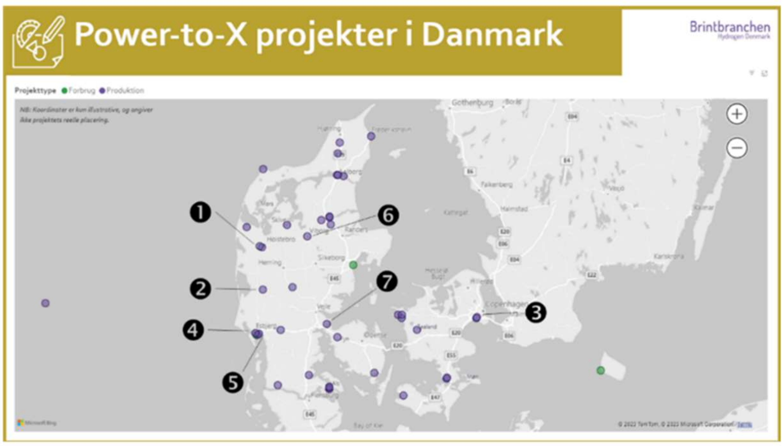


Figure 4. Selected Power to X projects planned in Denmark in GW size. Source: Brint i tal[20]

4. REACTRF-22-0054 - FEASIBILITY STUDY FOR POWER-TO-X PRODUCTION ON BORNHOLM

REACTRF-22-0054 - Feasibility study for Power-to-X production on Bornholm is a project that brings together private companies, academia, and local authorities to explore the viability of Power-to-X production on the island of Bornholm and address uncertainties surrounding its establishment. The project is linked to the work of Baltic Energy Island, formerly known as Nationalt Center for Grøn Energi, aiming to unlock business opportunities for local companies as Bornholm becomes the world's first energy island.

Leading this effort is Port of Roenne, working with Bornholms Energi & Forsyning, Bornholms Regionskommune, Danfoss Power Electronics, DTU Management, DTU Wind and Energy Systems, Gate 2, Ramboll, Skovgaard Energy, Topsoe, and Ørsted Hydrogen.

The project aims to develop two simulation tools. The first tool from the Sustainability Division at DTU Management will enable the modelling of optimal dimensions and configurations for Power-to-X production at specific locations. The second tool from the Electric Power and Energy division at DTU Wind and Energy Systems will facilitate simulations of how Power-to-X plants can integrate into existing power systems, providing valuable system services. These simulation tools will aid in developing the Bornholm project and benefit partners seeking to explore Power-to-X production in other locations across Denmark.

4.1. Work packages

4.1.1. WP 1: Input for Power-to-X Plant

This work package focuses on mapping and analyzing the local sources, quantities, and prices of critical inputs for PtX production, including green power, water, and carbon dioxide. The supply of green energy from offshore and onshore wind, solar energy, and the grid is investigated.

Alternative water sources such as purified wastewater, stormwater, low-quality drinking water, and seawater are explored. The potential use of biogas and carbon dioxide from a biogas plant is also examined.

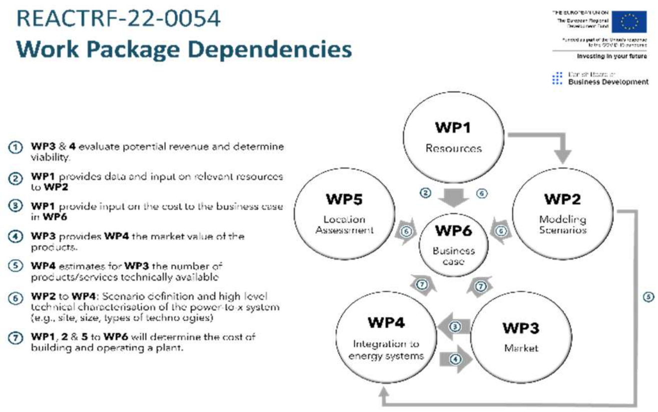


Figure 5. REACTRF-22-0054 - Work Packages Dependencies

4.1.2. WP 2 - Modelling of Scenarios for *Power*-to-X *Production*

This work package involves the development of an open-source optimization model, OptiPlant, to simulate different scenarios for PtX production based on various technologies and local input parameters.

The model considers the capacity of different plant components, fluctuating electricity prices, and the integration of renewable power production. It aims to provide a state-of-the-art tool for evaluating the feasibility and optimizing investments in PtX facilities, focusing on ammonia and methanol production.

4.1.3. WP 3 - Market for Products

This work package investigates the market potential for PtX products, including ammonia, hydrogen, oxygen, methanol, and waste heat. It explores potential markets such as maritime fuel, heavy transportation, industrial processes, wastewater treatment plants, and district heating systems. The market analysis assesses each product's demand, potential customers, and economic feasibility.

4.1.4. WP 4 - Integration of Power-to-X into the Energy Systems

This work package focuses on integrating the PtX plant into the broader energy system, including the power grid and district heating system. Mathematical modelling optimizes the operations and economic output of the PtX facility, considering the fluctuating electricity supply, heat recovery, power grid services, and district heating integration. A tool for simulating PtX facility operations and assessing system services is developed.

4.1.5. WP 5 - Location of Power-to-X Plant and Storage

This work package aims to identify a suitable location for the PtX plant based on factors such as size, proximity to the energy island, access to water, solar power potential, and impact on residential areas. It also examines transportation methods for PtX products, including the possibility of establishing a pipeline for ammonia transport to Port of Roenne. Storage options for the port are investigated for hydrogen, ammonia, and methanol.

4.1.6. WP 6 - Business Case

The final work package focuses on developing a business case for a PtX plant at Bornholm. It includes estimating the cost of construction, operation, and product production. Market analysis and revenue estimation are used to assess the viability of PtX production at Bornholm. Project administration and reporting are also managed in this work package.

4.2. Activities

4.2.1. Scenario Selection Workshop

The project was conducted in three lines of investigation, which were selected as result of extensive discussions with all the project stakeholders. These scenarios considered various parameters, including the time horizon, plant scale, plant configuration, power and inputs supply type, renewable energy profiles, electrolyser technology, type of fuel produced, the demand profile type, and the sizing method used.

The feasibility studies were focused on the year 2030 as the timeframe. This choice allowed for adequate planning and action, and it aligned with Denmark's goal of reducing greenhouse gas emissions by 70% by that same year. All the techno-economic input data used in the OptiPlant model were based on predictions made for the year 2030.

The investigation for the large-scale PtX plant was aligned with the development plans for a 2-3 GW offshore wind energy island in Bornholm by 2030. In addition to the 2-3 GW planned for grid connection, developers have an option of establishing up to 800 MW of so-called overplanting. Overplanting is offshore wind energy, which cannot be integrated in the power system/market, and in case of Bornholm Energy Island it would therefore have to be used locally on Bornholm. A small-scale PtX plant study was focused on understanding Bornholm's renewable energy potential for local self-sufficiency and autonomy, utilizing the island's carbon sources.

Both the large-scale and small-scale scenarios operated under a behind-the-meter (BTM) power supply configuration. In this setup, the Power-to-X plant is directly connected to the renewable energy supply, if the plant owner also owns a share of the renewable power assets. The BTM configuration was preferred by the project stakeholders due to fewer economic uncertainties compared to other alternative layouts involving a grid connection. Additionally, this islanded configuration ensures that the produced fuels are completely green, which cannot be guaranteed with a grid-connected configuration. PtX production based on BTM also works very well with utilizing electricity from wind turbines established as overplanting.

4.2.2. Study Trip

The establishment of contemporary energy infrastructure necessitates meticulous preparation involving substantial investments and careful planning. Preceding instances, including the GreenLab Skive collaboration with the Danish Centre for Green Energy in January 2023, have emphasized the criticality of comprehensive readiness.

The REACTRF-22-0054 study trip constituted a significant endeavor aimed to comprehensively investigate expansive construction efforts from multifaceted perspectives. These viewpoints encompassed technological considerations, spatial dimensions, potential employment implications, as well as safety and noise concerns.

Active participation comprised members from the Economic and Climate Committee, together with counterparts from the Nature, Environment, and Planning Committee at Bornholms Regionskommune, alongside relevant stakeholders in the region. An informative discourse transpired, uniting political representatives and officials from Aabenraa Kommune and Fredericia Kommune.

The schedule encompassed various significant locations and included the subsequent highlights:

- Abenraa Kommune
  - From vision to implementation - how do you work politically with the conversion of a political vision into real policy in the citizens' backyard? by Mayor Jan Riber Jakobsen.
  - What political challenges do you face and what considerations do you have to consider when working with decisions about renewable energy in a democratic and close-to-the-citizen context?
  - How does Aabenraa work with planning the transition to PtX and green forms of energy – in the short and long term? by Director Planning, Technology & Environment Ditte Lundgaard Jacobsen.
- Kassø Solar Park:
  - Presentation on European Energy's strategic vision
  - Discussion on photovoltaic systems and PtX (Power-to-X) strategies
  - Examination of VE and PtX implementations by Aabenraa Municipality
  - Guided tour of the photovoltaic system, encompassing panels, substation, and PtX plant site.
  - Visualization of the Triangle area as a hub for changing energy supply, including the talk by Søren Schmidt Thomsen: Energy, value chains and partnerships: Who produces and who consumes the energy in Fredericia? Also visited Skærbækværket, Taulov Dryport/Logistics Centre , Google Data Center, Everfuel, HySynergy site (hydrogen production) and Crossbridge refinery, example of large-scale PtX plant.
- Port of Fredericia
  - Mayor Steen Wrist: From vision to implementation - how do you work politically with the conversion of a political vision into real policy in the citizens' backyard?
  - Energy and Environment Committee: Energy production close to the city - how do you do it?
  - Director Søren Schmidt Thomsen, Triangle Energy Alliance: The role of a PtX partnership in a public-private collaboration
  - ADP Energy Infrastructure A/S: How are changes in infrastructure managed in the transition to new energy sources in a commercial port?
  - Head of Secretariat Anja Schaumburg: How does Fredericia work with planning the transition to green forms of energy - in the short and long term?
  - Clerk Janni Skov Larsen, secretariat for Power-to-X Danish Energy Agency: PtX secretariat on location and process for PtX facilities

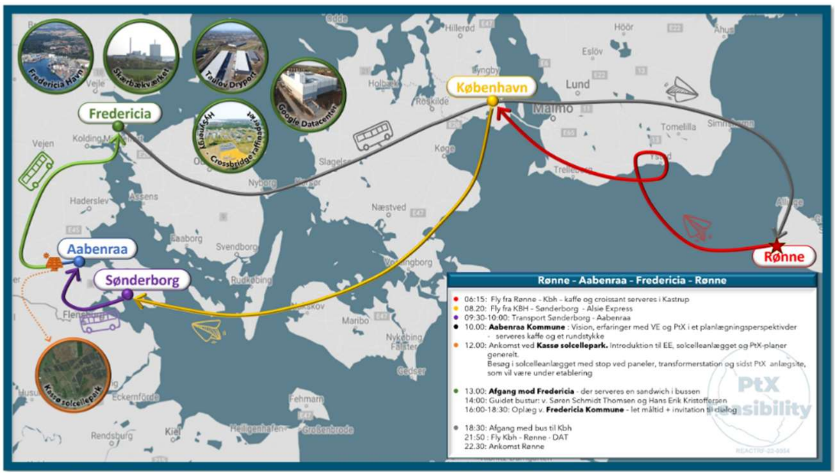


Figure 6. REACTRF-22-0054 schedule.

5. RESOURCES IDENTIFICATION (WP1)

The primary purpose of this feasibility study is to map the local sources and quantities of critical inputs required for Power-to-X production, including green power, biogenic carbon (CO2), and water. By analyzing these sources' availability, reliability, and feasibility, the study aims to provide valuable insights for stakeholders and decision-makers involved in the energy transition in Bornholm.

5.1. Green Power Sources

5.1.1. Onshore Wind Power

Bornholm's onshore wind power capacity currently stands at 37 MW, with no plans for further expansion according to the Energy Strategy 2040[21]. As a result, onshore wind power is not being considered for P-to-X production in the analysis.

5.1.2. Solar PV

Solar photovoltaic (PV) energy presents a promising green power option. The island's 20 MW solar PV capacity is expected to expand by 50 MW before 2025. Out of this expansion, an estimated 30-40 MW could be used for Power-to-X production. The simulation of fixed-axis solar PV plants has been validated against actual data, making it a reliable source for Power-to-X[22].

Table 2. Estimated PV Capacity for Power-to-X Production

Source	Capacity
PV (2022)	20MW
Increase in capacity by 2025	50MW
PV (2025)	70MW

5.1.3. Offshore Wind Power

The planned offshore wind capacity of 3 GW, including projects like "Bornholm Bassin Syd"[23] ,[24] offers a significant green power source for Power-to-X. The Energy Island Bornholm, with 3,8 GW[25] capacity, will be a central hub for receiving power from offshore wind farms. A minimum of 600 MW could be used for local P-t-X production, depending on export capacities and island consumption[22].

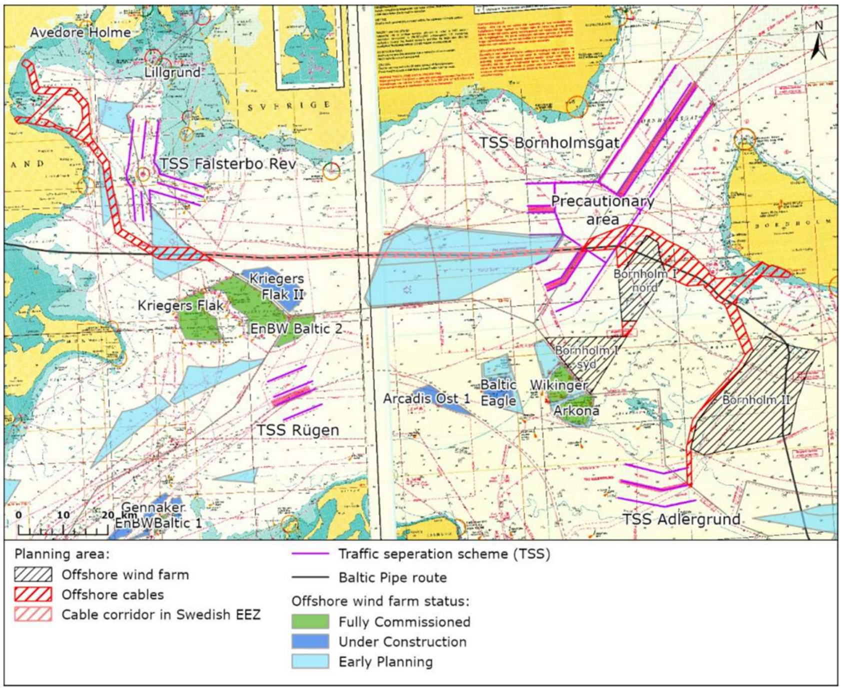


Figure 7. Location offshore wind farms for Energy Island Bornholm[25].

5.1.4. Technical setup for power supply

The technical setup between a renewable energy source and a PtX plant varies depending on the power supply set-up. The three alternatives are:

- Behind-the-meter (Off-grid):
  The PtX plant is directly connected to the renewable energy supply in this setup. This means the plant is located near a renewable energy source, and the energy produced is used on-site without being connected to the public grid. The PtX plant owner may own a share of the renewable power assets or have a Power Purchase Agreement (PPA) with the renewable energy producer to access the necessary electricity for the conversion process.

- Grid-connected:
  The PtX plant is solely connected to the public electricity grid in a grid-connected setup. The renewable energy source (e.g., solar, wind) feeds electricity into the grid, and the PtX plant draws electricity from the grid when needed for the conversion process. The PtX operator is responsible for paying the grid costs and purchasing electricity at the prevailing spot price.

- Semi-islanded:
  The semi-islanded configuration combines elements of both behind-the-meter and grid-connected setups. The PtX plant is partly connected to the public grid and directly connected to privately owned renewable energy assets. This hybrid approach allows the PtX plant to use electricity from both sources, providing stability and reliability.

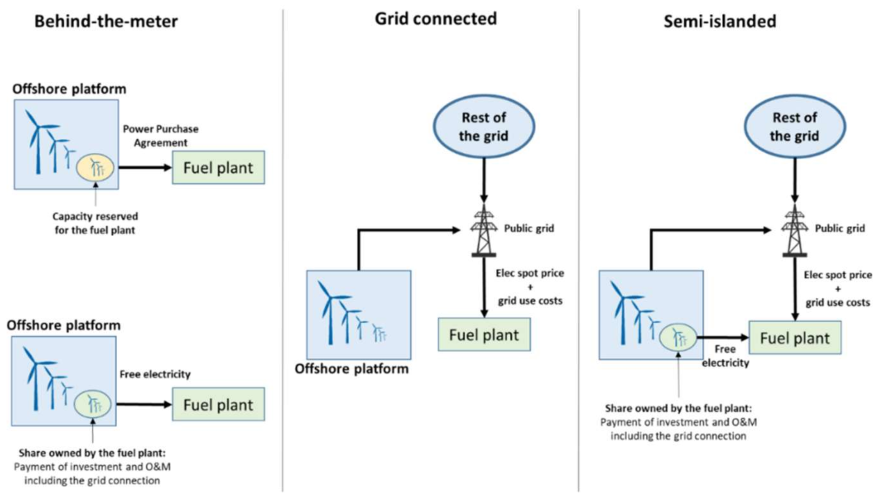


Figure 8. Power supply set-up

Based on the discussions held during the Scenario Selection workshop (See 4.2.1), the behind-the-meter setup was selected as it was considered to provide more stability and control over the electricity supply. It will avoid the consideration of potential price fluctuations in the public electricity grid and guarantee a 100% green power source, facilitating the certification process[26] for any products produced at the future plant.

5.2. Water Sources

5.2.1. Wastewater from WWTPs

Wastewater from WWTPs offers a significant and reliable water source for Power-to-X production, with the Rønne WWTP alone producing approximately 3 million m3/year. Utilizing this source also reduces nutrient outlets to the sea, benefiting the environment.

5.2.2. Seawater

Seawater is an alternative water source for Power-to-X production, especially if the plant's capacity requires additional water beyond what wastewater can provide. The salinity of seawater (approximately 7-8 o/oo) makes it suitable for electrolysis.

Table 3. Quantities of water available for use in Power-to-X production[22]

Source	Quantity (BEOFs estimate)	Conversion rate to demineralized water (electrolyser quality)	Salinity o/ooh	Conductivity µS/cm
Drinking water	< 100.000 m3/year	80-90 %	0,3-0,4	500-600
Low-quality drinking water	< 1 mio. m3/year	80-90 %	0,3-0,4	500-600
Stormwater/rainwater *	> 1 mio. m3/year	80-90 %	0 – 0.02	
Wastewater	Seven mio. m3/year	80-90 %	2	1000
Surface water Baltic Sea**	Infinite	80-90 %	7-8	1000 -2000
Surface water North Sea	Infinite		28-35	

*An assessment of the quality and use of rainwater as the basis for sustainable water management in suburban areas. E3S Web of Conferences 45, 00111 (2018)
** Basisanalyse I for vanddistrikt Bornholm, BRK, Natur & Miljø, Nov. 2004

5.2.3. Drinking Water

The limited availability of drinking water resources on Bornholm, approximately 3 million m3/year, makes reserving water for Power-to-X production unlikely.

5.2.4. Low-Quality Drinking Water

Certain Bornholm wells are unsuitable for drinking water production due to their poor quality. However, these wells could be considered for electrolysis in the Power-to-X process.

5.2.5. Stormwater

Utilizing stormwater for Power-to-X would require significant reservoir construction. Due to high costs and space requirements, this source may not be viable.

5.3. Local Biogenic Carbon (CO2) Sources

5.3.1. Biogas Production

The biogas plant owned by Bigadan A/S provides a reliable source of biogenic CO2. The production of 2.5-3 million m3/year is expected to increase to approximately 20,000 tons/year if Bigadan's expansion plans succeed. The accessibility and low cost of this CO2 source make it an attractive option for Power-to-X production. However, it has been considered that reductions in biomass use may impact its availability for Power-to-X production.

Table 4. Amount of CO2 from biogas available for use in Power-to-X production[22]

Source: Biogas	Quantity
Baseline in 2022	2,5-3 mio. M3/year = 4,700 - 5,600 tons/year *
Production in 2030	Ten mio. m3/year = app. 19.000 tons/year **

* Source: Bigadan. As conversion from m3 to tons is used 1,87 kg/m3 (15 °C, 1 atm.) ** The quantities in 2030 have yet to be discovered with certainty.

5.3.2. Heat Plants

There is limited CO2 production from heat plants, which presents two challenges. First, it follows a seasonal pattern, but also, they are scattered around the island (*See: Figure 9. Mapping resources available in Bornholm for Power-to-X production.*

Table 5. Amount of CO2 from Heat Plants available for use in Power-to-X production[22]

Source: Heat plants	Quantity 2022
Nexø Heat Plant	21.000 tons/Year
Hasle Heat Plant (woodchips)	18.000 tons/year

THE EUROPEAN UNION
The European Regional Development Fund
Funded as part of the Union's response to the COVID-19 pandemic
Investing in your future
Danish Board of Business Development

Aakirkeby Heat Plant (woodchips)	7.000 tons/year
Østerlars Heat Plant (straw)	6.500 tons/year
SUM	App. 50.000 tons/year

5.3.3. Central Heat and Powerplant (CHP) at Rønne Harbor

CO2 production from the CHP plant at Rønne Harbor emitted approximately 68,000 tons of CO2 in 2021, slightly exceeding the combined emissions of heat plants. The production is mainly linked to Rønne's heat demand and is completely halted for 6-8 weeks during the summer, resulting in relatively low quantities during that season. However, waste heat from Energy Island transformers and potential P2X production will significantly decrease the amount of available CO2 from Heat and Power plants. As a result, this is an unlikely reliable source in 2030.

5.3.4. Wastewater Treatment Plants (WWTP)

The sum of CO2 emissions from WWTP in the island is very low, less than 500 tons per year (See: *Figure 9. Mapping resources available in Bornholm for Power-to-X production.*) - so this source needs to be more significant.

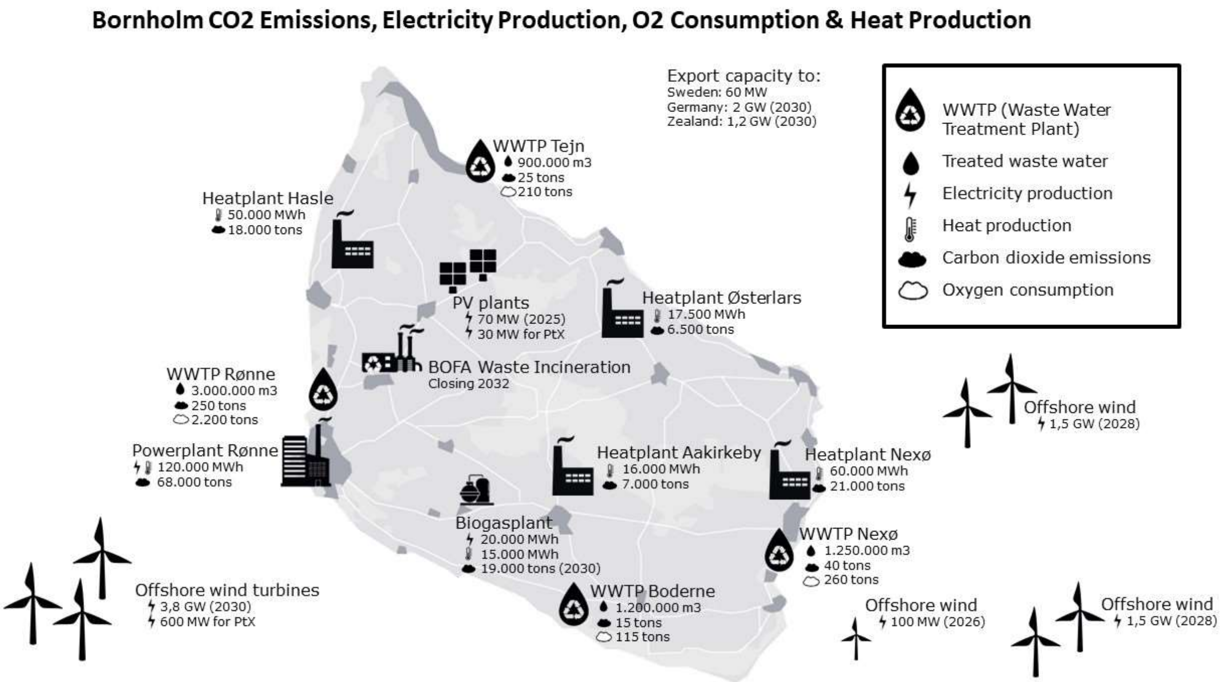


Figure 9. Mapping resources available in Bornholm for Power-to-X production.

6. MODELLING OF SCENARIOS FOR POWER-TO-X (WP2)

6.1. Methodology

This study outlines the technical requirements and specifications necessary for the successful implementation of PtX plants. It involves a detailed breakdown of infrastructure components, as well as technologies and tool required.

The study gathered input data from various sources and scientific literature. The techno-economic characteristics for different components of the PtX plants are presented in detail in WP2 - Modelling of scenarios for Power-to-X production in Bornholm, Table 15, and Table 16 and supplementary material in its Appendix.

Two main lines of investigation were followed, chosen as outcomes of the Scenario Selection Workshop. These scenarios were characterized by a by a set of combinations of various parameters, which are:

- Time Horizon
  The study chose the year 2030 as the timeframe to align with Denmark's greenhouse gas reduction goals and to allow for adequate planning. The techno-economic input data used in the model corresponds to predictions made for 2030.

- Power-to-X Plant Scale
  The large-scale investigation focused on a PtX plant around 600 MW, coming from overplanting in relation to the 2-3 GW offshore wind energy island, while the small-scale study aimed for local self-sufficiency using island carbon sources.

- Plant Configuration
  Both large-scale and small-scale scenarios operated under a behind-the-meter (BTM) power supply configuration, directly connected to renewable energy sources. This configuration was preferred due to economic stability and green fuel production.

- Power Supply Technologies
  Large-scale scenarios considered offshore wind turbines, while small-scale scenarios integrated solar photovoltaic (PV) and wind turbines for a more diverse power supply.

- Renewable Energy Profiles
  Profiles from wind and solar sources near Bornholm were utilized, spanning from 2016 to 2021.

- Electrolyser Technologies
  Different electrolyser configurations were explored for large-scale scenarios, including Alkaline Electrolyser Cells (AEC), Solid Oxide Electrolyser Cells (SOEC), and a mix of both. The system efficiency for AEC is in the range of 47-48%, 50-55% for the electrolyzer. The system efficiency for SOEC technology is 52-54%, with a 70-75% electrolyzer efficiency.
  .

- Fuel Produced
  Large-scale scenarios focused on producing hydrogen and ammonia, while small-scale scenarios aimed for methanol and biofuel production through pyrolysis and upgrading processes.

- Fuel Demand Type
  Annual fuel demand projections were made, with comparisons to Bornholm's energy consumption in different sectors. The large-scale PtX plant's energy production could meet the entire energy demand from the local industry, heavy transportation, and the ferry. It could also cover 5% of the energy requirement for vessels passing by the Baltic Sea.

- Sizing Method
  Two sizing methods, deterministic and stochastic, were employed for plant design. Deterministic used single-year weather data, while stochastic considered multiple years for diverse scenarios. This is very relevant as energy production can vary quite significant depending whether a year has much or little wind.

The specifics details of each scenario are shown in Table 6 (Source WP2 - Modelling of scenarios for Power-to-X production in Bornholm, Table 3)

Table 6. Parameters considered when designing the different relevant scenarios explored in the two main studies.

	Large-scale PtX plant investigation	Small-scale PtX plant investigation
Time horizon	Projections for 2030	Projections for 2030
Plant scale	Large-scale (0.5-1 GW)	Small-scale (10-100MW)
Plant configuration	Off-grid (behind-the-meter)	Off-grid (behind-the-meter)
Power supply technologies	Offshore wind only	Wind and solar energy
Renewable energy profiles	Weather data from 2016 to 2021	Weather data from 2016 to 2021
Electrolyzer technologies	AEC, SOEC and Mix (75%AEC-25%SOEC)	AEC and SOEC
Fuel produced	Hydrogen and ammonia	Methanol and biofuel
Demand profile type	Yearly demand	Yearly demand
Sizing method	Deterministic and stochastic	Deterministic

The various combinations of the parameters led to a collection of distinct situations. These unique scenarios underwent thorough analysis in both investigations. To illustrate, in the extensive PtX facility study, the model was executed with 36 deterministic iterations and 6 stochastic iterations. In the deterministic model, this count arises from utilizing data from 6 years of weather (2016 to 2021), 3 varieties of electrolysers (AEC, SOEC, Mix), and 2 categories of generated fuels (H2 and NH3). However, to concisely address the impact of weather fluctuations on plant sizing, only the results for the minimum (best year case), maximum (worst year case), and average (typical case) scenarios are presented in this chapter.

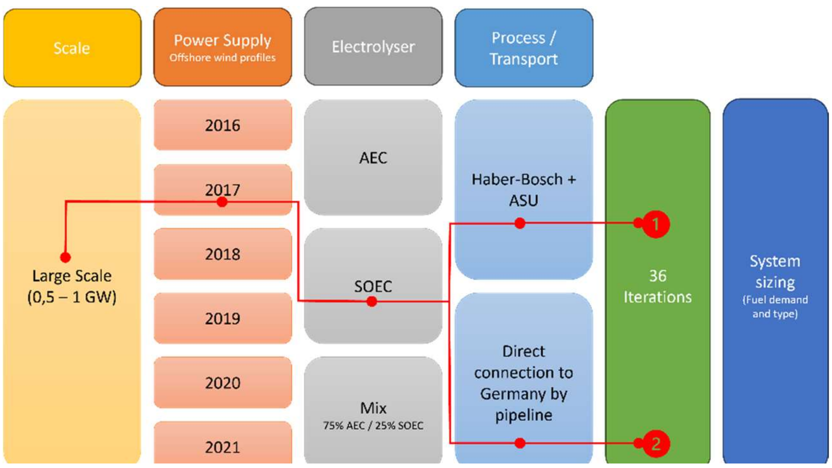


Figure 10. Example of iterations in the case of deterministic analysis for large scale.

The 6 stochastic situations originate from combining a single iteration of all the weather years (2016 to 2021), 3 types of electrolyzers (AEC, SOEC, Mix), and 2 categories of produced fuels (H2 and NH3). In addition to this, a cost estimation of hydrogen export to Germany via pipeline was done.

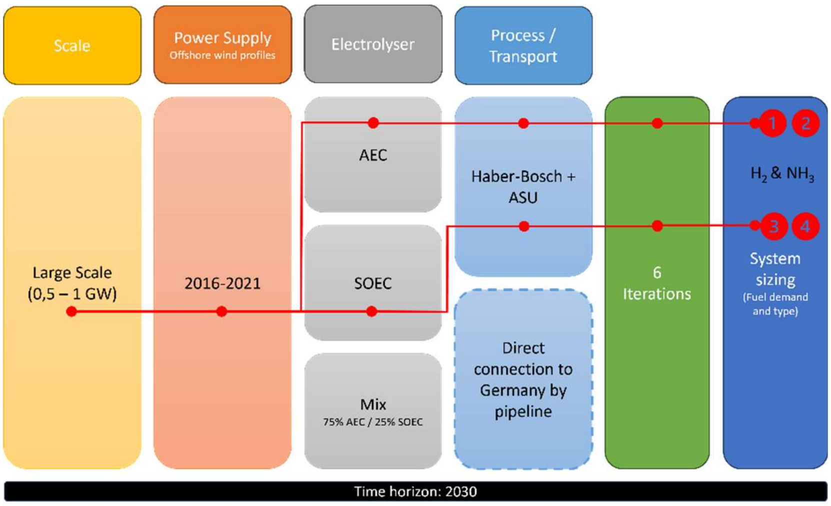


Figure 11. Example of scenarios in the case of stochastic analysis for large scale.

Regarding the investigation into the small-scale PtX plant, 8 iterations were run from a single year of weather (2018), 2 varieties of electrolyser (AEC, SOEC), 2 categories of generated fuels (Methanol and biofuel), and 2 types of limits on CO2 availability (local and, as well as combine local supply and import).

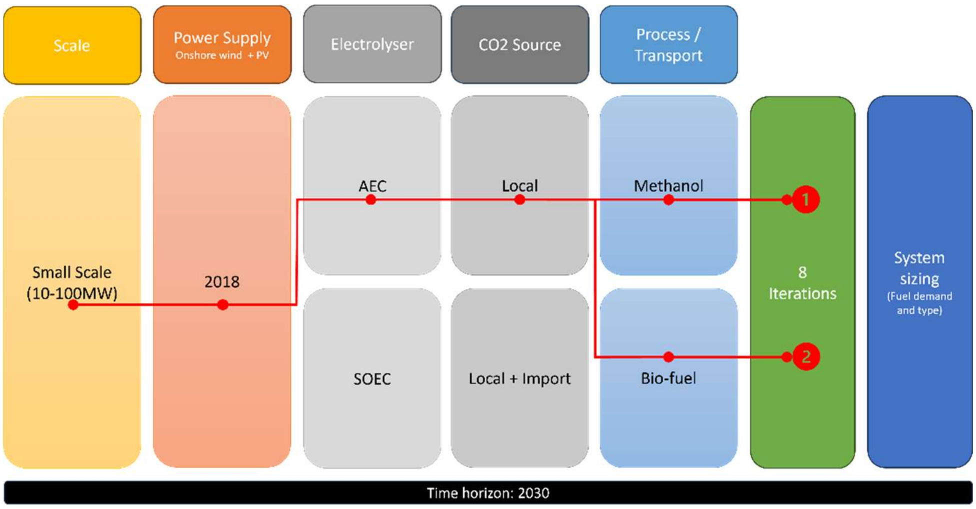
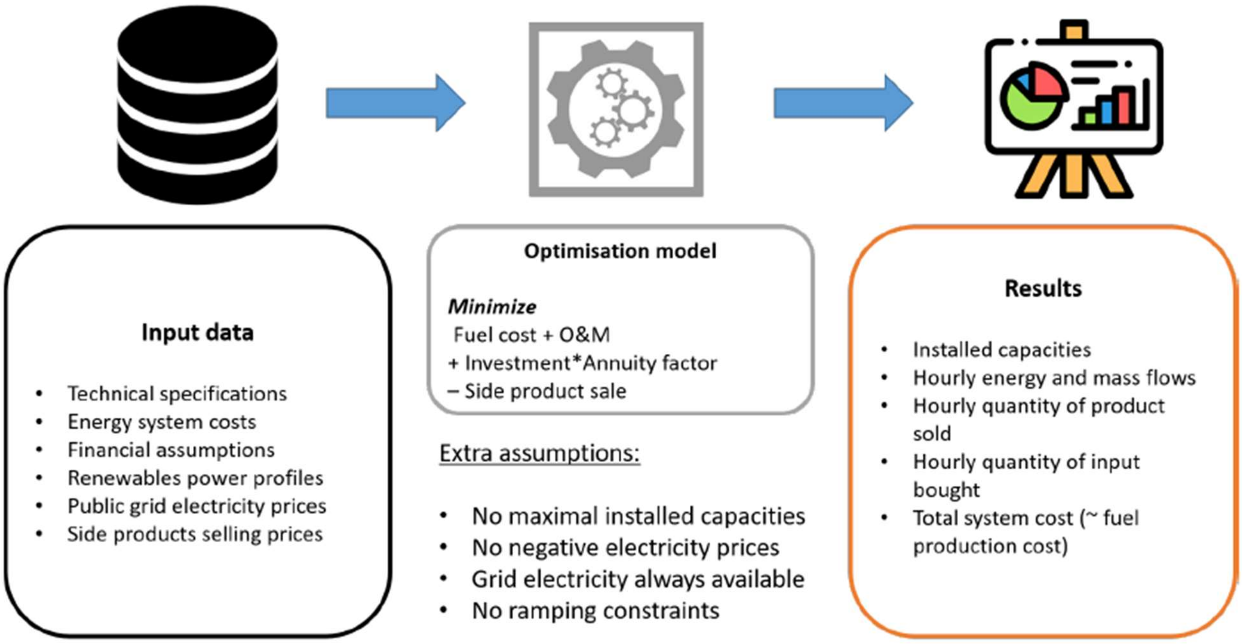


Figure 12. Example of iterations in the case of small scale.

6.2. Optimization model for Power-to-X plant

The fuel product systems were modelled and optimized using OptiPlant. OptiPlant is a tool initially developed by Nicolas Campion from the DTU Department of Technology, Management and Economics that enables the user to model Power-to-X fuel production systems with a high variety of customizable input parameters and to optimize them according to different criteria as detailed in the previous numeral.

The tool, in the standard version, models a Power-to-X plant using a linear deterministic programming model. Its purpose is to minimize the fuel production cost of a PtX plant by effectively managing the investments and operation of power-supply, storage, and fuel production units under certain constraints. The default model assumes perfect foresight (deterministic). However, the model can also incorporate stochastic elements to account for the variability and uncertainty in renewable energy profiles.



OptiPlant is an open-source and completely free tool. It is intended to be accessible to other researchers and include a User Guide, that facilitates the use of the tool by other researchers or interested parties. Refer to WP2 - Modelling of scenarios for Power-to-X production in Bornholm, Numeral 2.2 for further details.

6.3. Large-scale PtX plant study: hydrogen and ammonia

6.3.1. Deterministic analysis

The deterministic analysis examines how specific weather scenarios impact plant sizing. By considering a single year's weather data, three distinct scenarios—best-case, worst-case, and typical weather years—were selected.

These scenarios help uncover the influence of weather fluctuations on plant performance, allowing to determine the minimum (best-case), maximum (worst-case) and average (typical) plant size, as shown in Figure 14 and Figure 13, which represent the optimal sizing for PtX plants, using SOEC electrolyzer as modelled from 2017 weather data. The optimal sized for the cases 2018 and 2020 are found in WP2 - Modelling of scenarios for Power-to-X production in Bornholm, Table 4.

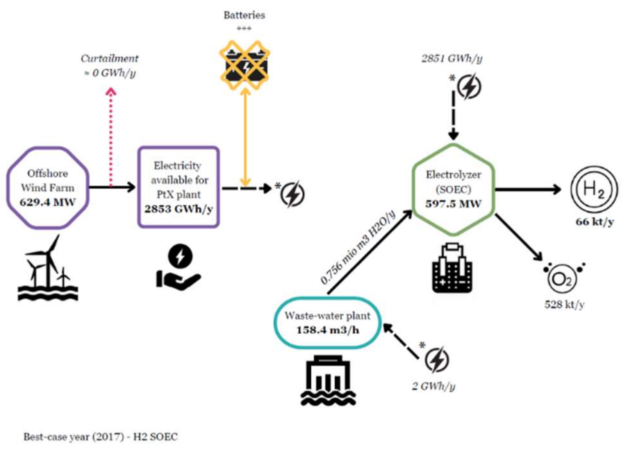


Figure 14. System diagram, for H2 SOEC, representing Best-case year (2017)-

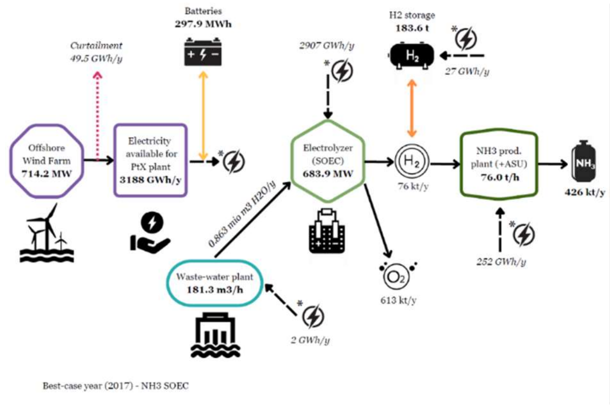


Figure 13. System diagram for NH3 SOEC, representing Best-case year (2017).

The most notable contributors to the overall costs of the PtX system are both the offshore wind farm (OWF) and the electrolyzers, pointing out to the main areas where to focus any effort at cost optimization.

An important point in the investigation was the comparison of costs for producing hydrogen and ammonia. This analysis revealed a significant difference, showing that hydrogen production is more cost-effective than ammonia production since the process involves complexities that lead to additional investment needs, especially for storage solutions like batteries and hydrogen pipelines.

In addition to this, the solid oxide electrolysis cell (SOEC) stood out as the best for producing both hydrogen and ammonia. This finding highlights the importance of making informed technological decisions to enhance the economic feasibility of PtX processes. See Figure 15. Comparative cost analysis for the scenarios of the best (2017), worst (2018) and average/typical weather year (2020).

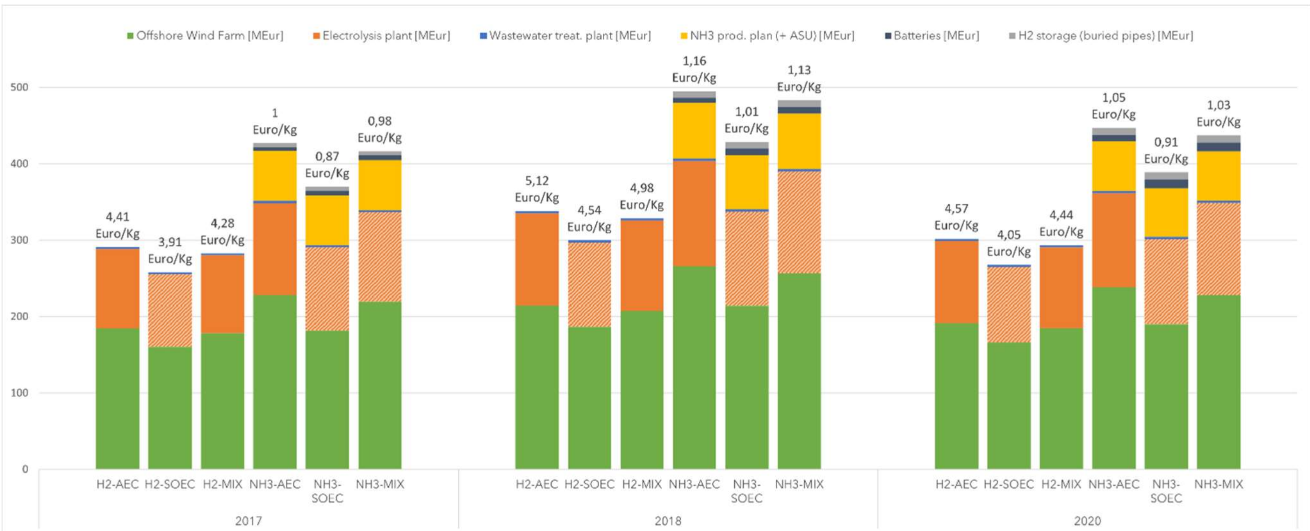


Figure 15. Comparative cost analysis for the scenarios of the best (2017), worst (2018) and average/typical weather year (2020).

6.3.2. Understanding Land and Water Resources – Stochastic approach

The impact of weather fluctuations on PtX plant costs emerged as the analysis discerned marked cost differentials between years characterized by favorable weather conditions and those characterized by adverse ones. This underlines the necessity of a stochastic analysis approach when determining plant size and capacity. Stochastic analysis, which factors in the inherent unpredictability of weather patterns over multiple years, offers a more resilient and adaptable framework for sizing PtX facilities.

Figure 16 presents the breakdown of total land use for different plant setups, including space for batteries and storage. While hydrogen producing systems require 20 to 30 Ha (variable in function of the electrolyser technology selected), ammonia systems evidently require more space. Ammonia plants require more equipment but also requires a safety distance, that needs to be evaluated under rigorous risk assessments.

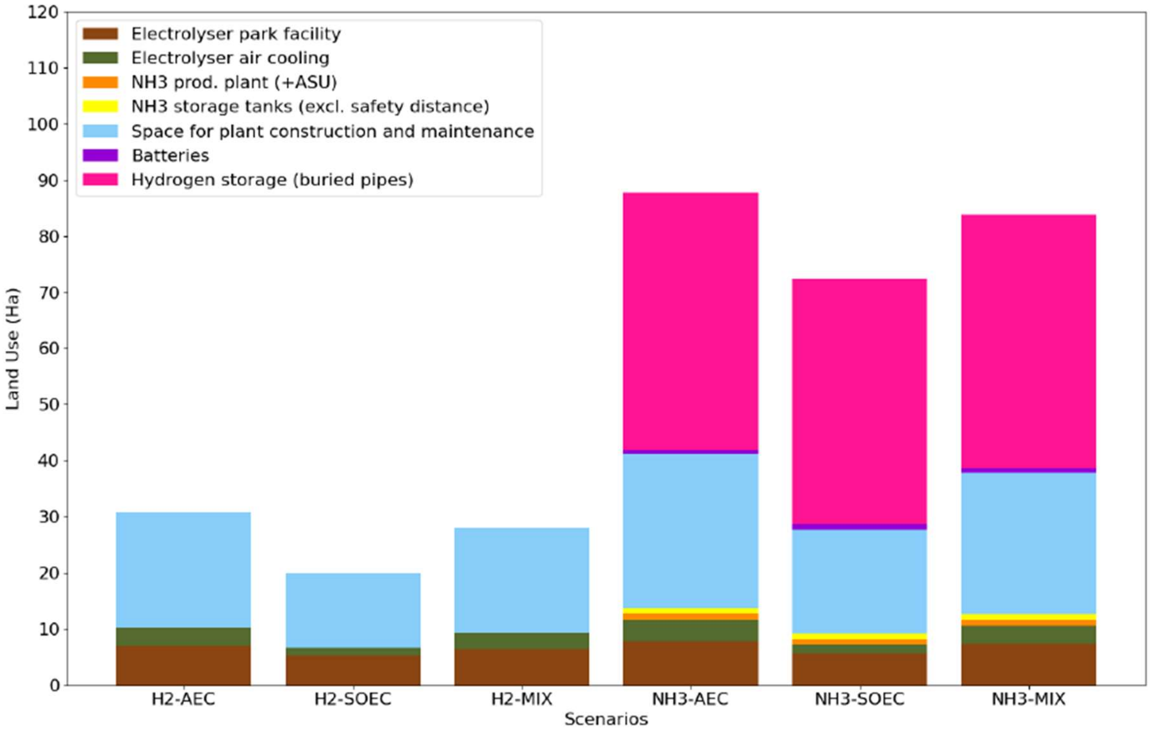


Figure 16. Breakdown of the total land use of the different PtX plant units.

Water availability is a critical concern among concerned stakeholders and for this reason it was a main focus point in the study. As result of WP2 iterations and supported by WP1 investigations, Rønne wastewater treatment plant emerged as a robust and reliable source of water to meet the Power-to-X plant's needs, consistently exceeding the maximum demand throughout the year.

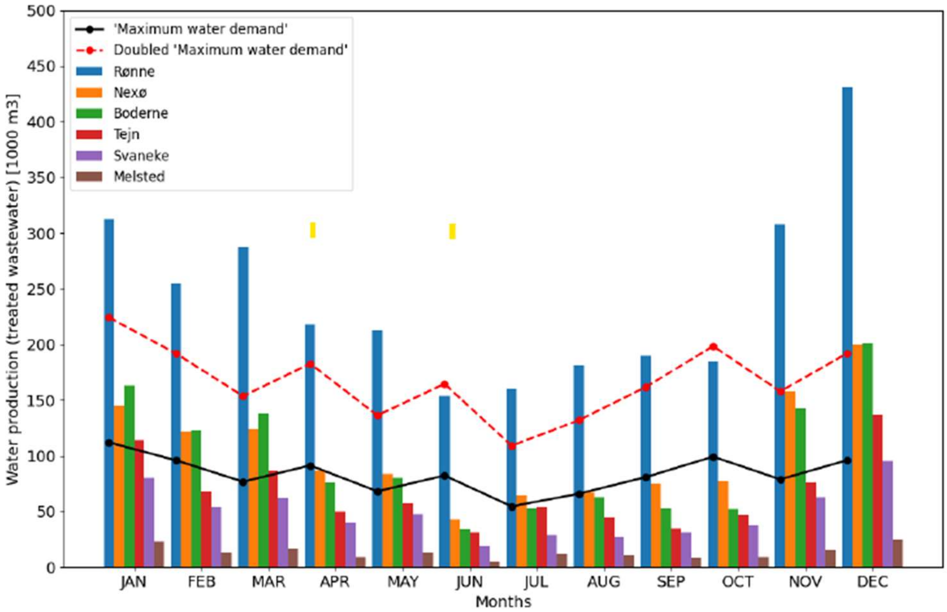


Figure 17. Monthly wastewater production from different treatment plants in Bornholm for 2021

The study modelled the consumption of water, and even when doubled the maximum amount of water required, the source can comply with demand most of the year. The exception for this would be June and October, where the shortage in the supply can be managed by careful planning for production and maintenance operations. (See Figure 17)

6.3.3. *Potential markets*

Assessing Export Potential

The investigation expanded its scope to consider the potential for exporting hydrogen to Germany, examining associated infrastructure and costs, which is a concept being explored already by several developers. As part of the collaboration between GASCADE and Copenhagen Infrastructure Partners (CIP)[27], a 140-km hydrogen pipeline connecting Bornholm to Lubmin, Germany, is set to be commissioned and begin operation in 2027. It will have an import capacity of 10GW, with plans to potentially extend it to 20GW.

The study examined the use of both newly constructed and repurposed existing natural gas pipelines for transporting hydrogen. The costs associated with capital expenditure (CAPEX) and operational expenditure (OPEX) for these pipelines are detailed in Table 7. According to the European Hydrogen Backbone (EHB) initiative, the estimated cost of transporting hydrogen through underground offshore pipelines is approximately 0.17-0.32 EUR/kgH2 per every 1000 km. However, these costs were not included in the model used in the study. If the intention is to export hydrogen, these additional costs should be added to the presented results.

Exploring Co-Products Revenue Generation

The investigation recognized the potential avenue of revenue generation through the sale of co-products resulting from the PtX plant processes, such as heat or oxygen. While acknowledging this prospect, the study refrained from incorporating co-product revenue into the cost analysis. This cautious approach was rooted in the complexities surrounding market dynamics, demand considerations, and the uncertain pricing of these co-products.

Table 7. CAPEX and OPEX for large offshore hydrogen pipelines

	CAPEX [MEUR/km]			OPEX[1] [EUR/year]		
	Low	Medium	High	Low	Medium	High
New H2 pipeline	4.3	4.8	5.8	0.8	0.9	1.0
Repurposed H2 pipeline	0.4	0.5	0.6	0.8	0.9	1.0

[1] Considered as a percentage of the CAPEX.

6.4. Small-scale PtX plant supplementary study: methanol and biofuel production

This research aimed to provide additional insights to a larger study by focusing on the feasibility and potential impacts of producing small amounts of methanol and biofuel on Bornholm. The study considered Bornholm's unique characteristics and examined various scenarios to determine the most efficient and cost-effective ways to produce these fuels, as well as how they could integrate into the local energy market.

The smaller plant evaluation helps us comprehend Bornholm's renewable energy potential. As mentioned previously, eight different iterations were considered, encompassing different weather conditions, two types of electrolyser technology, two types of produced fuels, and two methods of obtaining carbon dioxide (CO2) for the production process.

These approaches were differentiated by the availability of CO2. In the first case, the availability of CO2 was limited to the amount locally produced in Bornholm (20kton CO2/year), resulting in fuel demands of 13.3 kton/y of methanol and 7.9 Kton/y of biofuel. This production could supply 31% of the fuel demand of Bornholm's ferry company. The second case allowed for the possibility of importing additional CO2 from abroad, resulting in a fuel demand that was 125 kton/y of methanol and 75 kton/y of biofuel (approx. 10 times greater than the first approach), as seen in Figure 18.

The investigation reveals that when using standard cost analysis, there are minor disparities in the production costs between methanol and upgraded pyrolysis bio-oil, with methanol being slightly more cost-effective per e/MWh. Nevertheless, when factoring in the sale of co-products from pyrolysis, the contrast in production costs for these fuels becomes substantial, with upgraded pyrolysis biofuel emerging as significantly more economical thanks to the substantial revenue generated from selling biochar (Figure 19).

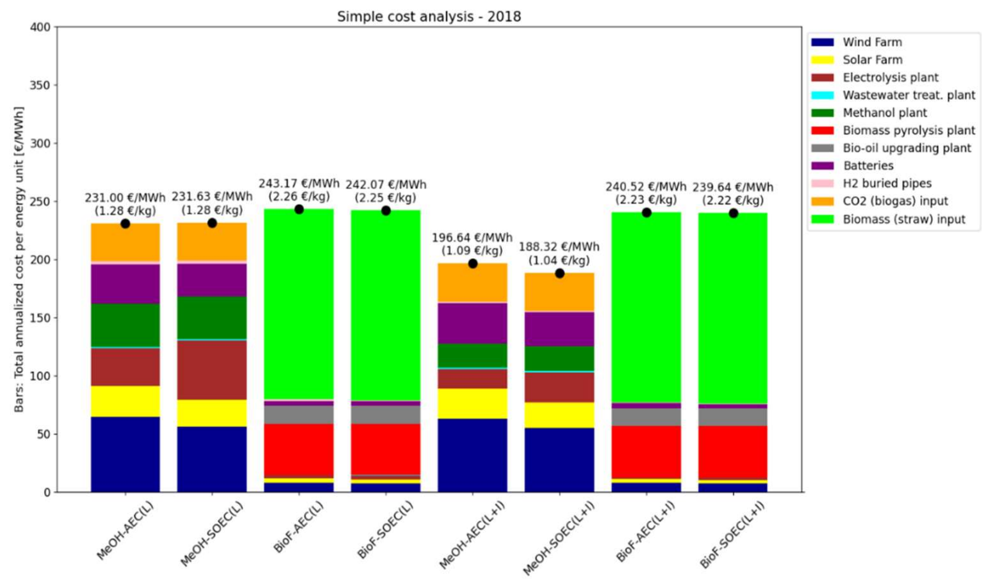


Figure 18. Comparative cost analysis for the scenarios for the year 2018. Small scale case.

In contrast to findings observed in studies conducted on larger industrial installations, the selection of electrolyser technology appears to exert a limited influence on the total system cost within the confines of this smaller-scale scenario. This outcome may be attributed to the reduced physical dimensions of the facility, thereby mitigating the magnitude of technological choice's impact on cost considerations.

The research indicates that economies of scale do not have a significant impact on the production of upgraded pyrolysis oil. However, when the size of the plant for methanol LCOF is increased nine-fold, there is a noticeable 15-19% reduction in price across different electrolyzer technologies. Therefore, it becomes intriguing to explore the potential cost reduction benefits of larger-scale facilities for the methanol pathway.

Considering involving methanol production incorporating a combination of domestically sourced and imported CO2, the primary drivers of the system expenditure encompass the wind farm, energy storage batteries, and the CO2 input. In contrast, across all instances of biofuel scenarios, the predominant costs emanate from the biomass input (straw) and the pyrolysis facility. This discernment imparts valuable insights conducive to devising potential strategies for the optimization of costs.

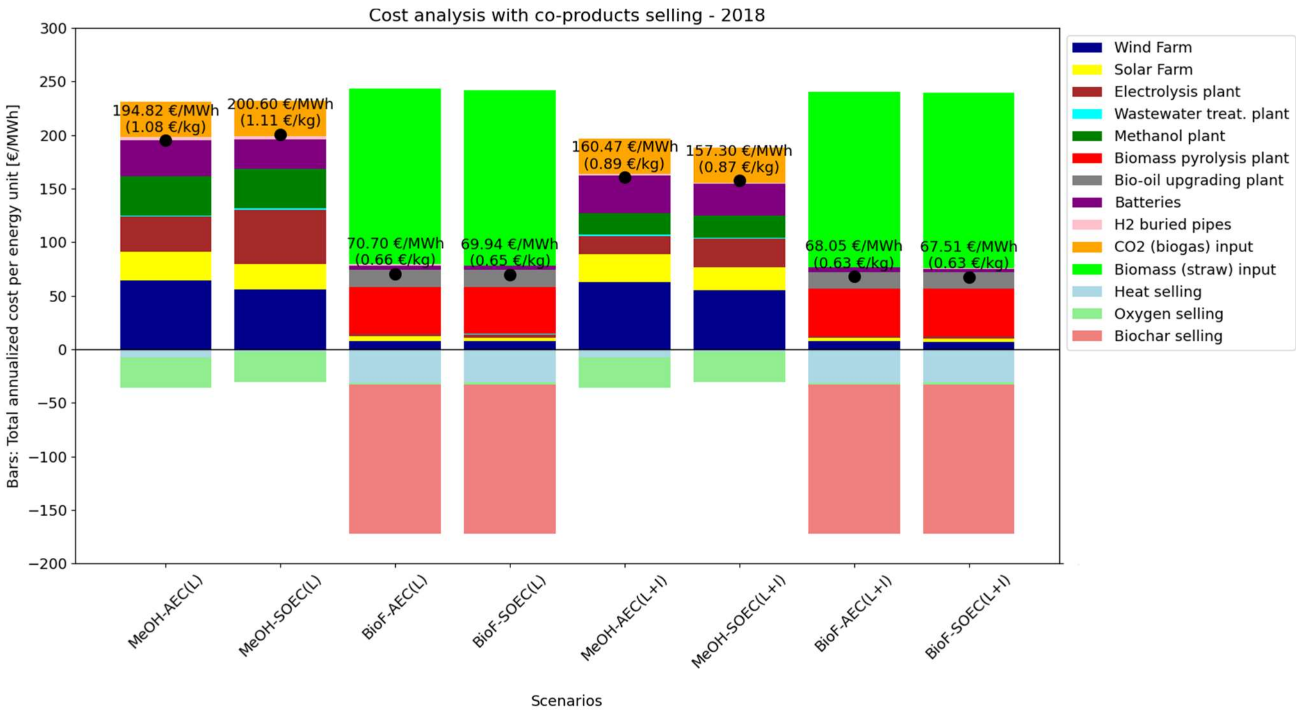


Figure 19. Small case, co-product selling.

7. MARKET FOR PRODUCTS (WP3)

The market investigation delves into the potential landscape and opportunities surrounding the Power-to-X sector in Bornholm. By analyzing various sectors, fuel consumption patterns, and emerging trends, this investigation aims to provide valuable insights into the evolving energy market. The investigation considers the needs of local industry, heavy transportation, maritime traffic, and the broader market for green fuels like ammonia, hydrogen, and methanol. Through a comprehensive analysis of consumption trends, policy dynamics, and technological advancements, this investigation highlights the prospects for a sustainable and vibrant Power-to-X market on Bornholm.

7.1. Identifying Potential Offtake Markets for e-Fuels

There are four potential offtake markets for e-fuels: local industry, local heavy transportation, ship traffic to and from Bornholm, and ships passing by and served in Port of Rønne.

7.1.1. Industry.

Bornholm's local industry, including Danish Crown, Bornholms Andelsmejeri, and others, consumes approximately 18.465 MWh of process energy annually, producing 4,435 tons of CO_2e emissions. The government's emission reduction goals aim to decrease this by 95% in 2030 compared to 1990. As per estimates, energy consumption may reduce by up to 50% due to efficiency gains and electrification, but the remaining is expected to be the result of converting to either biogas or hydrogen.

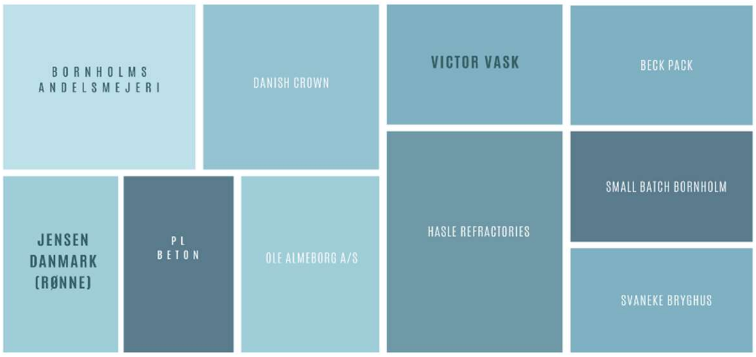


Figure 20. Main users of process energy on Bornholm.

However, this transition requires changes in the technical infrastructure, leading companies to evaluate the most viable solution for their individual needs. Implementing a CO_2e tax on industries not covered by the EU Emission Trading System will result in additional costs for LPG users, which further incentivize the change.

7.1.2. Heavy Transportation

The island's transportation sector, comprising vans, trucks, buses, and farming machinery, consumes a substantial 155,000 MWh of energy annually, mainly relying on diesel fuel.

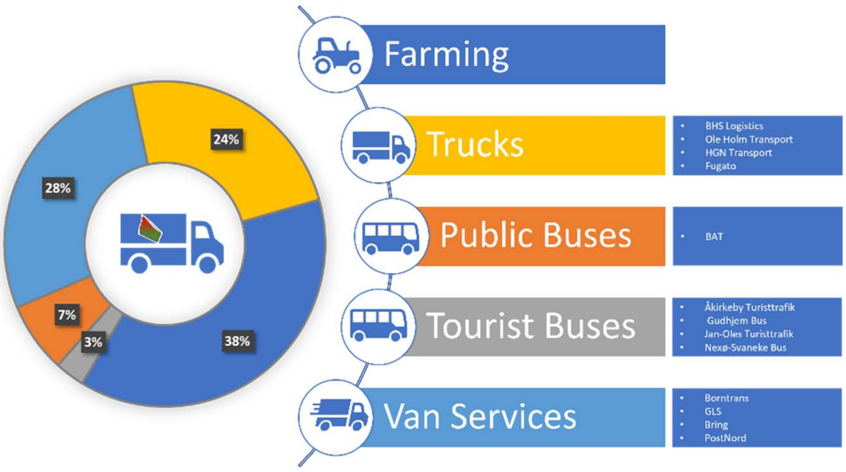


Figure 21. Bornholm Heavy Transportation Segmentation

It is expected that the green transition will be a combination of green fuels and electrification, since trucks, farming vehicles and tourist buses driving patterns and operational needs will not necessarily align well with direct electric vehicles. It is estimated that half of these can be electrified, the other half will be dependent on green fuels. Hence Nearly 33% of the market is likely to demand green fuels, amounting to approximately 50,000 MWh of energy or 5,000 m3 of diesel equivalent (**Error! Reference source not found.**).

7.1.3. Ship Traffic to and from Bornholm

The current ship traffic to and from Bornholm has been traditionally dominated by the ferry operator. Recently, Port of Rønne has worked as an installation port for wind park projects in the Baltic. From the ferry perspective, the market driver for transition is being pushed by the fact that ferry services will likely be required to be emission free from 2030, as the ferry service is community-based and partly paid by the Danish Government. Wind Park owners will have a similar requirement, for example Ørsted intends to have their supply chain to be CO2-neutral by 2040 and RWE also aims for a 30% reduction in the supply chain by 2030[28].

7.1.4. Bornholm Bunker Hub & Traffic around Bornholm

Port of Roenne have launched the project Bornholm Bunker Hub in cooperation with Ramboll, Ørsted, Topsoe, Bunker Holding, Molslinjen, Wärtsilä and Bureau Veritas in spring 2021. The project's primary aim is to supply green fuels to vessels passing by Bornholm each year and to cater to the local ferry service's green fuel requirements. This maritime traffic shapes the potential target market for the Bornholm Bunker Hub, offering insights into the potential fuel demand that a local Power-to-X plant could meet.

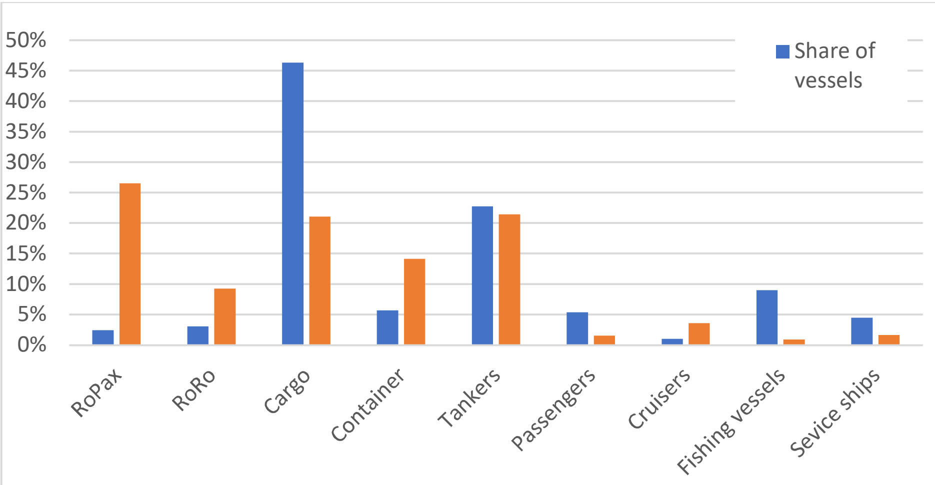


Figure 22. Distribution of fuel consumption and number of vessels by segment.

According to estimates from Helcom[29], energy-intensive segments, including RoPax, RoRo, Cargo, Container, and Tankers, collectively account for a significant consumption of 4,360,000 tons of fuel for sailing in the Baltic Sea, equivalent to approximately 43,600 GWh of energy (**Error! Reference source not found.**).

In terms of geographical divisions, the Baltic Sea can be segmented into distinct areas defined by crossing lines (refer to *Figure 23. Different crossing lines and geographic areas in the Baltic Sea.*). Upon closer examination of how vessel segments are distributed across these crossing lines, it becomes evident that Cargo, Container, and Tanker ships are predominant in the waters around Bornholm. Conversely, the presence of Passenger/RoPax and RoRo segments remains comparatively limited (see Figure 24. Distribution of segments on crossing lines in the Baltic Sea around Bornholm.).

Figure 23. Different crossing lines and geographic areas in the Baltic Sea.

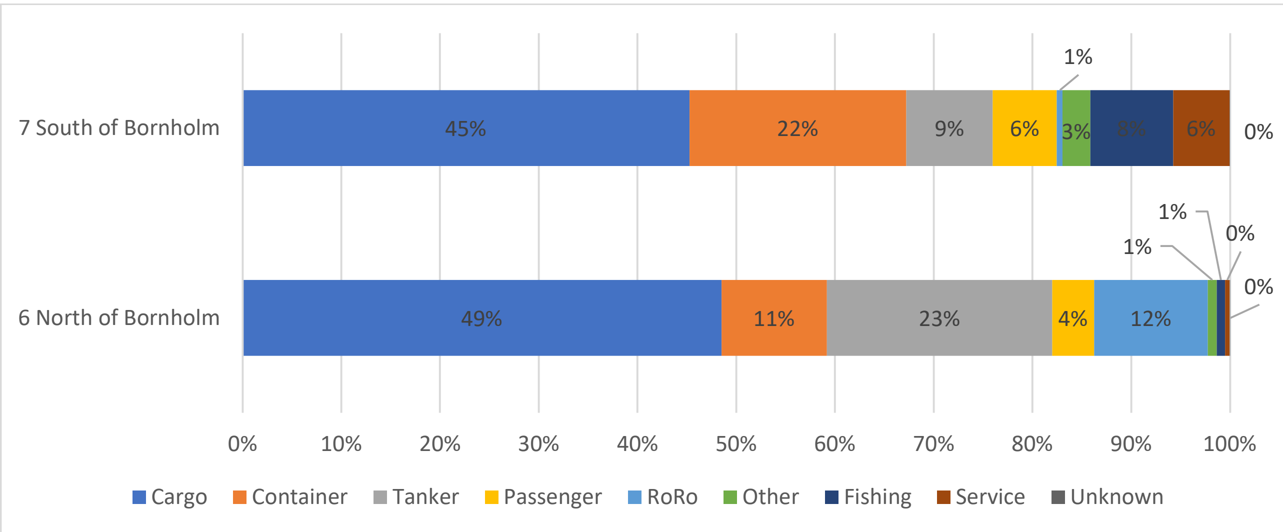


Figure 24. Distribution of segments on crossing lines in the Baltic Sea around Bornholm.

The maritime traffic around Skagen comprises an estimated 60,000 vessels per year. Among these, approximately 3,500 vessels make stops to refuel, collectively consuming around 1,000,000 tons of fuel within Denmark. Similarly, a comparable number of ships pass in proximity to Bornholm annually. The Bornholm Bunker Hub envisions that if just 0.1% of these vessels choose to refuel with green fuels from the hub by 2030, this would translate to approximately 60 vessels bunkering about 17,100 tons of fuel[28].

While this figure might appear remarkably high, the force behind this potential market surge is the Fuel EU Maritime directive, which mandates a minimum adoption of 1% RFNBOs (Renewable Fuels of Non-Biological Origin) by 2030. Looking ahead to 2040, there's a formidable target of reducing CO2e emissions by 38%, a notable escalation from the 6% target set for 2030. This perspective makes it reasonable to anticipate that RFNBO consumption will at least double by 2040. Consequently, the projected Bornholm Bunker Hub could potentially supply 34,000 tons of fuel in 2040, thus establishing a flourishing market for locally produced e-fuels generated through Power-to-X technology.

7.1.5. Bornholm Potential Market

The findings of the potential market in and out of Bornholm can be summarized in the table shown in Figure 25

	Local Industry	Local Heavy Transportation	Marine Traffic (From/To Bornholm)	Marine Traffic (Passing / Servicing)
Market Status	**Primary fuel used**: LPG (12,78 MWh/ton) **Yearly Consumption** 18.465 MWh **CO2e emissions** 2.900 Kg CO^2 /ton LPG	**Primary fuel used**: Diesel **Yearly Consumption** 155.000 MWh (15.500m^3) **CO2e emissions** 41.540 Kg. CO^2	**Primary fuel used**: MGO **Yearly Consumption** Ferry: 29.000-ton MGO 1 GW WF project (est.): 1700-ton MGO **CO2e emissions** 3,2 ton CO2e / ton MGO	**Primary fuel used:** MGO **Yearly Consumption - potential** 17.100-ton MGO assuming 1% of passing traffic bunkering locally. **CO2e emissions** 3,2 ton CO2e / ton MGO
Drivers for change	• Decarbonization efforts. • Government partnerships for emissions. • Need to comply with CO^2e taxation.	• Decarbonization efforts. • ETS will include road transportation from 2027 • Liable for CO2e taxes	• Decarbonization efforts. • EU Emissions Trading System (EU ETS) • Fuel EU Maritime Directive	• Decarbonization efforts. • EU Emissions Trading System (EU ETS) • Fuel EU Maritime Directive
Green Replacement	• Biogas or Hydrogen • Efficiency gains, electrification	• Biogas or Hydrogen • Electrification	• E-Methanol or e-Ammonia • Size and type of ferries servicing Bornholm they will likely not be fit for direct electrification	• E-Methanol or e-Ammonia
Challenges	• Changes to infrastructure, including storage and transport • Stable Supply • Establishing a new business case for the most viable solution. • Cost -effectiveness	• Infrastructure requirements • Technical modifications to engines or fleets • Stable supply of e-fuels • Cost -effectiveness	• Safety concerns for Ammonia as a fuel. • Technical modifications required. • Stable supply chain	• Reliable and cost-effective supply chain • Acceptance / agreement from shipping industry • Complex maritime regulatory landscape
Keys for success	• Moderate to high. • Government's plans and CO2e taxes incentivizes companies • However, individual company assessments, logistical challenges, and cost considerations may influence the speed of adoption.	• Medium to High • Inclusion of road transportation in the ETS likely to drive adoption of green fuels. • Cost advantages of green fuels over time will encourage adoption in heavy transportation. • Development of necessary infrastructure and fuel supply chain may take time.	• Moderate. • Willingness of the shipping industry to adopt green fuels. • Safety considerations and technical challenges may slow down the transition.. • Willingness of the shipping industry to adopt green fuels.	• Moderate. • Willingness of the shipping industry to adopt green fuels. • Safety considerations and technical challenges may slow down the transition.. • Willingness of the shipping industry to adopt green fuels.
Economy	• LPG Price: 9700 DKK/ton • Estimated CO2 tax (2030): 2.175 DKK (750 DKK / Ton) • LPG Displace price: 929 DKK / MWh	• Estimated CO2 tax (2023): 0,44 DKK / l • Estimated CO2 tax (2030): 2,99 DKK/l • Diesel Displace price: 795 DKK / MWh	• Estimated CO2 tax ~2.400 DKK/ton MGO with additional 375 DKK/ton CO2e for vessels sailing in Danish waters • MGO Displace price: 804 DKK / MWh	• Estimated CO2 tax ~2.400 DKK/ton MGO with additional 375 DKK/ton CO2e for vessels sailing in Danish waters • • MGO Displace price: 804 DKK / MWh

Figure 25. Overview of Bornholm Energy market.

7.2. Exploring Opportunities and Overcoming Challenges

The political stage is set and Bornholm's trajectory towards sustainability is fact. The alternatives to the current energy consumption can be summarized as interplay of hydrogen, ammonia, and methanol. These zero-carbon fuels present a landscape of challenges, safety considerations, infrastructure evolution, and economic analyses.

7.2.1. Hydrogen

The anticipated demand within the local industrial market is calculated to amount to half of 18,465 MWh. This energy need could be met by approximately 282 tons of hydrogen. The production of hydrogen in Bornholm is expected to be a small part of the overall European demand, therefore any considerations for export will be driven by hydrogen price but not by volume exported.

7.2.2. Ammonia

-

Looking at the possible market for ammonia out of Port of Roenne in 2030 it could be 40% of the potential 17.000 tons, which could be delivered to vessels passing by, hence 6.800 tons. The market for vessels visiting the port is less likely as the ferry will be a late adapter to ammonia as fuel and the majority of the market is related to the ferry operation. Besides this there is a potential global market for green ammonia, which can be used both for fertilizer production as well as energy carrier.

Ammonia is a toxic chemical and even though there are many initiatives investigating safe handling, re-design of engines and vessels, progress has been made in cargo vessels. Implementation of ammonia as fuel for shipping is more challenging than methanol but it is forecasted to slightly overtake methanol towards 2040[30].

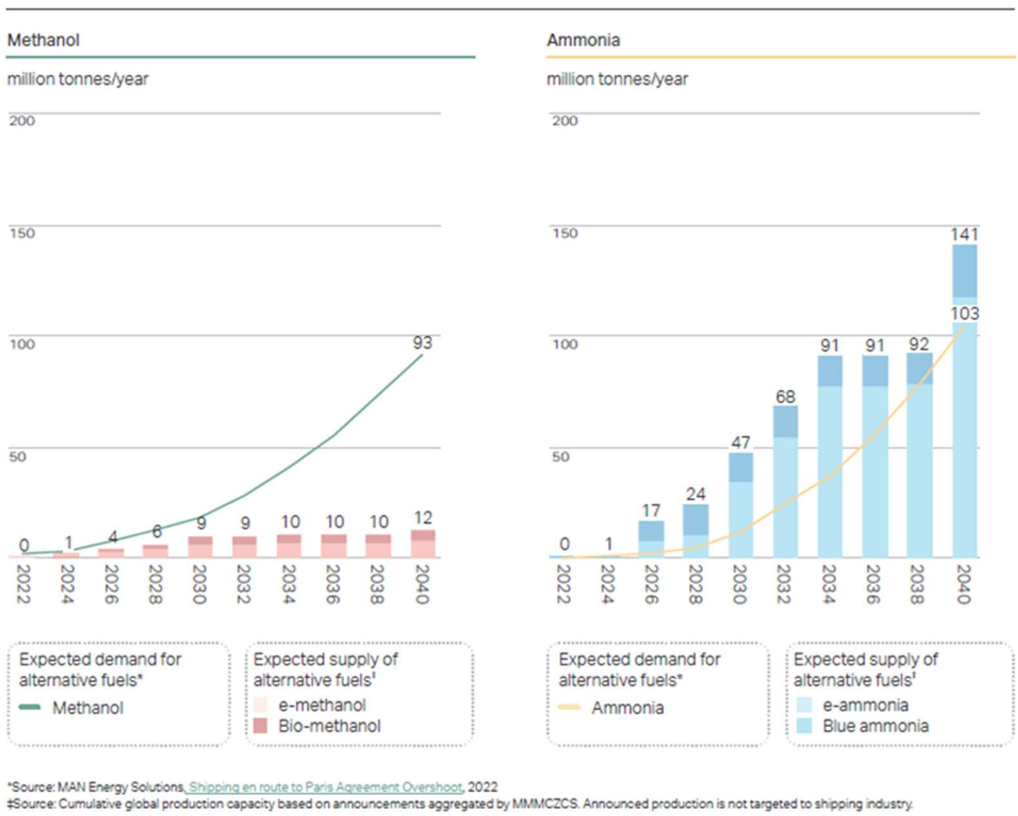


Figure 26. Projected demands for methanol and ammonia as fuel for the shipping industry.

7.2.3. Methanol

As noted in the Ammonia market, the projected consumption patterns for methanol and ammonia as maritime fuels indicate a comparable market share for the years 2030 and 2040. Methanol consumption is expected to surpass that of ammonia due to its faster and easier implementation.[30, 31]

The ferry operations to and from Bornholm currently rely on approximately 29,000 tons of Marine Gas Oil (MGO) annually, suggesting the potential for a transition to methanol as a fuel source starting from 2030. However, it is important to consider that methanol has a lower energy density compared to MGO[28]. To fulfil the same energy demand, an approximate equivalence of 62,000 tons of methanol could be required.

Furthermore, the offshore wind installation operation originating from the Port of Roenne shows promise as a potential consumer of methanol. The increasing orientation of the offshore installation sector towards methanol is evident through a notable influx of orders for installation vessels and Service Operation Vessels (SOVs). Drawing from the port experience, the realization of a 1 GW offshore installation initiative could necessitate a consumption volume ranging from 1,100 to 1,700 tons of MGO, or alternatively, 2,360 to 3,650 tons of methanol[28].

Considering the planned expansion of the Port of Roenne and the concurrent proliferation of offshore wind projects, an annual installation capacity of 1.5 GW is envisioned to be established. This would catalyze an augmented demand for methanol amounting to 3,540 to 5,475 tons, primarily starting from the year 2040[28.]

Overall, the use of methanol and ammonia as fuels for ships has the potential to substitute 25 million tons of oil, which is approximately 10% of the world fleet's energy[31]. Methanol is gaining prominence as a marine fuel due to its availability, potential for decarbonization and safer handling. However, it is important to note that other carbon-neutral fuels, such as bio-MGO, bio-LNG, e-ammonia, blue ammonia, and bio-methanol, are expected to dominate the energy mix in 2050[32]

7.3. Alternative revenue sources

As result of the processes associated with PtX, there are sizable amounts of bi-products, namely Oxygen and Waste Heat that can be incorporated, improving the circular economy applicability of the project.

7.3.1. Oxygen

Oxygen is transported to the Island by ferry in tank lorries (or gas cylinders) and filled into local tanks placed at the consumer sites, which are mostly:

In the industrial sector, companies like the Jensen group and Almeborg, among the Island's major employers, utilize oxygen for their metal construction and machinery production. Nevertheless, the oxygen consumption estimate remains minimal, accounting for less than 1 ton of O2 per year.

Within the medical domain, the primary oxygen consumer is the local Hospital, which consumed around 3.5 tons of O2 in 2022 at an approximate cost of 10 €/kg (information received through direct communication with Bornholms Hospital).

Apart from the existing consumers in industry and healthcare, there are additional sectors on Bornholm that could become potential consumers of oxygen. Wastewater Treatment Plants (WWTPs)[20, 22]20 stand out as a substantial opportunity. These plants demand a significant amount of oxygen for efficient wastewater purification. By replacing atmospheric air with pure oxygen, WWTPs can drastically reduce their electricity consumption, which accounts for the majority of their operational costs. The potential savings in electricity costs, as demonstrated by the Rønne WWTP case, can incentivize WWTPs to invest in oxygen-based systems, benefiting both the environment and their financial bottom line.

Drinking Water plants / Water Works[21, 22] also present a potential market for oxygen. Oxygenation is essential in the treatment of groundwater to produce safe drinking water. Using oxygen instead of atmospheric air can lead to improved water quality and hygiene, which is particularly important for public health. While the oxygen demand for drinking water treatment is lower compared to WWTPs, the cumulative demand across Bornholm's multiple water facilities can still create a notable market for oxygen.

7.3.2. *Waste heat*[33]

Waste heat generated by PtX plants holds promise for revolutionizing the energy landscape on Bornholm. There are two main possibilities of application, either in district heating systems or new and innovative industries. Through this the island can achieve economic growth, environmental sustainability, and enhanced local identity.

- Applicability
  In terms of existing industries, the potential to use waste heat is limited due to their higher temperature requirements. However, there are local opportunities in new industries that can leverage lower temperature waste heat effectively, which include:
  - Algae Cultivation: Waste heat can be used for drying algae, which can serve as a protein source for humans or livestock, or as raw material for other industries.
  - Thermal Desalination: Waste heat-driven desalination processes can be employed to produce water for hydrogen production. This has the potential to significantly benefit PtX industries by reducing water use and costs.
  - The Paleo Dome: Establishing a simulated ancient climate dome for tourism and education purposes, utilizing waste heat to recreate past climatic conditions.
  - Low-Temperature Direct Air Capture (DAC): This emerging technology uses low-temperature waste heat to capture CO2, contributing to environmental efforts and potentially supporting PtX industries' carbon needs.
  - Greenhouse Farming: Niche greenhouse farming, particularly for specialized products like medical plants, can be developed using excess heat, providing a competitive advantage.
  - Wastewater Treatment: Waste heat can improve wastewater treatment processes, leading to enhanced purification while also synergizing with PtX facilities' carbon utilization.

- Cost Considerations:
  To utilize waste heat effectively, investments in transmission lines, heat pumps, and storage facilities are required. The price for excess heat delivered to district heating systems is regulated by the Heat Supply Act[33]. This ensures a balance between reasonable pricing and protection for heat consumers. Contractual agreements must align with regulatory price caps and substitution prices, creating a framework for collaboration between district heating companies and PtX facilities.

7.3.3. *Grid services / off-grid power off-take service to the energy island*

The original power setup consider in the project uses the concept of "behind-the-meter-power," which establishes a direct link between power generation and Power-to-X facilities. But it is possible to connect the plan to the local grid.

This integration could enable a PtX plant to offer valuable grid services, including rapid response capabilities for balancing supply and demand. Such integration aligns with the goals of Denmark's national Power-to-X strategy, emphasizing the seamless integration of these technologies into the existing energy infrastructure.

From an economic standpoint, there are promising outcomes for Energy Island Bornholm resulting from the establishment of Power-to-X production. Specifically, the analysis indicates positive socio-economic impacts associated with the adoption of Power-to-X production. Moreover, these benefits appear to be slightly more pronounced when the Power-to-X facility is situated in close proximity to the transformer facility on Bornholm, as opposed to being located elsewhere in Denmark.

The study also identifies a potential market for ancillary services within the Danish energy landscape. These services encompass the provision of 623 MW/hour of mandatory Frequency Restoration Reserve (mFRR) and 90 MW/hour of automatic Frequency Restoration Reserve (aFRR) services by 2030. Power-to-X production facilities are suitably positioned to fulfil these services, which play a critical role in maintaining grid stability.

The introduction of Power-to-X production is anticipated to yield significant cost reductions associated with activating these ancillary services.

In terms of economic viability, the calculations are based on an LCOE value of 58.6 €/MWh for offshore wind. Furthermore, future projections for power prices are taken into consideration. These projections suggest that there will be approximately 3000 hours per year when the spot market power prices exceed 50 €/MWh. This implies potential profitability for Power-to-X production during these hours. However, caution is advised due to the volatile nature of power price trends, exemplified by unexpected developments in 2022 that caught the industry off guard. Therefore, any decisions and plans related to Power-to-X production based on these projections should be carefully evaluated and adjusted as market conditions evolve.

7.4. Regulatory and policy landscape

The regulatory and policy landscape has a significant impact on the Power-to-X market on Bornholm. Here are the key factors that influence the market:

- Government Initiatives: Government initiatives, such as CO2 taxes and emission reduction targets, drive the transition towards green fuels. These initiatives aim to reduce carbon emissions and incentivize the adoption of low-carbon alternatives[1].
- EU Emission Trading System (ETS): The inclusion of shipping, road transportation and buildings in the EU Emission Trading System and the establishment of carbon pricing mechanisms impact fuel prices. This incentivizes the adoption of low-carbon alternatives by making them more economically viable[34].
- Fuel EU Maritime Directive: The shipping industry is required to use a minimum of 1% Renewable Fuels of Non-Biological Origin (RFNBOs) by 2030, according to the Fuel EU Maritime directive. By 2040, CO2e emissions will have to be reduced by 38%[35]. While the reduction can be achieved through various means, it is reasonable to expect that the use of RFNBOs will at least double by 2040.

As the market evolves, policymakers play a critical role in shaping the framework for sustainable energy solutions. Their decisions and regulations have a direct impact on the development and growth of the Power-to-X market on Bornholm.

8. INTEGRATION INTO ENERGY SYSTEMS (WP4)

A 1 GW electrolyser refers to an electrolysis system with a capacity to produce 1 GW of hydrogen. In the context of the Energy Island Bornholm project, the 1 GW electrolyser would be a key part of the infrastructure, hence, a portfolio of this capacity was investigated to analyze the integration of a Power-to-X plant into the energy system.

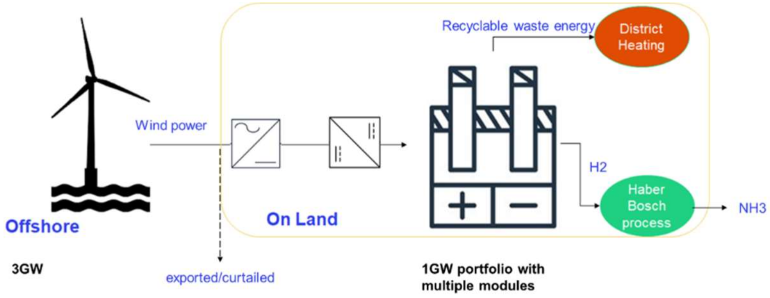


Figure 27. System model

The analysis initiated collecting actual wind data and modelling a 3GW wind power input into 1 GW electrolyzer portfolio. Then hydrogen production was calculated in different technical setups and operation strategies for the electrolyzer portfolio, followed by an estimation of the quantities of ammonia and waste heat generated by the different models of setup and operation strategies.

8.1. Datasets

8.1.1. Wind Power Data 3 GW

The wind power dataset is based on real 2021 data, aligned with hourly wind data used in WP2. The dataset was modelled to obtain 10min data resolution and calibrated with actual offshore wind turbines.

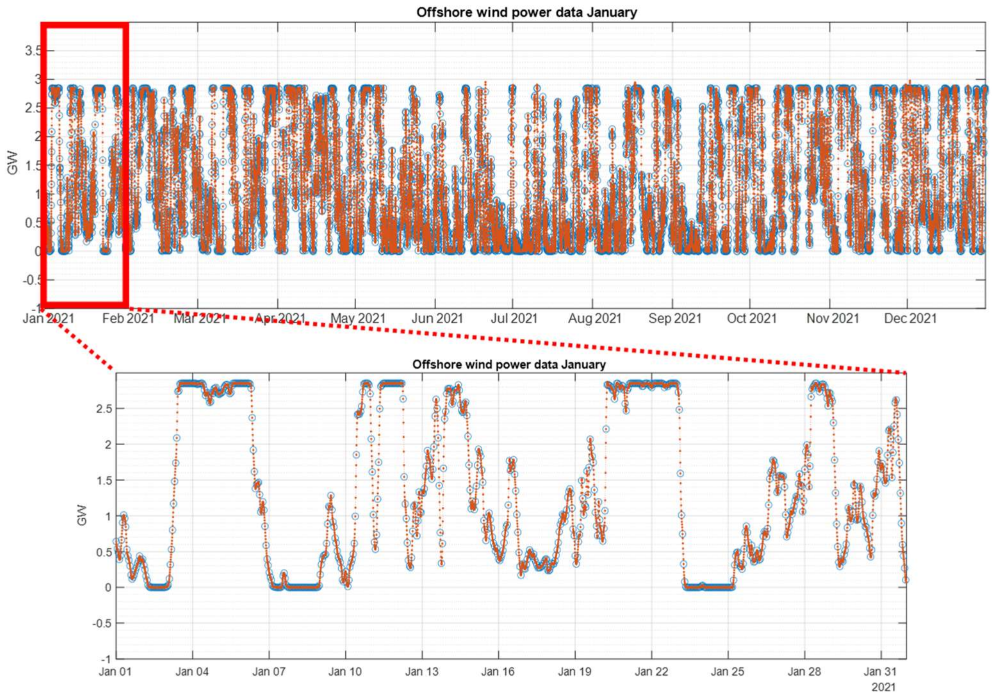


Figure 28. 2021 Wind Data[36].

The dataset highlights significant changes in power generation. As seen in Figure 28, when wind power increases, it can ramp up by as much as 1.5 GW. On the other hand, when wind power decreases, it can decrease by as much as -0.32GW[36]. These patterns in the dataset help better understanding how wind power varies and its potential impact on energy systems.

8.1.2. Bornholm District Heating

BEOF provided operational data from Bornholm District heating system to understand demand and temperature ratings needs, as shown in Figure 29 and Figure 30.

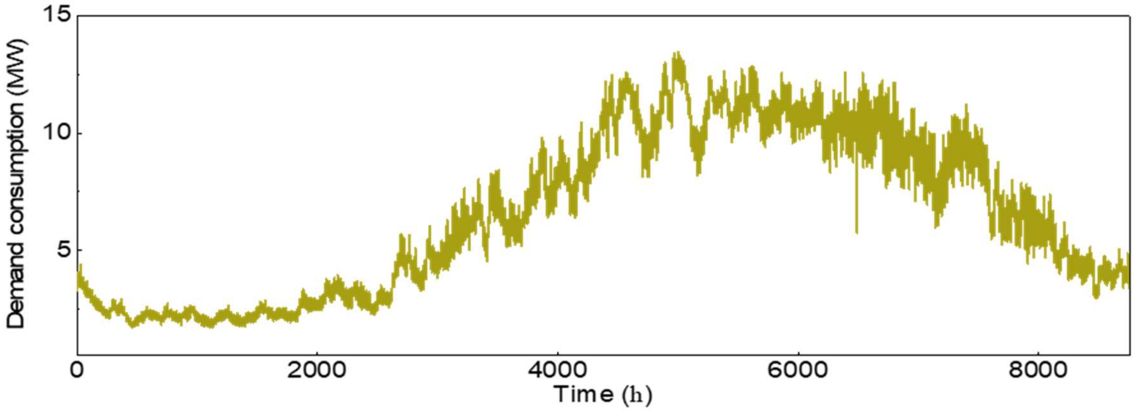


Figure 29. Illustration of District Heating in Bornholm

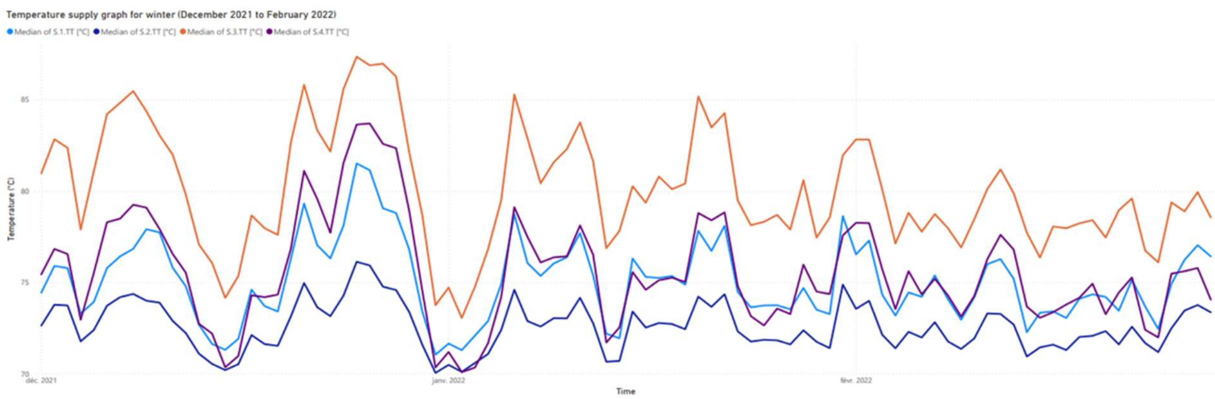


Figure 30. Temperature Supply for winter December 2021 to February 2022[36].

8.2. Hydrogen Production and Electrolyzer Portfolio Operation

Considering the planed capacity, several different system configurations can be achieved, as seen in the work done by DTU Wind and Energy Systems[37]. The choice was narrowed down two scenarios using alkaline electrolysers with the only difference being the planned capacity, 5 stacks of 200MW and 20 stacks of 50MW, with the intention to cover scenarios with large capacity units but being able to analyze the effect of the number of stacks in the system flexibility (See Table 8).

Table 8. WP 4 - Electrolyzers Technical Specifications

	Scenario 1	Scenario 2
Total capacity of offshore wind	3 GW	3 GW
Electrolyser capacity	5 x 200MW	20 x 50MW
Initial temperature of stack	56.4 °C	56.4 °C
Cooling water temp.	10 °C (could be higher 15°C)	10 °C
Mass flow rate of cooling water for one module	16E+05 kg/h	4E+05 kg/h
Efficiency	Variable	Variable
Operation range	20-100%	20-100%
Ramping rate (operation mode)	10% per min	10% per min
Start-up time (cold)	60 mins	60 mins
Start-up time (warm)	< 10mins	< 10min
Time resolution	10 mins	10 mins

It is expected that different systems will produce different operational performance, however a 5 x 200MW system shows a very similar performance in comparison to a 20 x 50MW system (See Table 9 and Figure 32). This was mainly because the goal was optimizing usage of the electrolyzer in function of wind power availability, using all the available wind power and powering up stacks as required with the wind conditions. Figure 31 illustrates how a 10-stacks system is operated by following a typical Fixed Order Operation Sequence, starting up electrolyzer sequentially to accommodate to variable wind conditions.

Table 9. WP4 Hydrogen Production Results.

	Scenario 1	Scenario 2
Module number and capacity	5 x 200MW	20 x 50MW
H2 production (kton)	102.0	102.6
El consumption (GWh)	5650.7	5669.9
Waste heat produced (GWh)	1581.7	1590.5
Waste heat recovered (GWh)	1483.2	1485.7
Rate of waste heat recovery %	93.8	93.4
Electricity curtailed / exported (GWh)	5237.7	5217.5

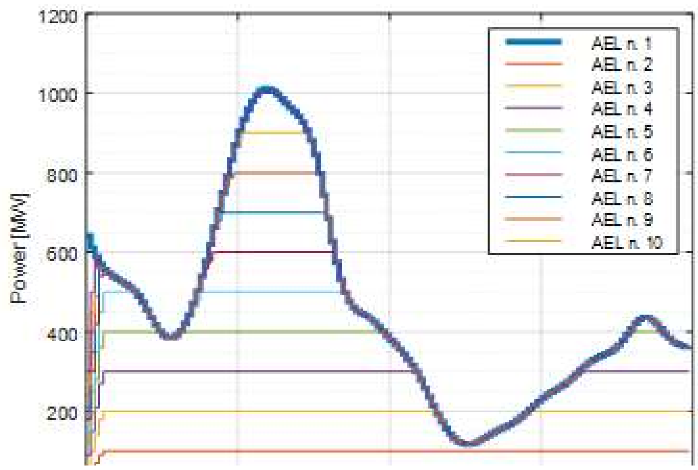


Figure 31. Operating electrolyzers in function of wind power availability

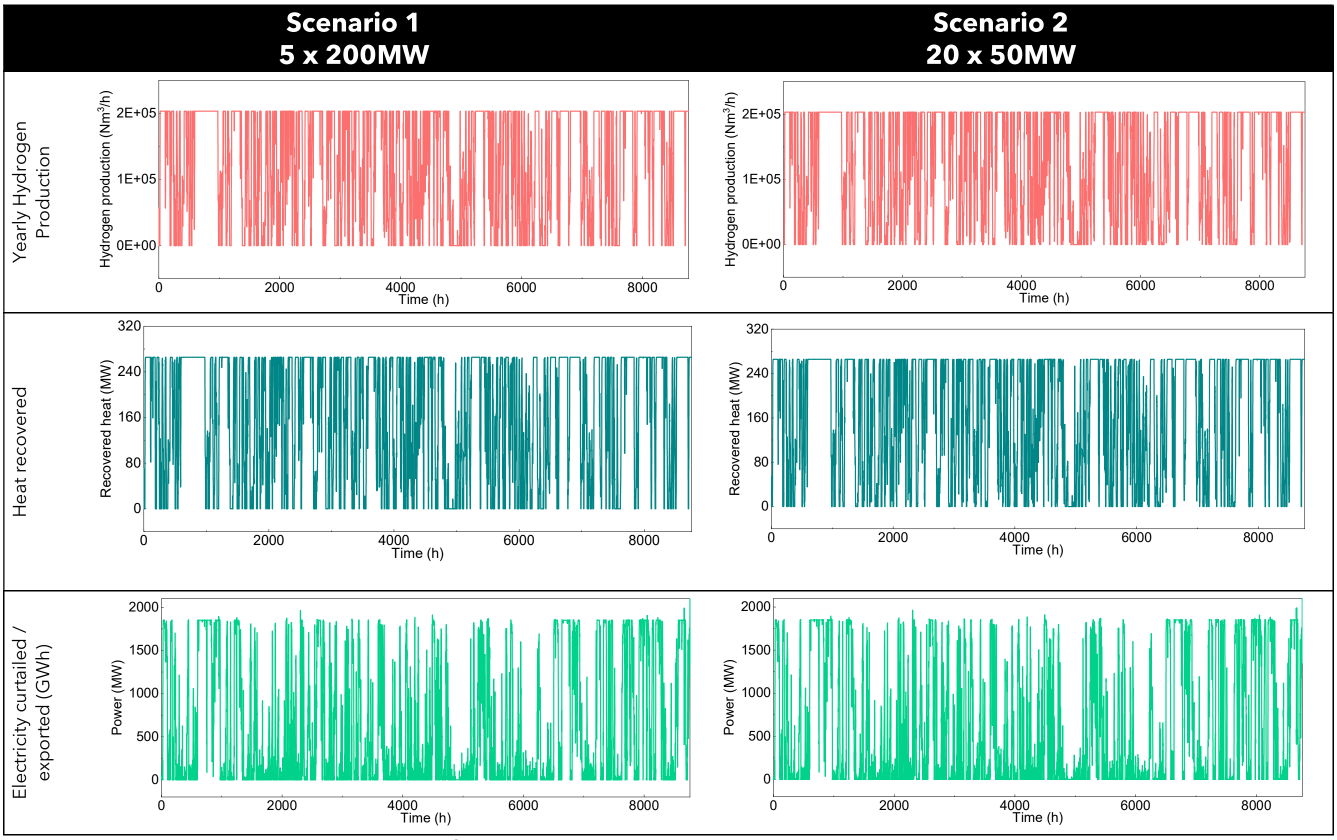
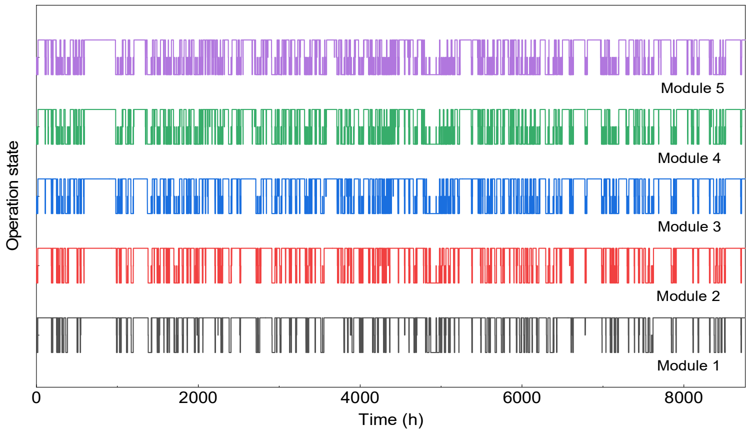


Figure 32. 5 x 200MW vs 20 x 50 MW Performance Comparison

Table 10. On / Off Status and Start / Stops times - 5 x 200 MW System.

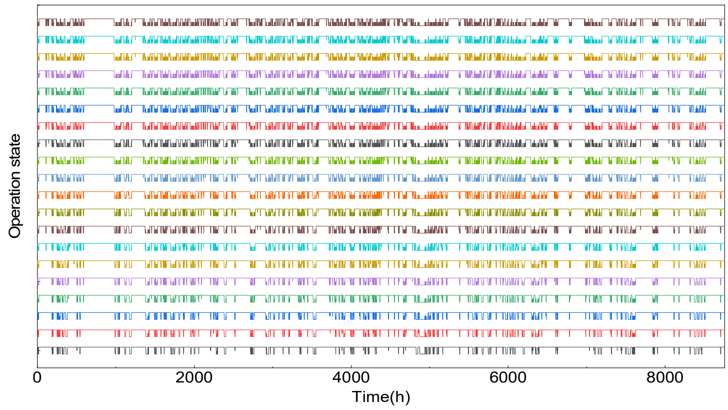


	Stop times	Load factor %	El_consumption (GWh)
Module 1	158	81	1419.6
Module 2	186	72	1256.0
Module 3	189	63	1097.1
Module 4	190	56	984.0
Module 5	197	51	894.4

Although the overall energy production looks similar, the operation of each electrolyzer module within each portfolio is different. Table 9 and Table 10 show the On / Off Status and the number of start / stops for each scenario. Both scenarios are operated using the Fixed Order Operation Sequence illustrated in Figure 35.

The first electrolyzer in the scenario will have the least number of start/stops and the higher load of all the electrolyzers in the system, meaning that is on almost all the time. It will be on as long as there is wind power available. The last electrolyzer has a larger amount of start/stops and the lower load of all the electrolyzers in the system. This observed in both scenarios.

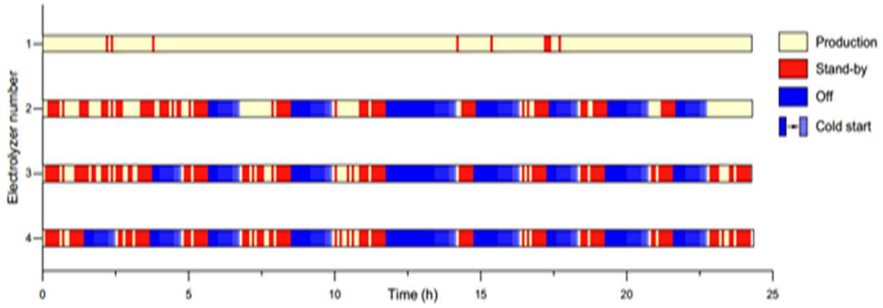
Table 11. On / Off Status and Start / Stops times - 20 x 50 MW System.



Item	Stop times	Load factor %	El_consumption (GWh)
Module 1	146	86	375.1
Module 2	164	82	360.5
Module 3	172	82	351.7
…	…	…	…
Module 20	204	49	215.2

Operating a system like this means that there will be electrolyzers in the system with much higher start /stops cycles but little utilization, which will impact negatively its operating life and the overall performance of the portfolio. Therefore, it is important to investigate other operating methods.

DTU Wind and Energy Systems has explored different strategies[38], operating 4 modules in a 24 hrs. period of time using the fixed sequence and comparing with other two alternatives. As mentioned previously, the fixed sequence (Figure 33) allows modules to start on demand in function of wind. In this case Module 1 is always on (yellow area) and rarely on stand-by (red area). The other modules are operating for a much-reduced period of time and the stand-by and off periods are alternating with off periods (blue area) increasing from module 2 to module 4, which is off for a much larger period of time.

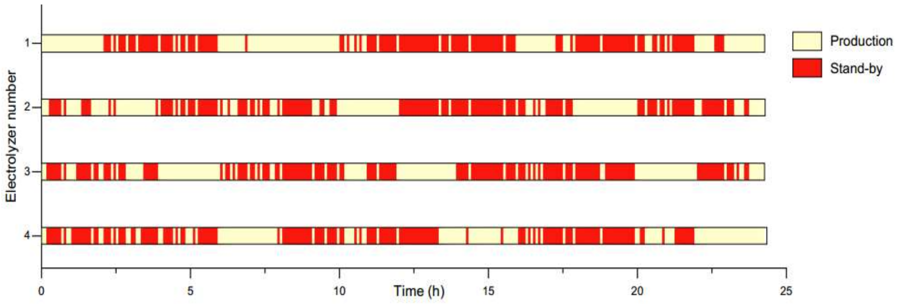


Operational details given strategy S1 (A)Electrolyzer power trajectory (B)Electrolyzers' state transition

Figure 33. 4 x Module Portfolio - Fixed Sequence

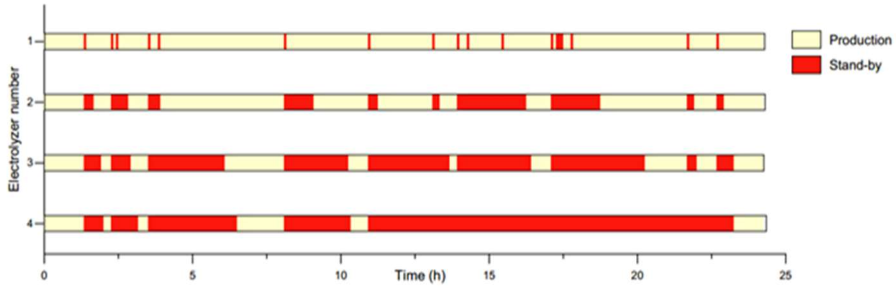
If the sequence is rotated (See Figure 34), starting each module every couple of hours, none of the modules is put in the off mode, all the modules are operating during the 24 hrs. period.

The third strategy (Figure 35. 4 x Module Portfolio - Optimal SequenceFigure 35) planned also to have none off the modules in off-mode but introduced calculations to have all the modules in some operation state, alternating on and stand by states and optimizing the operation while still using all the wind power available.



Operational details given strategy S2 (A)Electrolyzer power trajectory (B)Electrolyzers' state transition

Figure 34. 4 x Module Portfolio - Regular sequence update



Operational details given strategy S3 (A)Electrolyzer power trajectory (B)Electrolyzers' state transition

Figure 35. 4 x Module Portfolio - Optimal Sequence

The performance of each strategy was then calculated for a year period and the performance assessment indicators were compared (Figure 36), showing that the third sequence strategy has a better system efficiency than the traditional operating sequence or the rotational, which can be translated into a reduced LCOH calculation for the portfolio. Using this strategy, the portfolio will produce more hydrogen for the same amount of energy used to operate the electrolyser.

Performance assessment indicators for a yearly operation

Strategy	Hydrogen production (kg)	System efficiency	LCOH(€/kg)
S1	293436.5	0.576	4.29
S2	307005.6	0.588	4.06
S3	318686.9	0.620	3.81

Figure 36. 4-Module - Yearly Performance Assessment Indicators

Complementing WP4 findings, there are also the results from other parallel studies carried out by DTU Wind and Energy Systems[37, 38]that concluded the larger the number of electrolyser units or the smaller the unit capacity is, the more flexibility the portfolio has. The smaller the unit is, less power is required to keep it operating making the system more flexible to withstand lower or variable electricity inputs during low wind conditions. This is it based on the assumption that wind power will have large fluctuations (Figure 28. 2021 Wind Data36.)

The capital cost the investment varies in different electrolyser portfolios. In general, it is assumed the electrolyser with bigger capacity has much less investment cost per unit due to the scaling effects[37].

Operation wise if you have only one GW unit, the number of start and stops of this unit is completely dependent on wind, being function of the large energy consumption required for a unit of the size (hypothetically). If you have multiple units then it is possible to control the operation changing the start / stop sequence and including other technical variations such cold start, warm start, etc.[38], optimizing the unit's lifetime as well as the operational expenses. In this study was demonstrated that through optimal operation, using optimal operation strategies, it is possible to reduce the number of a start and stop effectively.

8.3. Power grid integration

Regarding the power grid integration power results are calculated based on the assumption that there is a 3 GW electricity supply and 1 GW electrolyser, so there will be residual power. The difference between the wind power available and the power consumed by the system needs to be curtailed or exported. The system is optimized to use up as much as wind power as possible, reducing the amount of curtailed power and aiding in the operation performance.
Nevertheless, the grid operator will have a great task optimizing the use of curtailed power. Selling for export will be limited by infrastructure, as the only existing connection cannot manage the scale of curtained power (Sweden). Also, if used locally, Bornholm's peak load is around 60 MW and the curtailed power is giga scale.

8.4. Waste Heat Recovery

The study estimated that for the type of electrolyser selected, which operates at maximum 60°C, the recovered waste heat will be in the range of 40°C (Figure 37). This could change if other technologies are used such us SOEC which operates in the range of 700°C but in overall the temperature of the waste heat will be function of the electrolyzer operating rate.

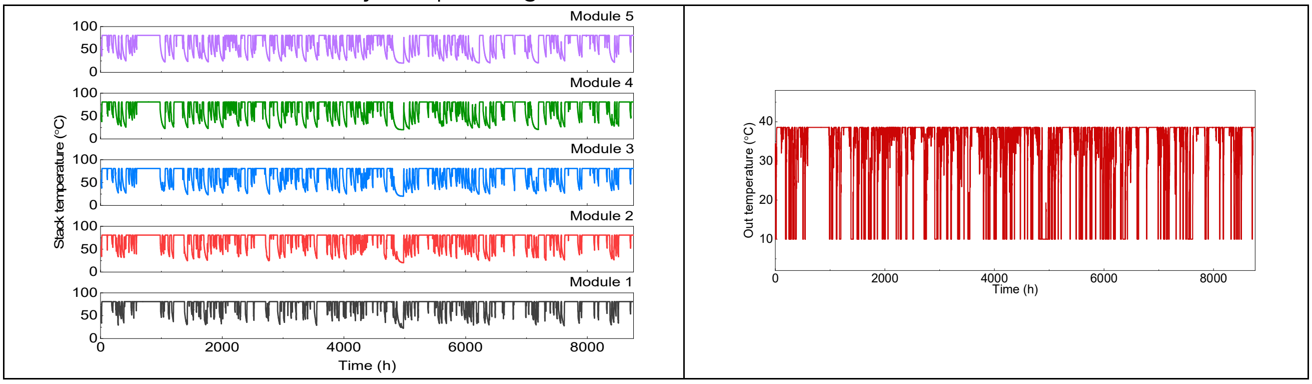


Figure 37. 5 x 200MW Portfolio Operating Temperature and Estimated Waste Heat

The temperature rating demand is shown in Table 12, which is far higher than the calculated waste heat temperature, however WP2 results show that in terms of energy, the demand will be satisfied.

Waste heat is not typically used as a co-product and integrated in the system but instead released. But using waste heat in terms of energy is feasible, only requiring conditioning waste heat to bring it to the temperature specification require. The process is costly and other systems, such the cooling system, must be given priority over waste heat recovery.

Once, the cooling system is optimized in relation to the scale, then consideration can be given to the heat exchangers requirements needs to optimize of waste heat recovery. In theory, to bring the waste heat from 40°C to 60°C or even 70°C, is possible but changes to the design of the recovery system must be made. This was not explored, as increasing the heating system will increase the system CAPEX but depending on the local requirements and potential out takers, but this is an interesting investigation line than could have a positive effect in the community. As well to further investigate its application in other process different than district heating where the temperature ratings are lower.

Table 12. Bornholm's East Coast Temperature Supply Ratings[36].

Location	Temperature requirement (°C)
Nexø	77,35
Årsdale	85,42
Svaneke	89,24
Snogebæk	84,98

There are several investigations in academia, investigating how to increase operation temperature. System efficiency increases with operating temperature, which opens the possibility of having a more efficient system that also generates usable waste heat. Academia is finding out how to operate this type of system because the operational requirements are different (e.g. using steam instead of liquid water). There is also the need for more information from the industry and more investigation to fully understand how to handle waste heat, all these open the door to other inquiry lines and future projects in the subject.

Other investigation line is upgrading the heating system from high grade heat to low grade heat. This, in principle, can use the waste heat generated, requiring additional heat boosting solutions.

8.5. Hydrogen to Ammonia

Ammonia synthesis is a much more complex process that requires several systems and subsystems (ASU, compressors, utility systems, etc.) with independent operating procedures and individual start/stop processes as shown in Figure 38 and Table 13.

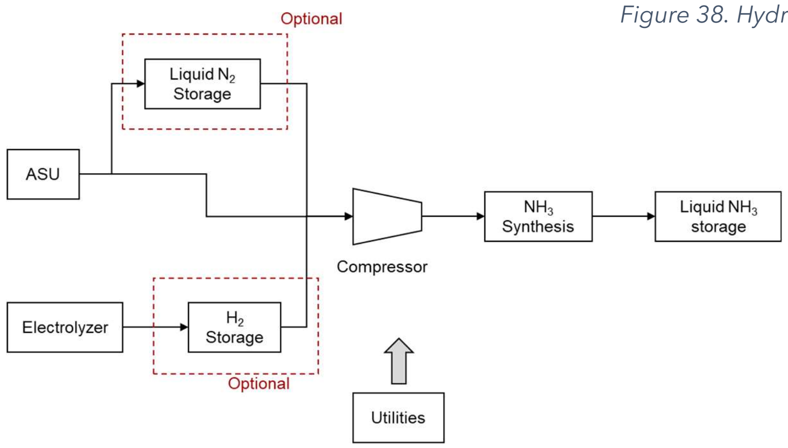


Figure 38. Hydrogen to Ammonia System

Table 13. Hydrogen to ammonia Technical Constrains

	Working prerequisites	Start-up time	Working range	Ramping rates	Power consumption
Utilities	None	3h	100%	None	1% Nominal power
ASU	Utility on	36-48h	75%-100%	None	2% Nominal power
Compressor	Utility on	1h	75%-100%	1%/min	5% Nominal power
NH_3 synthesis plant	Utility, ASU, Compressor on (Hot standby: utility on)	Cold start: 12h Hot start: 0-4h (depending on standby time)	20%-100%	3%/min	None

Component	Working Prerequisites	Scenario 1	Scenario 2	Scenario 3
Utilities	None	On	On	Off
ASU	Utility on	On	On	On
Compressor	Utility on	On	Off	Off
NH_3 synthesis plant	Utility, ASU, Compressor on (Hot standby: utility on)	Ignore lower limits of NH3	Stand-by	Off

Figure 39. Operational strategies for ammonia synthesis

All components of the ammonia synthesis process must be dynamically integrated in order to achieve the desired operational performance and their interdependency is complex. Some of these dynamic parameters have a considerable impact in the operation such the start-up rates, others influence operational performance or total power consumption of the plant.

Different operational strategies were designed to investigate the impact of these relationships in the overall operational performance (See Figure 39).

- In Strategy 1 all components are on. The synthesis plant was assumed to process ammonia regardless of how low the hydrogen input was.
- Strategy 2 assumes both utility and air separation units are on, allowing to shut down the compressor as it has a low start-up time but higher power consumption rate (Table 13). This case can be applied in a situation where there is not enough hydrogen to meet the minimum hydrogen demand of the reactor, then the compressor can be shut down and optimize power consumption.
- Strategy 3 allows ASU to be on and the other components to be off.

Table 14 shows the result of the first set of simulations, based on the parameters set in Figure 39 and keeping ramping rate constant at 3%/min.

The first strategy generates the larger amount of ammonia since the case assume the system must use all the hydrogen received in the system, it is the strategy that consumes the most electricity and has less unused hydrogen. The second strategy allow the system to be shut-down and, in some cases, then that means for some hours the systems can lose the ability to produce ammonia, resulting in less ammonia being produced and the volume of unused hydrogen increasing. Unused hydrogen can be used an as indication that storage is required. In conclusion, operational strategies oriented to reduce electricity consumption can lead to reduction in ammonia production and requiring additional hydrogen storage.

Table 15 and Table 16 show the results of the simulation varying ramping rates, which is the rate at which hydrogen is introduced in the system. Changing the ramping rate from 3%/min to 0,3 %/min percent to. 03 percent. It was simulated for both electrolyzer portfolio, showing similar results. In overall, decreasing the ramping rate decreases the volume of ammonia produced and increases the amount of unused hydrogen, regardless of the portfolio.

Table 14. Operational Strategies for Ammonia Synthesis

Scenario	Strategy	Annual Ammonia Production (kt)	Utility Energy Consumption (MWh)	ASU Energy Consumption (MWh)	Compressor Energy Consumption (MWh)	Overall Electricity Consumption (MWh)	Unused Hydrogen (kt)
5 x 200MW	1	579,59	90.229,00	180.459,00	451.148,00	721.837,00	0,03
	2	552,42	90.229,00	180.459,00	328.612,00	599.302,00	4,82
	3	468,57	68.364,00	180.459,00	328.612,00	577.436,00	19,62
20 x 50MW	1	581,29	90.229,00	180.459,00	451.148,00	721.837,00	0,02
	2	557,73	90.229,00	180.459,00	335.213,00	605.902,00	4,18
	3	479,29	69.842,00	180.459,00	335.213,00	585.515,00	18,02

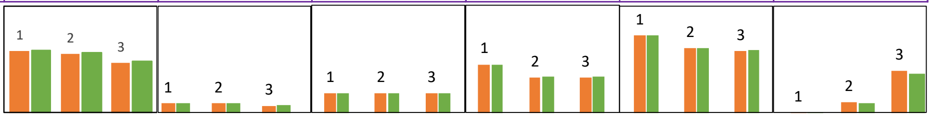


Table 15. Influence of Ramping Rates - 5 x 200 MW

5 x 200MW							
Ramping Rate	**Strategy**	**Annual Ammonia Production (kt)**	**Utility Energy Consumption (MWh)**	**ASU Energy Consumption (MWh)**	**Compressor Energy Consumption (MWh)**	**Overall Electricity Consumption (MWh)**	**Unused Hydrogen (kt)**
3% / Min	1	579,59	90.229,00	180.459,00	451.148,00	721.837,00	0,03
	2	552,42	90.229,00	180.459,00	328.612,00	599.302,00	4,82
	3	468,57	68.364,00	180.459,00	328.612,00	577.436,00	19,62
0,3% / Min	1	566,14	90.229,00	180.459,00	451.148,00	721.837,00	2,40
	2	529,67	90.229,00	180.459,00	335.213,00	599.302,00	8,84
	3	445,86	68.364,00	180.459,00	451.148,00	577.436,00	26,63

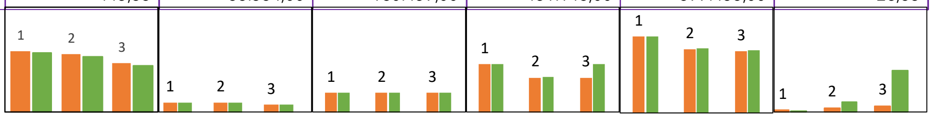


Table 16. Influence of Ramping Rates - 20 x50 MW

20 x 50MW							
Ramping Rate	**Strategy**	**Annual Ammonia Production (kt)**	**Utility Energy Consumption (MWh)**	**ASU Energy Consumption (MWh)**	**Compressor Energy Consumption (MWh)**	**Overall Electricity Consumption (MWh)**	**Unused Hydrogen (kt)**
3% / Min	1	581,29	90.229,00	180.459,00	451.148,00	721.837,00	0,02
	2	557,73	90.229,00	180.459,00	335.213,00	605.902,00	4,18
	3	479,29	69.842,00	180.459,00	335.213,00	585.515,00	18,02
0,3% / Min	1	569,23	90.229,00	180.459,00	451.148,00	721.837,00	2,15
	2	535,98	90.229,00	180.459,00	335.213,00	605.902,00	8,01
	3	457,10	69.842,00	180.459,00	335.213,00	585.515,00	21,93

9. LOCATION, TRANSPORT, AND STORAGE STRATEGIES (WP5)

As an island standing on the brink of exciting possibilities for a new energy industry, the potential for a Power-to-X plant associated with the chemical industry presents a transformative opportunity for Bornholm. Unlike other regions in Denmark, Bornholm has historically had limited exposure to the chemical industry, making potential PTX project's location and design a matter of utmost importance. We emphasize that the success of this project relies on careful consideration of context, strategic planning, and extensive dialogue with relevant authorities and stakeholders.

9.1. Political Considerations

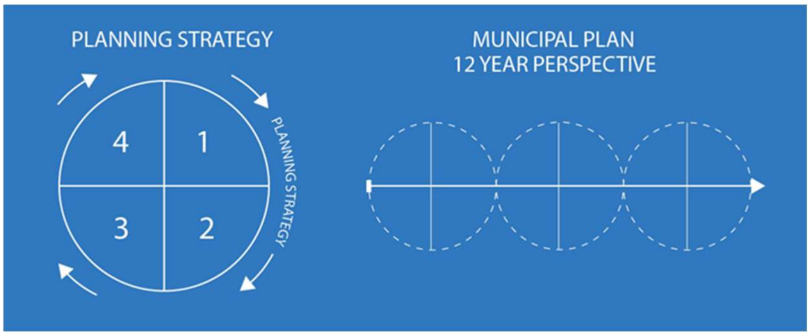


Figure 40. Planning strategy and municipal plan[39].

The political process and Political considerations play a vital role in the successful establishment of a PTX plant. This involves adhering to the municipal plan, a strategic document defining a municipality's spatial and land-use development objectives. The planning strategy within the municipal plan outlines the priorities for physical planning and must be devised and adopted by the municipal council within the first two years of their four-year election period[39].

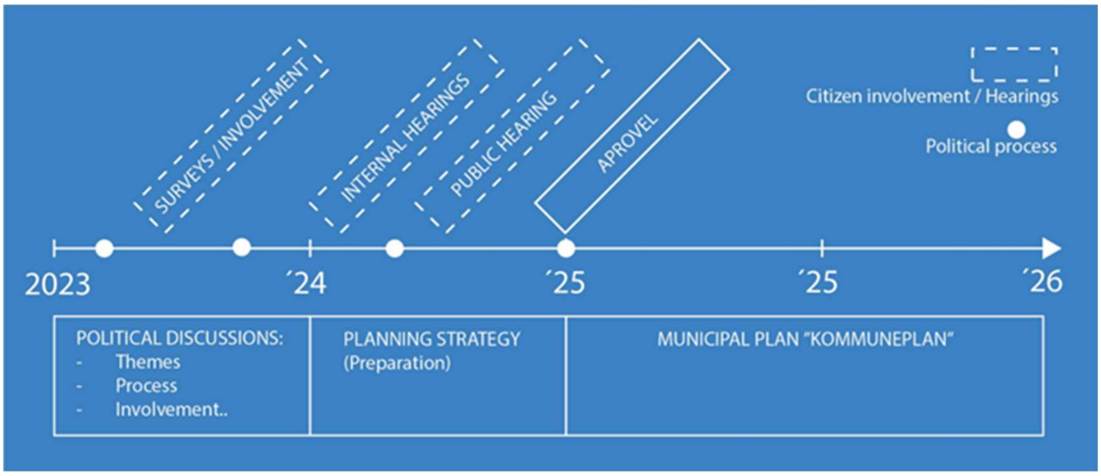


Figure 41. Planning strategy - Flow diagram.

Timely engagement in pre-project dialogue with authorities, politicians, and interest groups is essential for large-scale projects. Furthermore, parallel work in the planning and development phases is recommended as they are interdependent.

9.2. Suitable Location Assessment

9.2.1. Factors Mapping

Bornholm's unique topology and natural landscapes must be carefully considered during the planning phase. The PTX project should aim to minimize its environmental impact, preserving the island's scenic beauty and ecological balance. Conducting thorough environmental assessments and engaging environmental experts will help identify suitable areas for the project without compromising the island's sensitive ecosystems.

A set of maps was developed to visualize the key factors that require consideration when planning for a large-scale Power-to-X facility:

Figure 44. Mapping Bornholm's size and distances.

Figure 42. Infrastructure.

Figure 43. Major Cities.

- Size and Distances and Major cities: This involves assessing the proximity to major cities and existing infrastructure, with a focus on minimizing transport times and avoiding densely populated areas. Additionally, it includes evaluating the appropriate scale for the facility relative to the island' s size.

  Farming, Commercial and Industrial Areas: Exploring potential synergies with existing zones and determining the need for new zoning to accommodate Power-to-X plants. It will help visualizing the effect that any industry will have in agriculture.

Figure 45. Farming.

Figure 46. Commercial and Industrial Areas.

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- Power-to-X Facility, Energy Island, and Grids
  Analyzing the potential benefits of connecting the Power-to-X facility with the Energy Island project and its transformer station to utilize surplus energy effectively. Also understanding how to connect to existing grids or establishing new ones, like the 60 KV power grid and the district heating grid.

Figure 48. Energy Island.

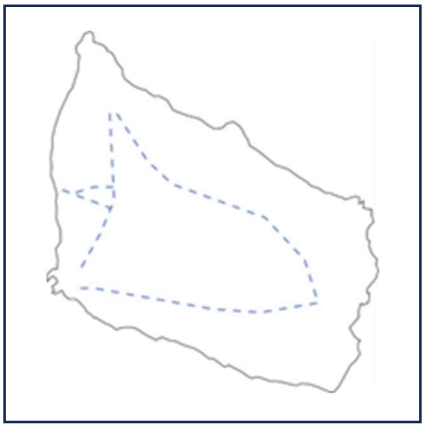


Figure 47. Power Grid.

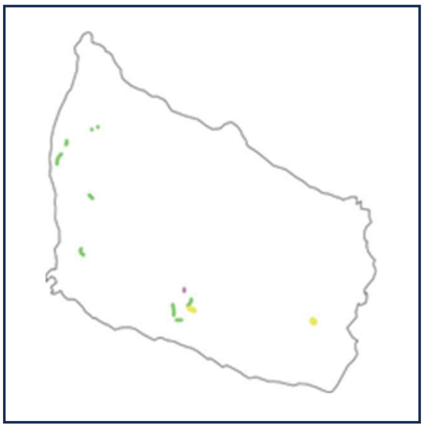


Figure 50. Wind, Solar and Biogas.

Figure 49. BEOF Grid for District heating.

- Preserving Coastal Zones, Protected Areas, and Cultural Heritage
  The project encompasses various aspects of sustainable development in the region. It includes addressing specific planning needs for coastal zones to ensure environmental and coastal protection. The strictest designations by conservation boards and authorities are considered to preserve protected areas and forests, protecting environmentally sensitive locations. Measures are also implemented to identify safety zones and preserve the cultural and historical heritage of the region. Moreover, the project ensures compliance with Natura 2000 sites and streams regulations to safeguard environmentally significant areas.

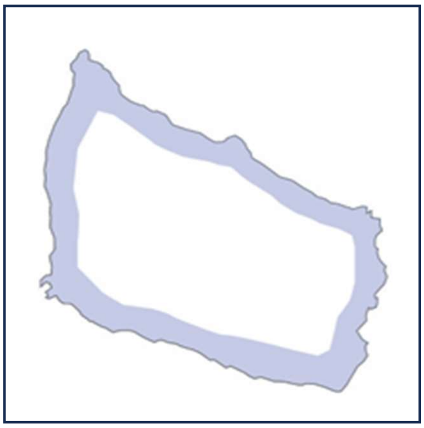


Figure 51.Coastal Areas.

Figure 52. Streams.

Figure 53. §3 Areas

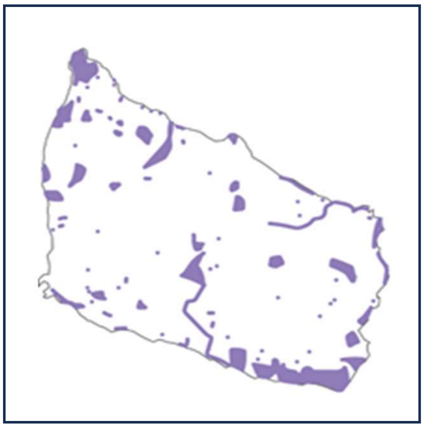


Figure 54. Protected Areas.

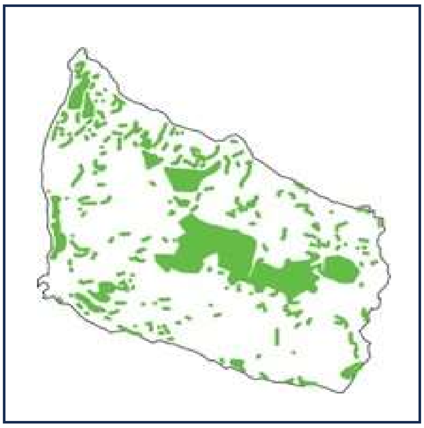


Figure 55. Protected Forests.

Figure 56. Natura 2000.

Figure 57. Cultural Areas.

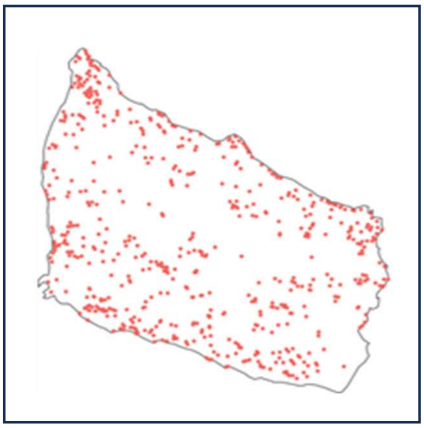


Figure 58. Historical Areas.

Figure 59. Combined maps.

9.2.2. Plant size in context

The size of a PtX Plant and its storage capacity is influenced by various factors, such as project structures, buildings, infrastructure, and safety zones. During the feasibility study, two scenarios are considered with potential plant footprint of 30 and 50 hectares (See Figure 60. Example of footprint in local context.), and these choices significantly impact the landscape.

To determine the optimal location, storage facility, and design programs, conducting landscape analyses at a more local scale is crucial. These analyses should be combined with the mapping of the relevant factors to understand future needs and potential requirements for infrastructure, water courses (See Blue Plan[39]), the landscape and the environmental impact (See Green Plan[39]).

It is necessary to analyze the available infrastructure and anticipate future needs. A focus on strengthening nature, landscape, and biodiversity should be central to the plan. By considering these aspects, the PtX project can incorporate sustainability measures and ensure a positive environmental impact.

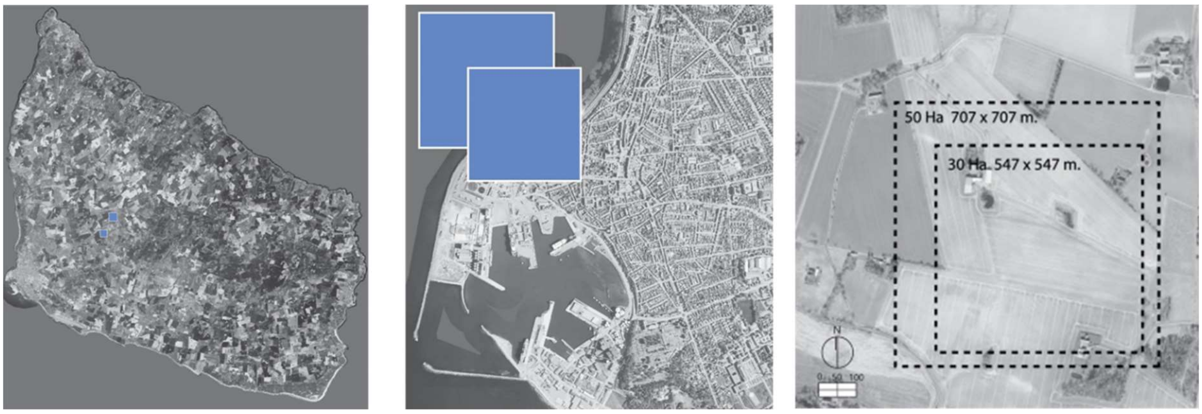


Figure 60. Example of footprint in local context.

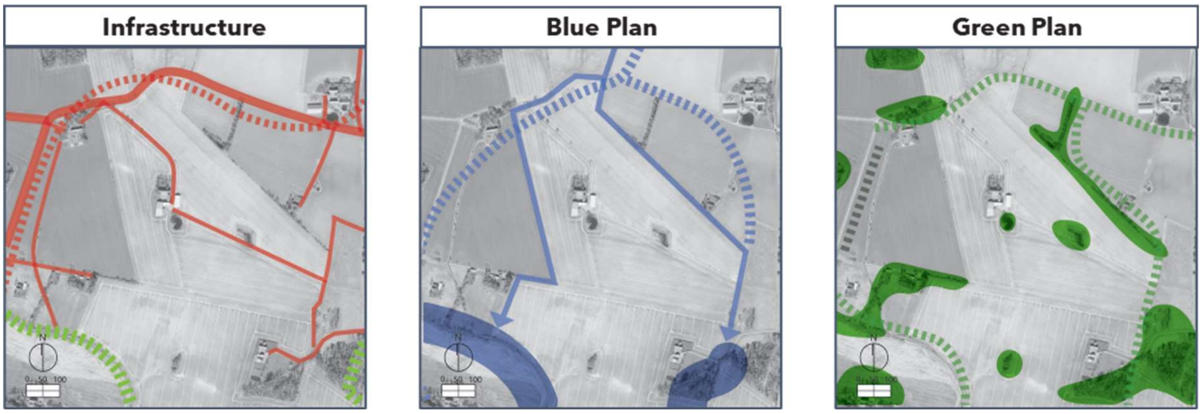


Figure 61. Example of mapping relevant factors in local context

9.2.3. Transport and Storage Requirements

Ensuring the safe and efficient transportation of PTX products is of utmost importance in today's energy landscape. Three viable scenarios have been identified for this purpose: underground transportation, on-ground/piped transportation, and transportation by trucks. Each of these options must be carefully evaluated prioritizing the safety of the communities and the environment during the transportation process.

The storage of e-fuel at the Port of Roenne presents a sensitive issue due to its close proximity to a densely populated city. To address this concern adequately, a comprehensive strategy that involves the public is highly recommended. By engaging the community in the decision-making process, potential concerns and issues can be addressed proactively, fostering transparency and trust.

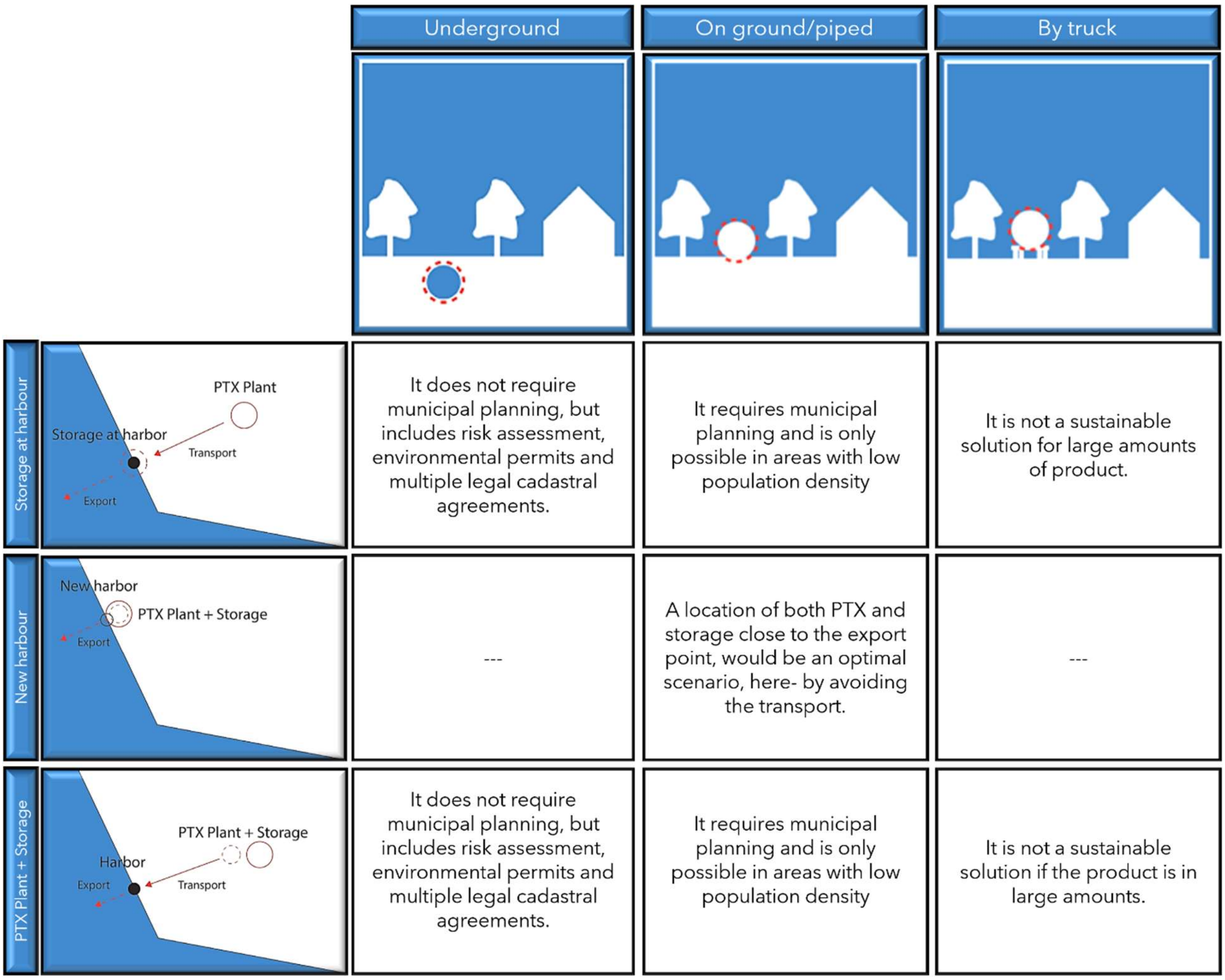


Figure 62. Transport and Storage Scenarios

A vital aspect of this strategy involves the implementation of rigorous environmental screening, encompassing comprehensive environmental reports and obtaining all necessary building permits. These measures are crucial in ensuring that the e-fuel storage facilities meet stringent environmental standards and adhere to all relevant regulations. Furthermore, conducting regular assessments and monitoring programs can help mitigate any adverse impacts that might arise over time.

In the pursuit of public involvement, local residents, environmental organizations, and relevant stakeholders should be consulted to ensure that their concerns and perspectives are considered. This collaborative approach can lead to the development of a well-rounded and sustainable e-fuel storage facility that benefits both the region's energy needs and the community's well-being.

Expanding on the transportation aspect, underground transportation offers the advantage of enhanced safety and security, protecting PTX products from external factors such as weather conditions and potential accidents. It also minimizes the risk of leaks and spillages that could harm the environment. On the other hand, on-ground/piped transportation might prove more suitable for short distances and where the terrain is favorable. This method can potentially leverage existing pipeline infrastructure, reducing the need for additional construction and minimizing environmental disturbances.

Transportation by trucks, while flexible and readily available, requires careful planning to ensure that routes are optimized to avoid congested areas and reduce emissions. Implementing efficient logistics and scheduling systems can help minimize transport times and increase overall transportation efficiency.

9.3. Landscape Design and Architecture

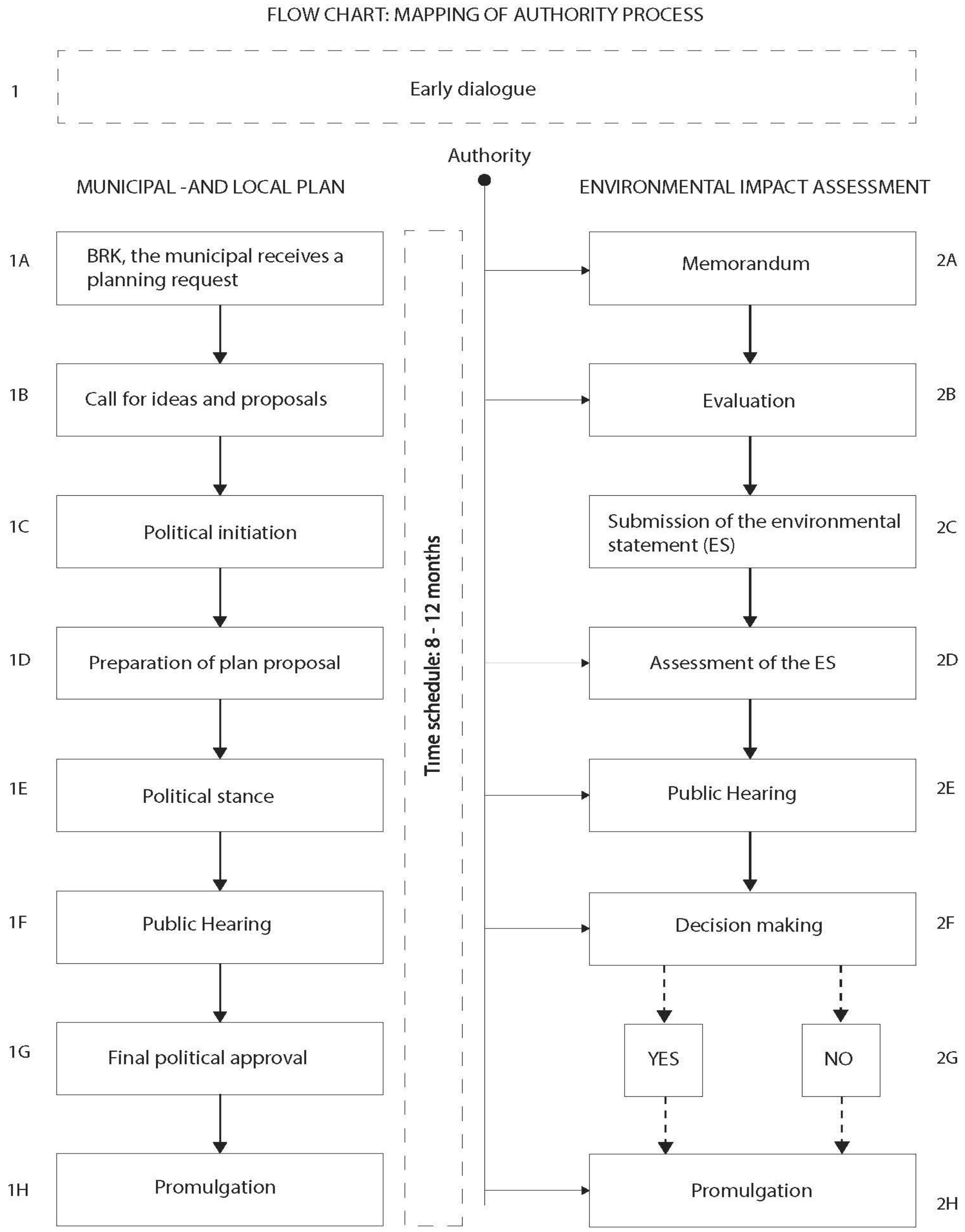
Considering the picturesque nature of Bornholm, landscape design and architecture should be integral components of the PTX project. Designing the plant and associated facilities to harmonize with the island's natural beauty will not only enhance visual aesthetics but also demonstrate a commitment to sustainable development. Collaborating with experienced architects and landscape designers will help strike a balance between functionality, efficiency, and visual appeal.

9.4. Approval Process

The establishment and operation of a PtX facility requires a number of approvals, permits and other official processing, which must ensure that the facility is placed appropriately and complies with requirements for, among other things, environmental protection, and safety. Several authorities are involved in the process – both before, during and after establishment of the facility.

WP5 has mapped out the process for applying for project approval from the planning and environmental authorities (See: *Figure 63. Mapping of Authority Process.*). The process is explained in detail in WP5 Report

Further guidance is provided by The Danish Energy Agency and the Power-to-X Task Force[40] which leads an authority working group with a view to ensuring transversal knowledge sharing and coordination.



Legal basis:
Planning Law: https://www.retsinformation.dk/eli/lta/2020/1157
Environmental Assessment Act: https://www.retsinformation.dk/eli/lta/2021/1976

Figure 63. Mapping of Authority Process.

9.5. Recommendations

- Political Process:
  - Initiate early dialogue with authorities, politicians, and interest groups regarding large-scale projects.
  - Coordinate planning and development phases simultaneously, as they are interdependent.
  - Engage in an early overall political discussion about the new potential industry, considering ongoing planning strategies and municipal council approvals.
- Large Scale Planning:
  - Prioritize sustainable locations that align with the context.
  - Conduct thorough context analyses to inform decision-making.
  - Establish early dialogue with authorities to prevent potential conflicts.
- Local Planning:

- Prepare comprehensive context analyses.
- Adopt an ambitious landscape approach, striving to "add more than you subtract."
- Map public interests in relation to local interests.

- Transport of Product from Power-to-X Plant:
  - Avoid long transport times and routes through densely populated areas.
  - Locate the plant and storage facility as close to the export point as possible.
- Storage of e-Fuels in Port of Rønne:
  - Handle storage of e-Fuels at the Port of Rønne with sensitivity due to its proximity to a dense city, requiring a public strategy and involvement.
- Authority Process:
  - Establish early dialogue and cooperation with relevant authorities such as Bornholms Regionskommune and Miljøstyrelsen.
  - Ensure transparent processes throughout the project's development.

10. PESTEL ANALYSIS (WP6)

A PESTEL analysis serves as a strategic framework employed to evaluate the external macro-environmental factors that wield influence over the viability and triumphant execution of a project, exemplified by the Power to X initiative in Bornholm. The acronym PESTEL encapsulates Political, Economic, Social, Technological, Environmental, and Legal factors. Each category corresponds to distinct external forces that can significantly shape the project's feasibility and eventual outcomes.

In opting for this method over alternative analytical approaches, the intention was to secure a panoramic viewpoint. While methods like SWOT analysis adeptly address internal strengths, weaknesses, opportunities, and threats, the goal here was to provide insight into a varied array of stakeholder queries. These inquiries could span not only the 'how' of project implementation but also the 'when' and 'why.' The method's simplicity, accessibility, and aptitude for facilitating comparative evaluations render it a versatile tool for comprehending how the external environment orchestrates its impact on the project's trajectory, be it towards accomplishment or adversity.

10.1. Methology

Factors were identified through a comprehensive analysis of core studies spanning from WP 1 to WP 5, systematically documented in an Excel matrix. Additionally, the scope of factor identification encompassed a wide range of pertinent sources, including press releases, websites, academic papers, workshops, market reports, and expert consultations.

To gauge impact and relevance, individual experts entering factors into the matrix assessed these aspects, followed by validation from either a team or a WP lead. By multiplying relevance and impact scores, each factor was assigned a value (value = relevance x impact), serving as the basis for prioritization based on their potential significance.

The outcomes of this analysis will shape the project's conclusions. Moreover, the insights garnered will inform recommendations aimed at developing strategies for risk mitigation, capitalizing on opportunities, and optimizing the project's likelihood of success. These recommendations might entail adapting the project plan, seeking strategic partnerships, or advocating for pertinent policy adjustments.

10.2. Political Factors

The successful realization of a Power-to-X (PtX) project in Bornholm relies on a complex interplay of factors, intricately shaped by political decisions and collaborative efforts. There were 23 political factors identified and group into 6 different categories. The analysis of these factors involves evaluating how government policies, regulations, and stability influence PtX technologies. This spans energy policies, subsidies, incentives, and political backing for renewable energy and PtX advancement. The assessment considers political stability and geopolitical factors impacting energy resource availability and affordability.

Figure 64. Political Factors Classification and Value

10.2.1. Collaboration and International Cooperation

Effective collaboration with stakeholders, such as local communities, government authorities, and industry partners, is crucial for the successful execution of the Power-to-X initiative in Bornholm. Open dialogues and strong partnerships yield numerous favorable outcomes. Local communities offer insights, support, and concerns, making them integral to the project's prosperity. Government cooperation ensures regulatory approval and policy consistency. Industry partners bring technical know-how, resources, and investments, bolstering project viability. Collaborative endeavors cultivate a shared duty and can generate synergies that enhance project results.

Moreover, international collaboration significantly benefits Bornholm's Power-to-X endeavor. The Ostend and Esbjerg Declarations exemplify a commitment to regional cooperation, uniting nations like Belgium, Denmark, Germany, and the Netherlands to tap into the North Sea's renewable energy potential. This cooperation seeks interconnected energy islands and clusters, fostering a resilient, interlinked energy grid. These agreements facilitate knowledge exchange, best practice sharing, and joint research, expediting Bornholm's project by granting access to resources, expertise, and cross-border infrastructure development.

10.2.2. Energy Independence and Security

Bornholm's role as the first energy island in Denmark has far-reaching implications for national energy independence and security. By expanding offshore wind capacity and integrating PtX technologies, Bornholm is poised to reduce reliance on imported fossil fuels, enhancing energy security and bolstering national resilience. The Marienborg Declaration's ambition to strengthen European energy independence from Russia is of particular significance for Bornholm's PtX project. It reflects a broader geopolitical strategy to diversify energy sources and decrease vulnerabilities to external disruptions. The commitment to reducing greenhouse gas emissions, coupled with the expansion of renewable energy infrastructure, positions Bornholm as a pioneer in contributing to energy security and transitioning towards a greener energy landscape.

However, external geopolitical factors can pose risks to energy security. The ongoing conflict in Ukraine has the potential to impact energy supplies and prices, disrupting the stability of the energy market. Bornholm's Power-to-X project must navigate these geopolitical uncertainties, ensuring that it remains resilient and adaptable in the face of potential energy supply disruptions. The project's success will hinge on its ability to balance national energy independence goals with the need to address and mitigate geopolitical risks.

10.2.3. Environmental Impact

The environmental impact of Bornholm's Power-to-X project is a focal point from a political perspective, aligning with global climate change mitigation efforts. PtX technologies offer a pathway to decarbonize sectors that are challenging to electrify directly, such as heavy industry and transportation. By utilizing renewable energy to produce low-carbon fuels and chemicals, Bornholm's PtX project contributes positively to greenhouse gas emissions reduction and supports the transition to a sustainable energy economy. The project's alignment with Denmark's commitment to cut GHG emissions by 70% from 1990 levels by 2030 demonstrates a robust political commitment to environmental sustainability.

The recognition of hydrogen's pivotal role in the EU's decarbonization strategy enhances the relevance and significance of Bornholm's PtX project. The project's emphasis on producing green hydrogen aligns with EU-wide efforts to reduce carbon emissions. Bornholm's project can potentially serve as a model for other regions aiming to integrate hydrogen-based solutions into their energy systems, thus making a broader impact on environmental sustainability.

10.2.4. Funding and Employment

The Power-to-X project in Bornholm not only contributes to the energy transition but also has tangible socioeconomic benefits, particularly in terms of funding and employment. From a political standpoint, these aspects play a crucial role in garnering support and ensuring the project's viability.

Employment generation is a key positive outcome of the project. The various phases of the project, including the establishment of service ports, installation, and the operational phase of the power-to-x plant, create a demand for skilled labor and local workforce engagement. This employment potential aligns with broader regional development goals, contributing to the growth of Bornholm's population and economy. Politically, the creation of jobs resonates with local communities and can foster support for the project's implementation.

Funding mechanisms, such as PtX tenders and government support, are essential to mitigate financial barriers and encourage private sector involvement. The availability of funding incentivizes investments in PtX production, which can accelerate the project's deployment and contribute positively to the region's economic growth. Funding initiatives like PtX tenders demonstrate political commitment to renewable energy transition, making PtX technologies economically viable and driving interest from major developers. Moreover, these funding mechanisms align with broader national and European green investment goals, showcasing Bornholm's contribution to the larger sustainable development agenda.

10.2.5. Infrastructure and Capacity

Bornholm's ambitious goals for electrolysis capacity and interconnection underscore its dedication to PtX technologies and the broader energy transition. The commitment to achieving 4-6 GW of electrolysis capacity by 2030 positions Bornholm as a key player in the green hydrogen market. This level of capacity expansion signals political determination to advance the deployment of PtX technologies, enabling the integration of renewable energy sources and promoting the production of green hydrogen.

The development of cross-border infrastructure, such as the hydrogen pipeline connecting Bornholm to Germany, reflects regional cooperation and alignment with EU energy objectives. This infrastructure enhances energy export potential, fostering collaboration between countries and expanding the reach of Bornholm's renewable energy production. However, challenges like changes in offshore wind schemes can impact energy availability and project stability. Addressing these challenges requires adaptive strategies and close collaboration with stakeholders and regulatory authorities, ensuring a robust energy infrastructure that supports PtX technologies.

10.2.6. Innovation and Environmental Impact

From a political perspective, Bornholm's Power-to-X project exemplifies Denmark's dedication to innovation and environmental responsibility. The project underscores Denmark's commitment to pioneering renewable energy solutions and technological advancements. By exploring PtX technologies, Bornholm showcases its political will to foster sustainable growth while addressing environmental challenges. This commitment to innovation resonates both locally and internationally, positioning Bornholm as a leader in the transition to a more sustainable energy future.

The project's focus on the integration of renewable energy sources aligns with political goals to enhance grid stability and reliability. PtX technologies offer a solution to the intermittent nature of renewable energy sources by enabling energy storage in the form of synthetic fuels. This integration strengthens the energy system's resilience and contributes to the overall stability of the grid. The political implications of this integration are significant, as it supports the successful integration of variable renewable energy sources and advances the region's energy transition goals.

10.2.7. Regulations and Policies

Bornholm's Power-to-X project operates within a complex regulatory framework, shaping the project's trajectory and outcomes. The approval process from planning and environmental authorities influences project timelines and feasibility. Clear understanding and compliance with these processes are essential to navigate potential challenges and ensure positive project outcomes. Political support for transparent and efficient regulatory processes is crucial to accelerate project deployment.

The Danish Climate Act and participation in the EU Emissions Trading System (ETS) demonstrate political commitment to greenhouse gas emissions reduction and carbon pricing. These policy frameworks create a conducive environment for PtX technologies, aligning the project with broader national and international sustainability goals. However, changes in policies, such as the cancellation of offshore wind schemes, can introduce uncertainties. Adapting to policy changes while maintaining project viability requires strategic planning and collaboration with policymakers to ensure that the project remains aligned with evolving regulations.

10.2.8. Challenges identified.

Table 17. Political Challenges Impact-Effort Table

Factor Name	Challenge	Solution	Solution Description	Impact Score	Explanation of Impact Score	Effort Score	Explanation of Effort Score
Infrastructure and Capacity	Changes in offshore wind schemes affecting power supply	Adaptive strategies	Diversify energy sources, enhance grid, plan for flexible capacity	4	Significant impact due to direct project implications	3	Moderate effort due to technical adjustments required
Regulations and Policies	Uncertain policy landscapes impacting project stability	Regulatory collaboration	Work closely with authorities for policy alignment and adaptability	3	Moderate impact, ensures regulatory compliance	3	Moderate effort in continuous monitoring and coordination
Energy Independence and Security	Geopolitical risks affecting energy supply	Risk assessment strategy	Assess and diversify energy sources and supply routes	3	Moderate impact, enhances energy security	4	Substantial effort in comprehensive risk assessment
Funding and Employment	Sustainable funding in competitive markets	Innovative funding mechanisms	Utilize PtX tenders, engage private sector for investments	4	Significant impact by securing funding	3	Moderate effort to establish new funding avenues
Collaboration and International Cooperation	Sustaining effective collaboration with stakeholders	Engaging partnerships	Foster open dialogue, align partnerships with shared benefits	3	Moderate impact, ensures stakeholder support	3	Moderate effort in continuous engagement and communication

10.3. Economic Factors

The economic factor evaluates the financial aspects and market conditions related to PtX technologies. It includes factors such as the cost of production, market demand and price for PtX products, energy prices, government incentives and subsidies, as well as the availability and cost of infrastructure and raw materials required for PtX processes. Economic viability and competitiveness of PtX technologies are assessed under this factor.

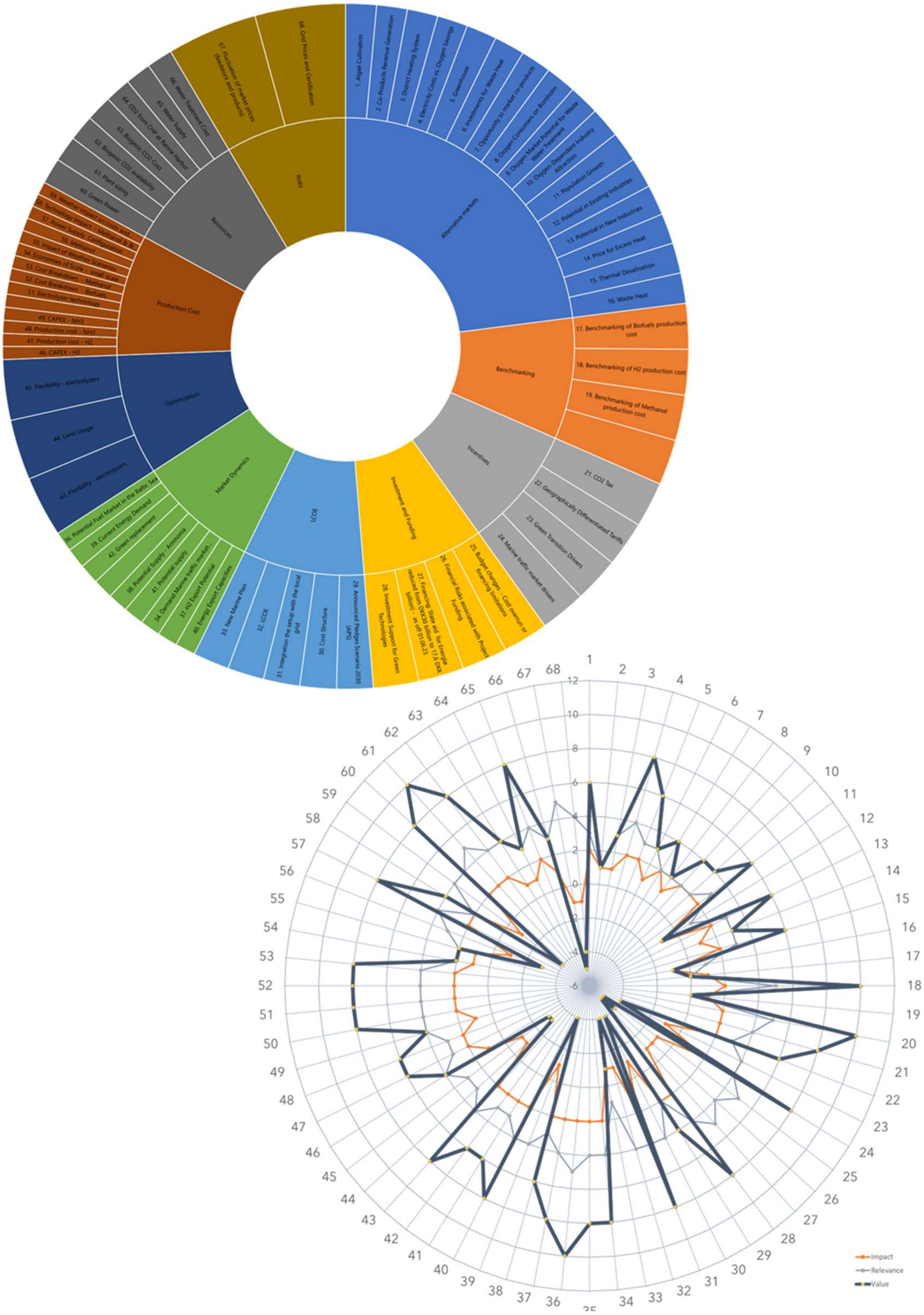


Figure 65. Economic Factors Classification and Value

10.3.1. Market Dynamics

- Current Energy Demand

The current energy demand on Bornholm is primarily driven by local industries, heavy transportation, and marine traffic. Local industries consume approximately 18,465 MWh of energy per year, primarily in the form of LPG. The heavy transportation sector consumes about 155,000 MWh (15,500 m3) yearly, primarily from diesel fuel. The ferry service on Bornholm consumes around 29,000 tons of MGO annually. Additionally, there are emissions from other sources such as local air traffic and heating demand.

- Future Demand

Bornholm is actively exploring options to replace traditional fossil fuels with greener alternatives. For instance, local industries that currently use LPG are considering biogas or hydrogen as suitable replacements. The heavy transportation sector, which relies heavily on diesel, is also exploring alternatives like biogas, hydrogen, and even electrification in specific sectors. The marine traffic sector, including the ferry service and vessels passing by, is planning to transition from using MGO (Marine Gas Oil) to environmentally friendly alternatives like e-Methanol or e-Ammonia. These shifts are motivated by the need to reduce carbon emissions, comply with EU ETS (Emission Trading System) regulations, and promote sustainable practices.

The island is strategically located in the Baltic Sea, with a high volume of vessel traffic passing through its waters. Approximately 60,000 vessels pass close by Bornholm each year. It's estimated that if 0.1% of these vessels stop and refuel with green fuels from Bornholm's Bunker Hub in 2030, it could equate to 60 vessels bunkering around 17,100 tons of fuel. The projected Bornholm Bunker Hub could potentially supply 34,000 tons of fuel in 2040, establishing a market for locally-produced e-fuels generated through Power-to-X technology.

The expansion of the Port of Roenne and offshore wind projects in the area could lead to an annual installation capacity of 1.5 GW. This growth could result in increased methanol demand of 3,540 to 5,475 tons, starting around 2040. For a 1 GW offshore installation, around 1,100 to 1,700 tons of MGO or 2,360 to 3,650 tons of methanol might be required.

- Supply

The potential supply of green energy on Bornholm is influenced by factors such as renewable energy sources (wind, solar), electrolyzer technology, and production capacity. The study has identified the potential for hydrogen and ammonia production, driven by the availability of renewable energy sources and suitable electrolyzer technology. However, specific supply volumes depend on various factors, including investment decisions, grid capacity, and market demand.

Ammonia is emerging as a potential zero-carbon maritime fuel and energy carrier. The Port of Roenne's expansion and offshore wind project growth could establish a significant ammonia market by 2040, with potential demand arising from vessels passing by and visiting the port. Forecasted increases in ammonia production and consumption for future marine fuel use until 2040 further underline the potential of ammonia as a green fuel but still much work is required before ammonia is used as fuel.

- Export

The concept of exporting hydrogen to Germany introduces additional complexity to the analysis. The associated infrastructure and costs of exporting hydrogen to Germany have strategic implications and could increase the relevance of a Power-to-X plant on Bornholm. However, transport costs are uncertain and challenging to predict accurately at this stage.

10.3.2. LCOE (Levelized Cost of Electricity)

LCOE, or Levelized Cost of Electricity, is a critical metric used to assess the cost-effectiveness of electricity generation technologies over the entire lifetime of a project. It provides a standardized way to compare different energy sources based on their total costs and takes into account both upfront capital costs and ongoing operational expenses. LCOE is expressed in terms of the cost per unit of electricity generated, usually in megawatt-hours (MWh).

The LCOE estimation considers various cost components that contribute to the overall lifetime cost of generating electricity. These components include:

- Capital Costs: The initial investment required for building the energy generation facility, including equipment, infrastructure, and installation expenses.
- Operating and Maintenance (O&M) Costs: The ongoing expenses associated with operating, maintaining, and repairing the equipment and infrastructure. This includes costs for labor, spare parts, maintenance contracts, and other operational activities.
- Fuel Costs: For renewable energy sources like wind and solar, there are no fuel costs. However, for conventional sources like natural gas or coal, fuel costs play a significant role.
- Financing Costs: Interest rates on loans, financing terms, and other financial aspects that impact the project's total cost.
- Expected Lifetime: The estimated number of years the energy generation facility will be operational before requiring significant upgrades or replacement.
- Policy and Regulation- Regulation like the newly adopted Marine PLan[41] can also affect the LCOE projections. As seen in the study "Our Energy, Our Future", 35GW capacity are forecasted for 2050 in Denmark alone, off which 22,9 GW could be in areas where the LCOE is in the very low range if no spatial exclusions are included. If there are spacial exclusions, only 6,1GW will be located in the very low area. North Sea projects are more likely to be affected but projects near Bornholm are also at risk as since after the cancellation of the Open Door Scheme[42]

10.3.3. Resources

- Green Power

The project analyzed Bornholm's renewable potential, primarily focusing on offshore wind for large scale projects and in combination with photovoltaic (PV) solar power for small scale (domestic) projects.

Currently, Bornholm boasts an onshore wind power capacity of approximately 37 MW. This existing capacity, although substantial, there are no plans further expansion as per the Energy Strategy 2040.

In the other hand, offshore wind expansion plans are still on going as well as the Bornholm Energy Island. Denmark and Germany have signed an agreement on a joint offshore wind project that creates the basis for future green electricity imports to Germany.

Regarding, Solar Power, Bornholm's vision includes a 20 MW capacity for PV solar power, with plans to escalate this capacity to 50 MW by 2025. Integrating these green power sources into the local energy grid significantly reduces carbon emissions and bolsters energy sustainability.

- Water

Rønne wastewater treatment plant was identified as a reliable water supply source for the Power-to-X plant. Rigorous analysis indicates that this plant can comfortably meet double the maximum water demand of the Power-to-X facility throughout most months, ensuring operational robustness. Sea water is also an alternative due to its low salinity.

Different water sources necessitate varying degrees of treatment before they can be used in energy production processes. Seawater, groundwater, surface water, and treated wastewater each incur distinct treatment costs, exerting an influence on the overall project economics.

- Biogenic CO2

Bornholm's Bigadan biogas plant stands as a substantial source of biogenic CO2. Projections indicate a substantial increase in biogenic CO2 production by 2030, presenting an opportunity for carbon capture and utilization.

Another alternative is the combined heat and power (CHP) plant at Rønne Harbor releases around 68,000 tons of CO2 annually, subject to seasonal fluctuations. Leveraging this CO2 availability holds implications for carbon capture and utilization initiatives.

The financial aspect of sourcing biogenic CO2 from various origins is a crucial consideration. While CO2 from sources like the Bigadan biogas plant is anticipated to be cost-effective due to its byproduct nature, intricate negotiations and agreements are imperative. REACTRF-22-0054 has been expanded until 31-Dec-2023 to explore this path further.

- Plant Sizing

Hydrogen producing systems require 20 Ha, if based in SOEC technologies and up to 30 Ha, using AEC technology. Ammonia systems are more demanding, requiring circa 70 Ha, not including safety zone. Safety zones must be calculated considering the specific volumes, weather conditions, geographical location, etc.

10.3.4. Production Costs

- Key Components:

The offshore wind farm (OWF) and electrolyzers are key components contributing to the overall production costs across various scenarios for hydrogen, ammonia, and methanol. Cost optimization potential lies in these areas. Weather significantly influences both fuel production and total system costs. Stochastic analysis, accounting for weather uncertainty over multiple years, is crucial for robust plant sizing.

- Hydrogen Production:

Hydrogen production is found to be more cost-effective than ammonia production. The solid oxide electrolysis cell (SOEC) technology emerges as the preferable option for hydrogen production, with estimated CAPEX ranging from 257 to 299 million Euro. Hydrogen production costs range from 3.91 to 4.54 Euro per kg using SOEC technology.

- Ammonia Production:

Ammonia production costs are higher compared to hydrogen. SOEC technology is favored for ammonia production as well, with CAPEX estimates between 370 and 428 million Euro. Ammonia production costs range from 0.87 to 1.01 Euro per kg using SOEC technology.

- Methanol Production:

Methanol production costs vary based on technology and CO2 source. Using AEC or SOEC technology with locally sourced CO2, methanol production costs are 1.28 Euro/MWh. Importing CO2 reduces costs to 1.09 Euro/MWh. For biofuels, production costs range from 2.26 to 2.5 Euro/MWh, with a slight advantage for methanol.

- Electrolyzer Technology:

SOEC technology is the most cost-effective choice for both hydrogen and ammonia production, based on techno-economic data predictions for 2030.

- Plant Configuration:

Both large-scale and small-scale scenarios favor a behind-the-meter (BTM) power supply configuration, directly connecting the Power-to-X plant to renewable energy supply. BTM is preferred due to fewer economic uncertainties and assurance of green fuels.

- Technology Impact on Methanol & Biofuels:

In small-scale scenarios, electrolyzer technology has a reduced impact on total system costs due to the smaller electrolyzer size.

10.3.5. Bornholm Production Costs Benchmarking

- *Hydrogen*[43]

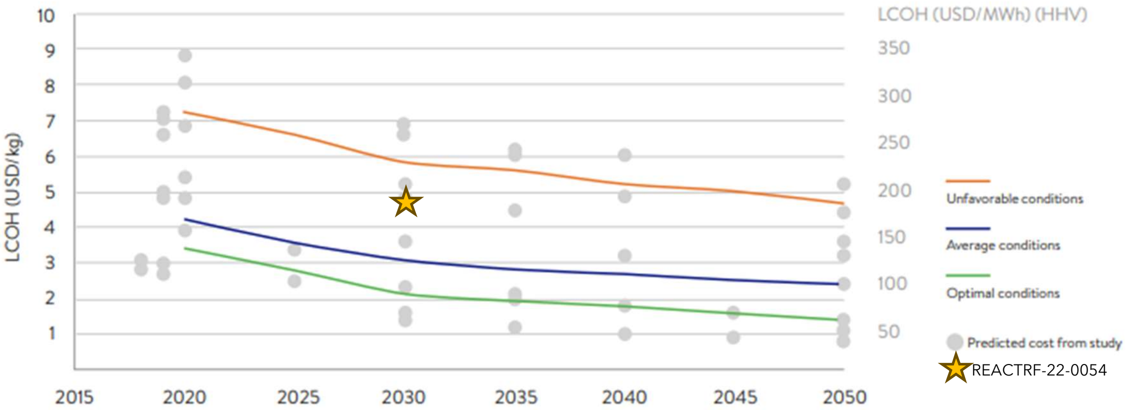
Work Package 2 modelled hydrogen production costs range from 3,91-4,54 EUR / H2 Kg using SOEC technology to 4,41-5,12 EUR / H2 Kg using AEC technology. Using a mix of AEC and SOEC, the costs range from 4,28 -4,98 EUR / H2 Kg. This is roughly a 4,54 Euro / H2 Kg average or 4,93 USD / H2 Kg (Average exchange rate in 2023: 0,9211 EUR / USD).

WP2 Production costs were modelled considering 2030 as time horizon. System efficiency is linked to the technology selected, AEC system efficiency is 47 to 48% and 52 to 54% for SOEC. It was also estimated a 28% reduction in CAPEX in relation to current levels[44].

At this moment, in Europe, green hydrogen production costs vary from €3 to €8/kg. The low end of these ranges can be achieved most easily in locations with access to low-cost renewable energies plants. The forecasted costs are in general expected to decrease towards 2030 and 2050 but there are wide variations on the hydrogen demand and hydrogen production costs projections, depending on the assumptions such projections are based upon.

World Energy Outlook (WEO) and the Energy Technology Perspective (ETP) use a scenario approach to examine future energy trends[45]. The first scenario is the Net Zero Emissions by 2050 Scenario. This scenario is designed to limit the global temperature rise by 2100 to 1.5°C. The other two scenarios, Stated Policies Scenario (STEPS) and Announced Pledges Scenario (APS) define a set of conditions as policies, targets, technological achievements, electricity costs and model their effect of such factors on the energy system and therefore in the production costs. STEPS aims to achieve a maximum rise of global temperature of 2.5°C and APS of 1.7°C.

Other forecasters use variations of these scenarios, with different approaches to technological achievements and CAPEX and electricity costs which are the main cost drivers in hydrogen production. The wide variation on the set of assumptions made by different studies and forecasters makes benchmarking challenging. However, in 2021, the World Energy Council review a set of 16 different scenarios and develop 3 different price corridors. These corridors mark unfavorable, average, and optimal conditions, and are based around the assumptions made by STEPS, APS and NZE respectively. Figure 66 provides a visualization of the different ranges.

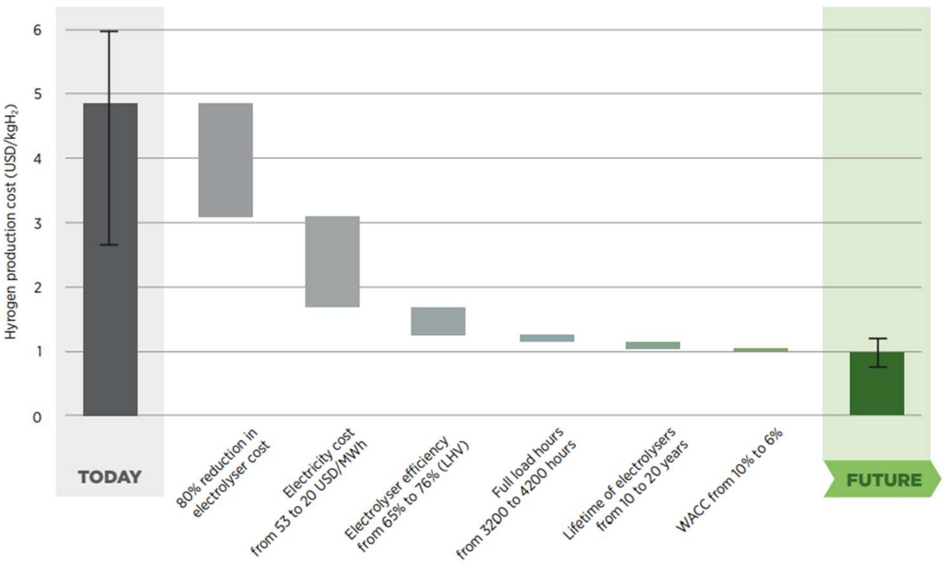


Source: World Energy Council*

[2] *Agora (2020). Klimaneutrales Deutschland. | Greenpeace Energy (2020). Blauer Wasserstoff. | Deutscher Bundestag (2020). Kosten der Produktion von grünem Wasserstoff. | Hydrogen Council x McKinsey & Company (2021). Hydrogen Insights. | Strategy& (2020). The dawn of green hydrogen. | DOE Hydrogen (2020). Hydrogen Production Cost From PEM Electrolysis.*

Figure 66. Renewable Hydrogen Cost Dynamics by 2050[46].

The modeled Bornholm hydrogen costs falls above the average conditions which are very similar by the assumptions considered by the APS scenario. Among others, this scenario assumes a technology cost drop of 80%, electricity cost as low as 20 USD/MWh and electrolyzer efficiency as high as 75% (see Figure 67). Assumptions that are considered very challenging by many analysts[47].



Note: 'Today' captures best and average conditions. 'Average' signifies an investment of USD 770/kilowatt (kW), efficiency of 65% (lower heating value – LHV), an electricity price of USD 53/MWh, full load hours of 3 200 (onshore wind) and a weighted average cost of capital (WACC) of 10% (relatively high risk). 'Best' signifies investment of USD 130/kW, efficiency of 76% (LHV), electricity price of USD 20/MWh, full load hours of 4 200 (onshore wind) and a WACC of 6% (similar to renewable electricity today).

Based on IRENA analysis

.Figure 67. Potential to cut hydrogen cost from 2021 level to 2030[48]

The project production costs are modeled considering higher LCOE prices and electrolyzer costs (Refer to WP2 - Modelling of scenarios for Power-to-X production in Bornholm, Appendix). This provides the most conservative estimation within the context of Bornholm the project could conceive.

This is only an illustration to put the project calculated costs in perspective with the forecasts available in literature. By using a worst-scenario-approach, WP2 intended to reduce as many in uncertainties as possible, since the future of the market depends not only on a low electricity price to be competitive but need also to be paired in advancements in technology. Both can't be really guaranteed, but if the forecasted scenario realizes, the estimated costs for Bornholm will follow that trend.

- Ammonia[49]

The modelled production cost ranges for ammonia vary from 810 EUR / Kg to 1000 Euro /Kg. or roughly 868 to 1085 USD/ Kg (Average exchange rate in 2023: 0.9211 EUR / USD). The cost is heavily determined by the electrolyzer technology being the SOEC system the one with more favorable results, which aligns with the forecasts in literature. This cost range falls within the IRENA estimates worldwide and close to the estimates in the European market (Figure 68).

As in the hydrogen case, the assumptions made in difference scenarios have a great impact on the production costs expected in 2030. Technology advancements, favorable electricity cost and electrolyzer efficiencies will be main cost drivers. Other studies carried out by DTU, also point out that the power setup (off grid vs grid connected) will have an impact on the costs, which must be considered in future analysis.

The modelled productions costs can be use as illustration of the Bornholm case but a detailed analysis based in the particular cases must be assessed in order to have a better grasps of the future production costs.

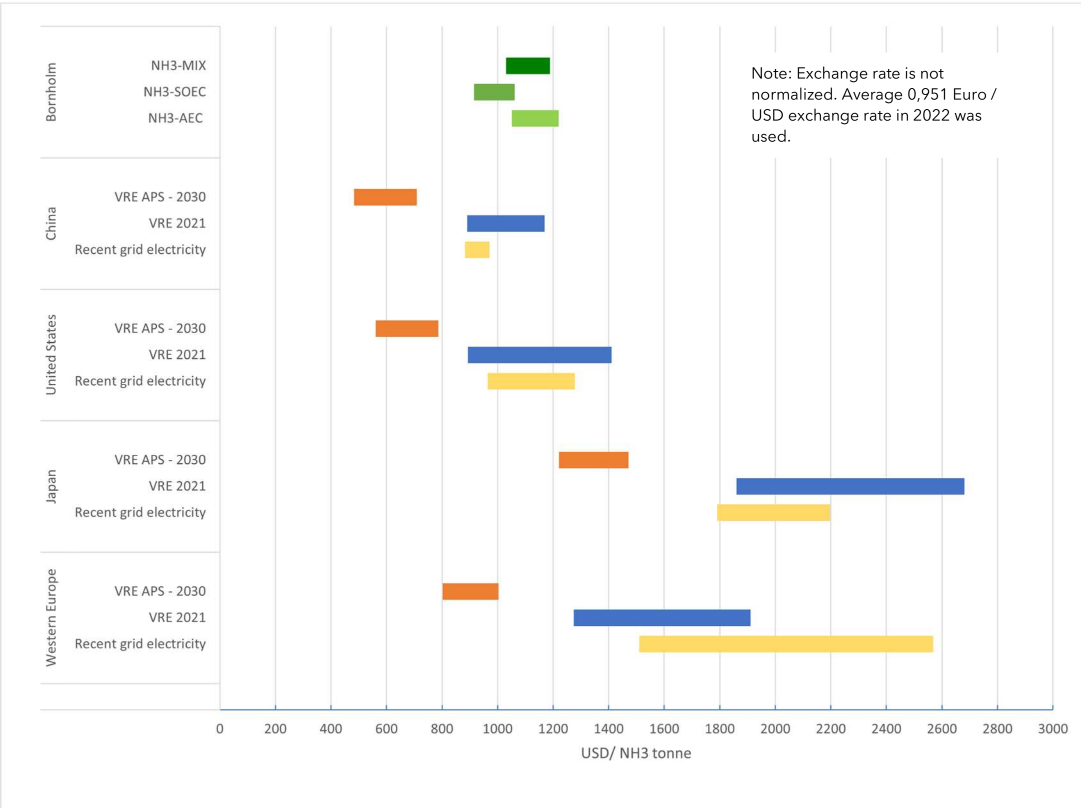


Figure 68. Comparative NH3 production costs, including WP2 estimate and VRE APS 2030 projections.

10.3.6. Optimization

- Flexibility - Electrolyzers:

Flexibility is identified as a critical component for a successful and cost-effective transition to a renewable electricity system. Electrolyzers, when integrated into hybrid plants alongside renewable sources and batteries, have the potential to provide reserves. This factor emphasizes the importance of designing operational strategies, portfolio configurations, and operational sequences that maximize the utilization of electrolyzers to enhance the flexibility of the energy system.

- Land Usage Optimization:

Efficient land usage optimization is imperative for ensuring the economic viability of renewable energy projects but also to reduce their environmental impact.

Future projects should reassess methods of land utilization to explore the feasibility of constructing additional facilities in already existent industrial states, assess safe alternatives to integrate storage space and common areas. Furthermore, the estimation of the required safety area requires a extensive risk assessment in collaboration with experts and authorities.

10.3.7. Incentives

- CO2 Tax:

The decision to implement a CO2e tax on industries not covered by the EU's allowance trading system (ETS) starting in 2025 will have significant implications for companies' operating costs. The CO2 tax will be gradually introduced, with different rates for companies inside and outside the ETS. By 2030, a CO2 tax rate of DKK 750 per ton of emitted CO2 will apply to non-ETS companies, while ETS-covered companies will face a rate of DKK 375 per ton. Additionally, road transportation will be integrated into the EU ETS by 2027, leading to higher CO2e emission prices by 2030 and promoting the competitiveness of green fuels.

- Geographically Differentiated Tariffs:

Energinet and large electricity consumers connected to the grid at 10 kV and above might encounter geographically differentiated consumption tariffs. These tariffs are aimed at incentivizing appropriate location choices, potentially favoring areas that align with green transition objectives.

- Green Transition Drivers:

Industries and transportation sectors contribute varying levels of CO2e emissions. The local industry emits 2,900 kg of CO2 per ton of CO2e emissions annually, while local heavy transportation emits 41,540 kg of CO2 each year. Marine traffic contributes approximately 3.2 tons of CO2e per ton of MGO (marine gas oil) emissions. Notably, efforts are underway to transition the local ferry service to emission-free operations by 2030. The government intends to propose green transition strategies for air traffic and explore the role of Power-to-X (PtX) technologies in sectors like shipping and heavy road transport.

- Marine Traffic Market Drivers:

Starting in 2026, vessels with a gross tonnage (GT) above 5000 will be required to report their CO2e emissions within the EU ETS. Emissions from intra-EU travel will account for 100% of the EU ETS, while travel between EU and non-EU ports will contribute 50%. Vessels will need to pay the prevailing European Carbon Market price for their emissions. Over time, the EU ETS will reduce the allowable CO2e emissions, leading to annual emission reductions of 2% (2022), 6% (2030), and eventually reaching a 75% reduction by 2050. These reductions will drive up the price of CO2e on the EU Carbon Market, influencing market dynamics and encouraging emission reductions.

10.3.8. Investment and Funding

- Budget Changes and Cost Overruns: The project's budget is vulnerable to fluctuating costs due to uncertainties in resource and product prices, regulatory changes, and access to finance or state aid. This introduces the risk of project costs exceeding the initially budgeted amount, which could potentially affect the project's financial feasibility and timeline.

- Financial Risks of Project Funding: Securing funding for the Power to X plant is exposed to financial risks stemming from fluctuations in interest rates and the availability of capital. Effective financial planning and the diversification of funding sources will be crucial to mitigate these risks and ensure stable financing throughout the project's lifecycle.

- State Aid Reduction for Energiø: The Danish Parliament's decision to reduce state aid for Energiø Bornholm's offshore wind farms from DKK 30 billion to DKK 17.6 billion introduces a challenge to the project's funding. While the Ministry of Climate, Energy, and Utilities estimate a higher need for state aid, the capped amount may not be sufficient to guarantee the successful construction of the energy island. This limitation underscores the need for efficient resource allocation and cost-effective project management.

- Investment Support for Green Technologies: The government's engagement with the European Commission to secure DKK 344 million from the REACT-EU initiative signifies an opportunity to accelerate the adoption of innovative green technologies. This investment support can play a pivotal role in enhancing the efficiency and sustainability of the Power to X plant, contributing to its long-term success.

10.3.9. Risks

- Fluctuation of Market Prices (Feedstock and Products): The variability in market prices for both feedstock and end products, such as hydrogen and synthetic fuels, poses a significant risk to the Power-to-X plant's revenue and profitability. Sudden and unexpected shifts in market prices can lead to reduced revenue and profitability, potentially hindering the plant's ability to achieve its financial objectives. Adequate risk management strategies are essential to mitigate the impact of market price fluctuations and maintain the project's financial sustainability. (i.e., Local Biogenic CO2)

- Grid Prices and Certification: Not applicable for Behind the meter, but a consideration if connected directly to the grid. Uncertainty surrounding future grid prices and renewable fuel certification for products generated by the Power-to-X plant introduces an element of risk to its economic viability. Fluctuations in grid electricity prices can affect the overall cost structure of the plant's operations, potentially impacting its competitiveness in the market. Additionally, uncertainty in obtaining renewable fuel certifications could limit market access and hinder the plant's ability to capture premium pricing for environmentally friendly products. Proactive planning to manage grid price risks and ensure compliance with certification requirements is crucial for the plant's success.

10.3.10. Alternative Markets

- Waste Heat:
  - Optimize cooling systems and heat exchangers for efficient waste heat recovery.
  - Evaluate waste heat sources for compatibility with district heating temperature requirements.
  - Explore integration of waste heat from industries and processes to supplement district heating.
  - Consider heat pumps to elevate waste heat temperatures if needed for district heating.

- Perform economic analysis to determine feasibility, accounting for infrastructure costs and potential benefits.

- Oxygen:
  - Investigate using oxygen instead of air in compressors for wastewater treatment and other industries.
  - Assess potential cost savings from transitioning to oxygen-based processes.
  - Identify existing oxygen consumers in industries and medical facilities on Bornholm.
  - Explore oxygen market potential for wastewater treatment, focusing on energy savings.
  - Analyze economic attractiveness of producing oxygen via electrolysis for attracting oxygen-dependent industries.

10.3.11. *Proposed Impact Effort Table*

Table 18. Economic Factors - Proposed Impact Effort Table

Challenge	Solution	Solution Description	Impact Score	Explanation of Impact Score	Effort Score	Explanation of Effort Score
Budget changes - Cost overrun or financing limitations	Rigorous Financial Planning and Diverse Funding	Implement thorough financial planning and secure diverse funding sources to manage cost overruns and financing challenges effectively.	5	Comprehensive financial planning and diverse funding require substantial effort but yield significant positive impacts on cost control and financial stability.	4	Implementing robust financial planning and securing diverse funding sources may involve complexity and resource allocation.
Financing: State aid reduction	Explore Alternative Funding Avenues	Engage stakeholders to explore alternative funding options and partnerships to bridge the financial gap caused by state aid reduction.	4	Exploring alternative funding options requires effort, but it can help mitigate the negative impact of reduced state aid on project viability.	4	Identifying and establishing alternative funding avenues may involve negotiations and collaboration with various stakeholders.
Fluctuation of market prices	Risk Management Strategies (Hedging, Scenario Planning)	Develop risk management strategies, such as hedging and scenario planning, to mitigate the impact of market price fluctuations on revenue and profitability.	3	Effective risk management strategies can moderate the negative impact of market price fluctuations on revenue and profitability.	3	Implementing risk management strategies requires analysis, planning, and continuous monitoring of market dynamics.
Weather impact on costs and stochastic sizing	Sophisticated Stochastic Modelling	Employ advanced stochastic modelling to consider weather uncertainties over multiple years for accurate plant sizing and cost projections.	4	Advanced stochastic modelling enhances accuracy in plant sizing and cost projections, reducing the negative impact of weather-related risks.	3	Developing and implementing sophisticated stochastic models requires specialized expertise and computational resources.
Grid Prices and Certification	Proactive Engagement	Establish proactive communication	4	Proactive engagement with regulatory	3	Maintaining consistent communication

	with Regulatory Authorities	with regulatory authorities to gain insights into future grid prices and certification requirements.		authorities provides insights that aid in adapting to changing grid conditions and maintaining financial resilience.		and coordination with regulatory bodies necessitates ongoing effort.

10.4. Social Factors

The social (sociocultural) factor explores the social and cultural aspects that may impact the acceptance and adoption of PtX technologies. This includes public awareness and perception of renewable energy, attitudes towards PtX products, consumer preferences, and societal values related to sustainability and environmental concerns.

Figure 69. Social Factors Classification and Value

10.4.1. Community Involvement & Acceptance

Community involvement and acceptance are essential aspects of any large-scale development project, particularly in the renewable energy sector. Ensuring positive relationships between developers and the local community can lead to smoother project implementation and better outcomes for all stakeholders.

- Authority Process: Early engagement with relevant authorities and the public is crucial for establishing a cooperative environment. Transparent processes help build trust and confidence among stakeholders. By involving authorities and the community from the outset, potential conflicts can be addressed, and concerns can be mitigated.

- Call for Clarity on PTX Plans: Local neighbors seek clear explanations regarding the plans for power-to-x and other industrial facilities. Providing comprehensive information about the project's purpose, potential consequences, and benefits can alleviate concerns and foster understanding.

- Communication Lines: Open and ongoing dialogue between developers and the community is vital. Platforms such as town hall meetings, public forums, and feedback sessions enable community members to express concerns and ask questions. Long-term communication, transparency, and feedback mechanisms contribute to a more informed and supportive community.

- Ownership Models for Project Acceptance Improvement: Implementing ownership models, common in the EU, can enhance project acceptance. These models, including RE-bonus schemes, loss of value schemes, option-to-sell schemes, and green fund schemes, offer incentives and compensation to residents and municipalities, aligning interests and fostering acceptance.

- Transparency and Decision-Making: The demand for transparency in decision-making from the Citizens' Association underscores the need to safeguard the interests of local residents. Transparent processes can help address concerns and ensure that the community's voice is heard in the project's development.

10.4.2. Cultural and Heritage

- Architectural Policy: The municipal council's focus on enhancing architectural quality highlights the importance of blending modern developments with the island's cultural and historical aesthetics. Balancing innovation with preservation is crucial to maintain Bornholm's unique identity.

- Bornholm's Changing Identity: The shift from a traditional island economy to a hub for wind energy and green fuel production signifies a significant transformation. This transition impacts various aspects of life on Bornholm, including its economy, industries, and cultural identity.

- Cultural Sensitivity: Respecting local cultural values and traditions is essential during project development. Aligning the project with the community's identity and considering cultural impacts can help maintain harmony between modernization and heritage.

- Tourism: The potential influx of tourists due to the PTX project necessitates careful planning to prevent straining local resources and impacting Bornholm's cultural heritage. Proper management can turn tourism into an economic boon while preserving the island's identity.

10.4.3. Effect on Local Communities

- Brownfield, Commercial and Industrial Areas: Utilizing brownfield and existing industrial zones for the PTX plant location can provide economic benefits and synergies. The proximity to the planned transformer station and established industrial areas can lead to efficient development.

THE EUROPEAN UNION
The European Regional Development Fund
Funded as part of the Union's response to the COVID-19 pandemic
Investing in your future
Danish Board of Business Development

- Loss of Value Scheme: The provision for compensation due to loss of value on residential properties offers protection to residents who might be affected by the project's development. This compensation mechanism addresses potential concerns over property value depreciation.

- Option-to-Sell Scheme: Allowing neighbors within a specific distance to sell their properties to the developer offers an exit strategy for those directly impacted by the project. This scheme acknowledges the local community's needs and concerns.

- RE-Bonus Scheme: The RE-bonus scheme, which involves developers paying neighbors an annual bonus, creates a financial incentive for local residents to support and benefit from the project's presence.

- Farming: The potential conversion of agricultural land for industrial purposes emphasizes the need to balance industrial growth with agricultural sustainability. Careful land use planning can mitigate conflicts between these vital sectors.

- Tourism: While tourism can boost the economy, managing increased tourism sustainably is essential to prevent overburdening local resources and negatively affecting Bornholm's cultural heritage.

- Use of Waste Products: Recreating a historical climate through the use of waste products offers tourism and educational potential. However, challenges in implementing this concept need to be addressed for successful execution.

10.4.4. Employment:

- Employment Opportunities: The projection of job creation through various roles related to offshore wind service, power-to-x plant building and operation, and other aspects of the energy transition underscores the potential for employment growth on Bornholm.

- Implementation on local training programs: Partner with local educational institutions, such as vocational schools, technical colleges, and universities, to design training programs that align with the identified skill gaps. Collaborating with these institutions ensures that training is tailored to local needs.
.
- Employer Engagement: Collaborate with local businesses, including potential employers in the PtX sector, to ensure that the local training programs aligns with industry needs. This can also lead to potential job placements for program graduates.

- Continuous Learning, Education and Training: Staying updated with the latest advancements in PtX through continuous learning, education, and training programs than enhances workforce competence and ensures that employees are well-equipped to contribute to the rapidly evolving field.

- Networking and Collaboration, On-the-Job Experience: Engaging with professionals in the PtX industry and gaining practical experience through networking, internships, and collaborations can enhance skills and competences, facilitating career growth and industry development.

10.4.5. Safety Concerns

- Education and Awareness: Educational efforts play a pivotal role in garnering support for the power-to-x project on Bornholm. By explaining the broader benefits of sustainable practices, developers can foster understanding and dispel misconceptions. Simultaneously, awareness campaigns through various channels help keep the public engaged and informed, making the community feel like active stakeholders in the project's success.

- Terrorism Risk Assessment: In today's security landscape, a thorough terrorism risk assessment is vital for the power-to-x project's safety on Bornholm. By evaluating vulnerabilities and potential threats, developers can design effective security measures that reassure both the community and investors. Sharing this approach demonstrates the project's commitment to safety, supporting long-term success and overall island resilience. DBI has developed a handbook for physical terrorism security. It includes a risk assessment tool and a knowledge database[50]. It can be accessed at https://www.terrorsikring.nu/Risikovaerktoj/.

Proposed Impact Effort Table

Table 19. Social Factors - Proposed Impact Effort Table

Factor	Challenge	Solution	Impact	Explanation of Impact	Effort	Explanation of Effort
Bornholm's Changing Identity	Transitioning to a new economic identity based on wind energy and green fuel production.	Develop strategies to integrate traditional industries with the new energy-focused economy.	2	Negative impact	3	Moderate effort
Call for Clarity on PTX Plans	Addressing community concerns and providing transparent explanations of potential impacts.	Engage in public consultations, workshops, and clear communication to address concerns.	4	Negative impact	4	Moderate effort
Tourism	Managing increased tourism's strain on resources and its impact on the cultural heritage of Bornholm.	Develop sustainable tourism management plans, including resource management and preservation.	1	Negative impact	2	Low effort
Transparency and Decision-Making	Balancing transparency with efficient decision-making while safeguarding local residents' interests.	Establish clear communication channels, involve stakeholders in decision-making, and ensure fairness.	4	Positive impact	3	Moderate effort
Oxygen Consumers on Bornholm	Identifying existing oxygen consumers and understanding their needs for market analysis and expansion strategies.	Collaborate with existing consumers to gather insights and align offerings with market demands.	3	Positive impact	3	Moderate effort

10.5. Technological Factors

The implementation of a Power to X (PtX) project in Bornholm is influenced by a multitude of factors spanning energy and input, infrastructure and setup, operational performance, environmental considerations, costs, market trends, location, transport, and storage. There were identified 51 factors influencing the implementation of a Power to X plant.

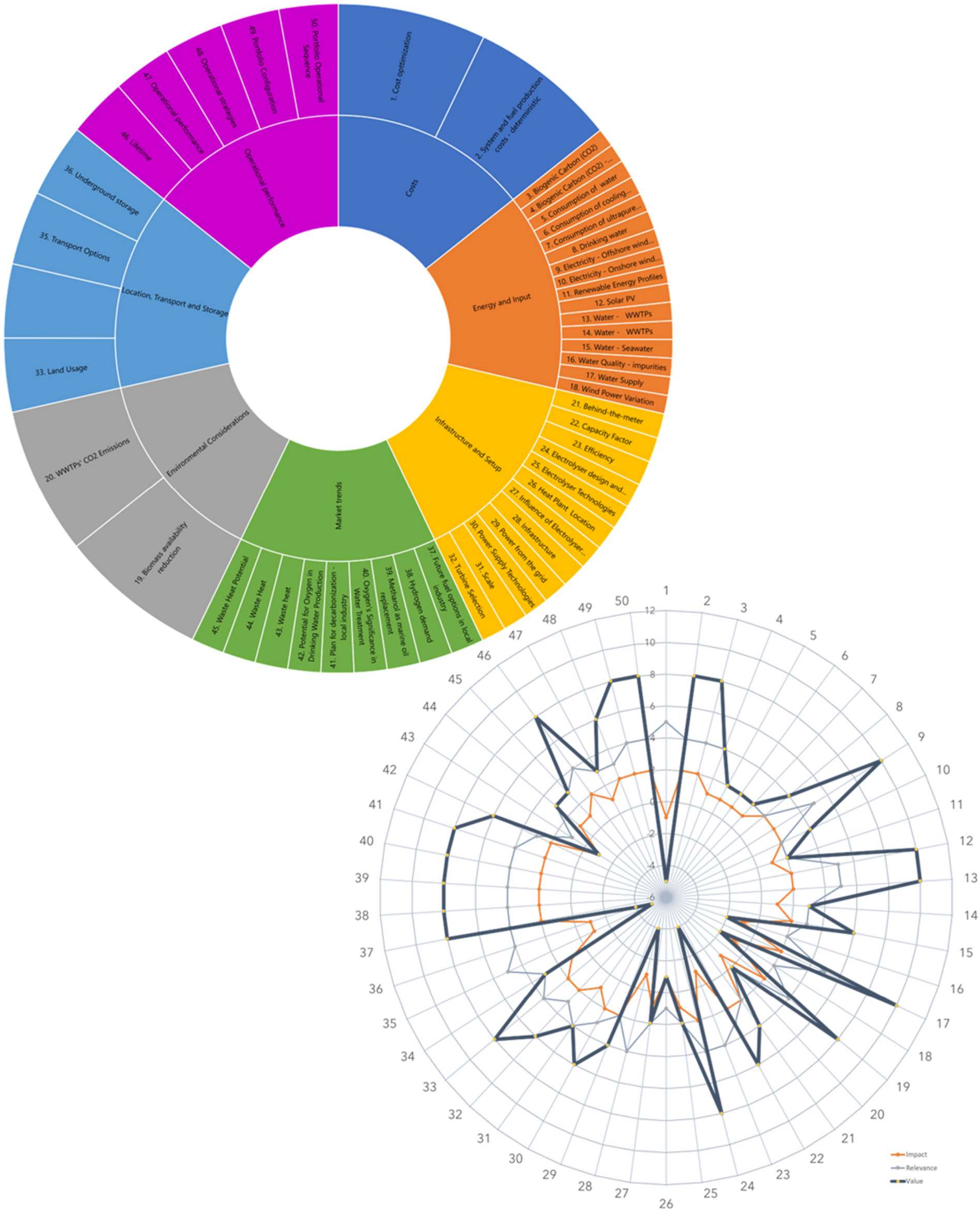


Figure 70. Technological Factors Classification and Value

10.5.1. Cost Optimization in Offshore Wind Farm and Electrolyzer System

The Offshore Wind Farm (OWF) and the electrolyzers emerge as the primary cost contributors across all the scenarios studied. This outcome highlights the critical importance of targeted cost optimization strategies in these areas to ensure the economic viability of the entire system.

- Offshore Wind Farm (OWF) Cost Optimization
  The Offshore Wind Farm component encompasses various expenses, including infrastructure setup, maintenance, and operation. Efficient cost management in this area involves optimizing the design and deployment of wind turbines, transmission systems, and support structures. By identifying cost-effective materials, streamlined installation processes, and advanced maintenance techniques, it is possible to mitigate OWF-related expenses.

- Electrolyzer Cost Optimization
  Electrolyzers are critical components for the conversion of renewable energy into hydrogen or ammonia. The study reveals that these components contribute significantly to the system's overall costs. To achieve cost optimization in electrolysis, advancements in technology, materials, and manufacturing processes need to be pursued. Moreover, efficient supply chain management and integration with renewable energy sources are essential to reduce the expenditure associated with electrolyzer production and operation.

- System and Fuel Production Costs: Hydrogen vs. Ammonia
  The analysis includes a comparison of deterministic scenarios, specifically focusing on the production costs of hydrogen and ammonia within a large-scale context. The findings shed light on the economic advantages of producing hydrogen over ammonia, considering both operational and investment-related aspects.

- Hydrogen Production Economics
  The study underscores that producing hydrogen proves to be notably more cost-effective than ammonia production within the studied scenarios. The simplicity of the hydrogen Power-to-X (PtX) plant design contributes significantly to the reduced production costs. The streamlined design minimizes complexities, resulting in efficient operation and lowered expenses.

- Ammonia Production Challenges
  Conversely, the production of ammonia introduces intricacies that demand additional investments in storage solutions, such as batteries and hydrogen pipelines. The need for these solutions stems from the increased complexity of the ammonia production process and the optimization challenges associated with its operation. These complexities lead to higher operational costs, making ammonia a less cost-effective option when compared to hydrogen.

10.5.2. Energy and Input:

- Wind Power

Wind power is a critical factor in the feasibility study for the proposed project. The island of Bornholm boasts varying capacities of both offshore and onshore wind power, which contribute in different degrees to the green energy supply. Wind power exhibits inherent variability, with fluctuations ranging from a rapid increase of 1.5GW to a decrease of -0.32GW based on the 10-minute modeling conducted by DTU (Work Packages 2 and 4). This variability must be accounted for in the project's design and energy management strategies.

The Energy Island Bornholm wind parks and other projects backed by the Danish government are central to the island's renewable energy profile. The combined offshore wind power capacity ranges from 100MW to an ambitious 3-3.8GW for the Energy Island Bornholm project.

The onshore wind power capacity currently stands at 37MW as of 2022. Despite its potential, no further capacity increase is anticipated by 2030. Due to this, the study has determined that no additional analysis on this source is necessary.

- Water:

The wastewater treatment plants (WWTPs) on Bornholm possess a collective wastewater capacity of 7 million m3. Rønne wastewater treatment plant is identified as the most suitable water source for P2X plants. Although there are seasonal variations in the characteristics of this water source, WP2 confirmed that the quantities are acceptable for the intended scale of the project.

Seawater is a viable alternative water source for the electrolysis process, with a salinity of approximately 7-8%. While it holds potential, the primary focus for water supply remains on wastewater sources. However, the study acknowledges the feasibility of using seawater if circumstances demand it.

The island's annual drinking water production is limited to approximately 3 million m3, with an estimated total resource of 5 million m3. Consequently, reserving a substantial amount of these limited resources for PtX production is improbable. However, the feasibility study does recognize the need to supply drinking water to employees working at P2X facilities. In case of contingencies, this water supply might also be utilized for the electrolysis process in the short term.

- Biogenic Carbon (CO2) Source and Plans

In 2030, the biogas plant is expected to provide the most reliable and continuous source of biogenic CO2. Bigadan's plan to increase biogas production and separate CO2 from methane could raise this source from around 5,000 tons/year to about 20,000 tons/year, pending success. While the cost of this CO2 is subject to negotiation, its by-product nature suggests a probable low price. Transporting it through pipelines to the Energy Island Bornholm's transformer area, situated 3 km south of the Biogas Plant, is straightforward.

As part of the REACT-22-0054 extension project, exploration into CO2 integration from external sources is scheduled from September 1, 2023, to December 31, 2023.

The municipal energy strategy aims to reduce biomass usage in heat and power plants by 2025. This necessitates alternatives like waste heat and heat generated through electricity in heat pumps and electrical boilers to compensate for biomass reduction in district heating production.

Anticipated biomass reduction in heat plants due to the energy strategy may render CO2 emissions from wastewater treatment plants (WWTPs) unsuitable for significant CO2 sourcing in P2X production. WWTPs exhibit relatively low CO2 emissions, insufficient to serve as a viable CO2 feedstock for the P2X process.
WWTPs' CO2 Emissions and Viability
Due to the municipal energy strategy's efforts to limit biomass usage, a decrease in CO2 emissions from heat plants is anticipated. This approach may render the CO2 emissions from wastewater treatment plants (WWTPs) unsuitable as a significant CO2 source for P2X production. The relatively low emissions from WWTPs are insufficient to serve as a viable CO2 feedstock for the P2X process.

10.5.3. Infrastructure and setup

In the domain of Power-to-X (PtX) technology, the infrastructure and setup of a PtX plant play an instrumental role in determining its operational efficiency, economic feasibility, and environmental impact. The configuration of the PtX plant, particularly its connection to the energy supply, holds significant implications for its overall performance.

- Behind-the-Meter Setup

One notable setup is the behind-the-meter configuration. In this arrangement, the PtX plant is strategically situated in close proximity to a renewable energy source. This proximity allows the plant to tap directly into the energy generated by renewable sources such as solar or wind. The energy produced is then utilized on-site for the conversion process, eliminating the need for connection to the public electricity grid.

In this setup, the owner of the PtX plant may have a vested interest in the renewable energy assets or have established a Power Purchase Agreement (PPA) with the renewable energy producer. This ensures a consistent supply of electricity for the conversion process. However, it's important to consider that this setup may come with increased costs. Industry insights, coupled with insights from academic literature, suggest that the costs associated with this configuration might escalate by at least 25%.

- Capacity Factor and its Implications

Another crucial factor is the Capacity Factor, which provides insights into the efficiency of energy conversion. Focused on the specific SP379-HH150 wind turbine, the capacity factor stands at 49.7%. This percentage indicates the proportion of time the turbine operates at its maximum capacity. The direct implication of the capacity factor is reflected in the Levelized Cost of Energy (LCOE), a metric widely used to assess the cost-effectiveness of energy generation methods. For the SP379-HH150 turbine, the resultant LCOE is calculated at 58.6 EURo/MWh.

- Efficiency Considerations

The viability of these projects can be affected by the energy efficiency of each involved process. Improving the efficiency of Power-to-X processes is crucial for a project and have deep implications in the techno-economic evaluation.

- Electrolyser Design and Technology

The design and construction of electrolyzers, which are pivotal in the PtX process, significantly influence cost and efficiency. Research suggests that scaling up the module size and introducing innovative stack manufacturing techniques can substantially reduce costs. Notably, transitioning from a 1 MW plant size (typical in 2020) to a larger 20 MW plant could yield cost reductions of more than 30%. Now, consideting up scale to giga scale, unique challenges emerge and larger scales may render established design parameters inapplicable. Consequently, a comprehensive investigation tailored to the specific scale becomes imperative for informed decision-making.

Various electrolyser technologies have been explored, including Alkaline Electrolysis Cells (AEC), Solid Oxide Electrolysis Cells (SOEC), and mixed configurations. These explorations are particularly relevant in large-scale scenarios, where different technologies offer distinct advantages based on specific operational requirements.

Contrasting the behind-the-meter setup, the Power from the Grid configuration involves connecting the PtX plant to the public electricity grid. Here, the renewable energy source, such as solar or wind, injects electricity into the grid. The PtX plant, in turn, draws the required electricity from the grid to facilitate the conversion process. However, this setup introduces uncertainties related to renewable fuel certification and future electricity prices, which have been discussed among project partners.

- Diverse Power Supply Technologies

PtX projects harness diverse Power Supply Technologies. On a large scale, offshore wind turbines are commonly employed, leveraging their significant energy-generating capacity. Conversely, smaller-scale setups integrate solar photovoltaic (PV) panels and wind turbines, optimizing the utilization of available resources.

- Heat Plant Locations and Influences

The locations of Heat Plants, which exhibit seasonal patterns of CO2 production, have ramifications for PtX plant placement and operational costs. The arrangement and distribution of Heat Plants across an island, for instance, can necessitate adjustments in PtX plant locations or lead to additional costs for connecting with existing Heat Plants. When envisioning future Heat Plant locations, careful consideration is given to their compatibility with potential Power-to-X plant installations.

10.5.4. Location, Transport and Storage

- Land Usage

Effective land utilization stands as a foundational consideration for hydrogen production systems. The area requirement for these systems exhibits variance, contingent upon the selected electrolyser technology. Hydrogen-producing installations typically necessitate an expanse of 20 to 30 hectares. In contrast, systems focusing on ammonia production will likely require more expansive land allocation. This is attributed to the additional equipment inherent to ammonia production, coupled with rigorous safety protocols when assessing the safety area that must surround the facility.

- Transport of Products and Options

The hydrogen production landscape is punctuated by the challenge of land-based product transportation, with safety considerations taking center stage. While land-based transportation maintains its allure for modest product quantities, its efficacy diminishes considerably when faced with substantial volumes. The complexities inherent in orchestrating the logistics of sizable hydrogen-based product quantities render land-based transportation unsustainable, particularly when the transportation routes traverse densely populated areas.

Safety assessments and considerations become paramount when contemplating the passage of hydrogen-based products through cities and areas with significant human presence. Ensuring the security of both the products and the inhabitants necessitates rigorous evaluations of potential risks and the implementation of appropriate mitigation strategies.

- Underground Storage

Among the spectrum of storage approaches, the proposition of underground storage stands out as an appealing alternative. A notable advantage is the circumvention of the need for municipal planning, expediting implementation timelines. However, the path to realizing underground storage is not devoid of challenges. It mandates a comprehensive risk assessment to identify potential hazards and devise mitigation strategies. Additionally, securing environmental permits becomes imperative to ensure adherence to regulatory standards. Furthermore, the establishment of legal cadastral agreements adds complexity. These agreements are indispensable for the seamless functioning of underground storage infrastructure, cementing its role as a secure and viable storage solution.

10.5.5. Market Trends

Market trends in the local industry are pointing towards significant changes in fuel options, hydrogen demand, and the adoption of alternative marine fuels. The future fuel landscape is expected to encompass various non-fossil options, including LPG, biogas, hydrogen, ammonia and electrification.

- Plan for Decarbonization - Local Industry

A strategic plan is in place to achieve substantial decarbonization within the local industry. The goal is to reduce energy usage by up to half of the current 18,465 MWh through a combination of efficiency gains and electrification. This ambitious plan aligns with broader sustainability objectives and reflects the industry's commitment to transitioning towards greener energy practices.

- Future Fuel Options in Local Industry

Future fuel alternatives are gaining prominence in the local industry, aiming to reduce reliance on fossil fuels. The spectrum of options includes non-fossil LPG, biogas, hydrogen, and electrification. This transition underscores the industry's commitment to environmental sustainability and the pursuit of cleaner energy solutions.

- Hydrogen Demand

Local industrial demands for hydrogen are projected to encompass approximately half of the current 18,465 MWh consumption. Meeting this demand would require an estimated 282 tons of hydrogen, primarily in the form of biogas. This presents a substantial opportunity for the expansion of hydrogen production and distribution infrastructure to cater to the evolving energy landscape.

- Methanol as Marine Oil Replacement

The marine sector is anticipated to witness a notable shift towards methanol as a replacement for traditional marine oils. Methanol's quicker and more accessible implementation compared to ammonia is expected to result in its increased adoption. Specifically, ferry operations between Bornholm and other areas are eyeing a transition to methanol by 2030. This transition could replace approximately 29,000 tons of Marine Gas Oil (MGO) annually. However, it's important to note that the lower energy density of methanol compared to MGO would necessitate a larger quantity of around 62,000 tons to meet the same energy demand. Notably, offshore wind installations from the Port of Roenne could emerge as significant users of methanol, driven by growing orders for installation vessels and Service Operation Vessels (SOVs).

- Ammonia as future fuel

Ammonia is considered one of the most promising future fuels in the maritime world but introducing it to the fuel mix is far from straightforward There are some challenges related to its toxicity, flammability, and combustion in traditional engines. Despite these challenges, ammonia has several advantages as a marine fuel, including high power-to-fuel-to-power (PFP) efficiency, carbon-free when produced using renewable energy. Ammonia has a large-scale distribution infrastructure that is already in place, and it can be stored at ambient temperature under a pressure of around 10 bar or without pressure refrigerated to minus 34°C, and the stable fuel supply is possible as the large-capacity ammonia synthesis technologies are already mature, To use ammonia as fuel, design requirements can be found in NR 671 Rules, and the design will have to be assessed through Alternative Design procedure of the IGF Code and SOLAS regulations

- Oxygen's Significance in Water Treatment

Oxygen plays an important role in both wastewater treatment and drinking water production. Its significance cannot be understated, as it contributes to enhanced oxygen transfer rates and reduced energy consumption. The impact of oxygen on efficiency and cost-effectiveness is paramount in the water treatment process, making it an indispensable element in improving overall operational processes.

- Waste Heat

Waste heat emerges as an intriguing yet complex aspect of the local energy landscape. Although the energy generated as a co-product from various processes has the potential to meet demands, current temperature ratings fall short of feasibility. Further investigations into waste heat recovery are essential to determine the viability of integrating it into the local district system. It's worth noting that prioritizing waste heat recovery might be challenging given its lower temperature profiles, and alternative systems like cooling systems could take precedence.

Waste heat derived from Power-to-X (PtX) processes presents a substantial energy resource. The potential energy output varies based on temperature profiles, with estimates ranging from 72 GWh to 435 GWh per year. This underscores the importance of efficient waste heat recovery technologies to harness this energy and contribute to the local energy supply.

10.5.6. Operational Performance

Operational performance directly impacts the overall efficiency and longevity of the electrolyzer system. Various factors play a crucial role in enhancing operational performance and extending the equipment's lifetime.

- Lifetime

The electrolizer's lifetime is closely tied to the frequency of start/stop cycles. To ensure optimal equipment longevity, it is imperative to minimize the number of start/stop events. Additionally, a rotational approach to module utilization should be adopted. This strategy ensures that modules wear out at a similar rate, preventing premature failure and maximizing their operational lifespan.

- Operational Performance and Grid Connection

The relationship between a stable power source and operational performance is significant. Connecting the electrolyzer system to the grid offers advantages such as increased electrical input capacity. This connection enables the units to operate at maximum capacity with fewer start/stop cycles, ultimately leading to improved operational efficiency. While this scenario holds promise, it requires further investigation. Notably, the study primarily focused on the behind-the-meter scenario and did not encompass grid-connected operations.

- Operational Strategies

Strategic planning and evaluation of operational approaches hold the key to optimizing electricity consumption and ammonia production. It's important to consider that certain operational strategies might result in unused hydrogen. In cases of hydrogen surplus, a comprehensive plan for hydrogen storage should be established. This allows for the recycling of unused hydrogen back into the system, minimizing wastage and enhancing overall efficiency.

- Portfolio Configuration

The configuration of the electrolyzer portfolio plays a pivotal role in its flexibility. A larger number of smaller electrolyzer units grants the portfolio greater flexibility. Smaller units demand less power to maintain operation, rendering the system adaptable to variable electricity inputs, especially during conditions of low wind. This flexibility is vital for maintaining hydrogen production even in challenging scenarios.

- Portfolio Operational Sequence

Optimizing the operational sequence of the electrolyzer portfolio directly influences system efficiency and module durability. Unlike a fixed sequence, an optimal operational sequence significantly reduces module start/stop cycles. Calculating when to activate or deactivate electrolyzer units based on wind demand, coupled with a module rotation strategy, ensures uniform module utilization. This approach maximizes hydrogen production for the energy invested in electrolyzer operation. It's important to note that while the optimal sequence is highly beneficial, its direct applicability may vary, requiring tailored calculations based on specific conditions.

10.5.7. Proposed Impact Effort Table

Table 20. Technological Factors - Proposed Impact Effort Table

Challenge	Solution	Impact Score	Explanation of Impact Score	Effort Score	Explanation of Effort Score
Optimal electrolyser technology	Invest in research and development to optimize electrolyser technology, improving	4	Implementing optimized electrolyser technology could significantly lower costs and enhance	5	Developing and implementing advanced electrolyser technology requires

	efficiency and reducing costs.		system performance.		substantial research and development efforts.
Transport Options	Explore innovative transport solutions like containerized systems or alternative transportation methods to mitigate challenges associated with PTX product transportation.	5	Innovative transport solutions can lead to cost savings and improved efficiency.	4	Developing and implementing new transport methods requires careful planning and investment.
Biogenic Carbon (CO2)	Develop efficient CO2 transportation methods and prioritize the construction of necessary pipelines to transport CO2 from heat plants to the Energy Island.	4	Effective CO2 transportation is essential for utilizing the benefits of reduced CO2 production.	3	Developing CO2 transportation methods requires coordination and investment but is less complex than other challenges.
Infrastructure	Plan and design the infrastructure with consideration for traffic management and environmental impact, aiming to minimize resource consumption and potential disruptions.	4	Efficient infrastructure planning can mitigate hindrances and optimize resource usage.	4	Careful planning and design of infrastructure require coordination with multiple stakeholders and thorough analysis.
Efficiency	Implement load management strategies and optimize power supply to mitigate efficiency losses at low load conditions, thereby improving overall system flexibility and economic viability.	4	Enhancing system efficiency at various load levels can lead to improved economic outcomes.	3	Developing and implementing load management strategies involves adjusting operational procedures and optimizing power supply, requiring moderate effort.

10.6. Environmental Factors

The environmental factor focuses on the ecological impact and sustainability of PtX technologies. It includes factors such as carbon emissions reduction potential, resource utilization efficiency, water, and land use, as well as the overall environmental footprint of PtX processes. Environmental regulations and policies related to renewable energy and greenhouse gas emissions are also considered.

Figure 71. Environmental Factors Classification and Value

10.6.1. Emission and Pollution

PtX systems are considered a potential pathway to decarbonize various sectors of the economy by converting renewable electricity into fuels and chemicals. While PtX systems themselves do not directly produce air pollutants, the source of electricity used for the conversion can influence associated air pollution emissions. If the electricity originates from fossil fuel-based power plants, there could be considerable air pollution emissions stemming from these sources. This highlights the importance of utilizing clean and renewable energy sources to power PtX processes and minimize air pollution.

Furthermore, the greenhouse gas emissions associated with PtX systems depend on the electricity source for electrolysis. While offshore wind farms and off-the-grid systems are assumed to be the main sources of electricity, uncertainties arise regarding the exact "greenness" of the electricity from offshore wind due to discrepancies in green certificates. In cases where grid electricity is used, confirming the authenticity of green certificates becomes a concern.

10.6.2. Energy Sources and Consumption

The energy consumption and sources in the local context play a crucial role in the environmental impact of PtX systems. For instance, local heavy transportation primarily relies on diesel fuel, with a yearly consumption of 155,000 MWh. Similarly, local industries contribute to energy usage, with an estimated process energy consumption of 18,465 MWh, primarily driven by LPG. It is evident that PtX implementation should consider optimizing energy sources to minimize emissions and resource depletion.

10.6.3. Environmental Impact and Conservation

The operation of PtX plants and associated processes can have significant environmental implications. The transportation and storage of PtX products could lead to air and water pollution, potentially affecting nearby agricultural areas and impacting crop yield and quality. To mitigate these effects, measures such as preserving coastal zones, protected areas, and cultural heritage must be implemented. Rigorous environmental screening, assessments, and monitoring programs are essential to ensure compliance, sustainability, and the reduction of negative environmental impacts.

The utilization of oxygen in wastewater treatment offers environmental benefits, including reduced energy consumption, emissions, and improved treatment efficiency. Proper waste management practices for the waste streams generated during PtX processes are crucial to prevent environmental contamination. Additionally, exploring synergies between PtX, wastewater treatment processes, and CO2 utilization can contribute to greener waste management approaches.

10.6.4. Infrastructure and Planning

The estimation of land area for large-scale PtX projects is a critical factor in infrastructure and planning. Various estimates for land area have been proposed based on engineering considerations. For instance, a 100 MW electrolyzer plant is estimated to occupy around 6,300 m² according to a study by the German government in 2014. Siemens estimated a land area of about 15,000 m² for a 300 MW electrolyzer plant in 2017. These estimates highlight the importance of efficient plot optimization and standardized designs to maximize space utilization for PtX facilities.

10.6.5. Seveso Directive

The Seveso Directive mandates safety protocols for industrial facilities with significant risks, including Power-to-X plants. These plants must generate safety reports assessing potential dangers tied to hazardous chemicals used in the processes. Additionally, they are obligated to secure a chemical safety permit to confirm compliance with safety requirements and must establish a Safety Management System to prevent accidents effectively. Clear communication of chemical hazards to workers and consumers is also a key directive aspect.

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10.6.6. Resource Availability and Usage

The availability and usage of resources are key considerations in PtX operations. The availability of CO2 on Bornholm is expected to increase significantly due to biogas plant expansion. This increase in CO2 output, along with its convenient proximity to the Energy Island Bornholm transformer area, presents an opportunity for easy transportation via pipeline. Moreover, water resources, particularly from wastewater treatment plants, contribute positively to reducing nutrient outlets to the sea.

The use of non-potable water sources, such as wastewater and seawater, for PtX operations ensures efficient resource utilization and contribute positively to reducing nutrient outlets to the sea. However, challenges arise in the proper disposal of concentrated brine from wastewater treatment plants which cannot be release into the sea.

Table 21. Proposed Impact Effort Table

Factor Name	Challenge	Solution	Solution Description	Impact Score	Explanation of Impact Score	Effort Score	Explanation of Effort Score
Greenhouse Gas Emissions	Uncertainty about green electricity source	Standardized Green Certificate Verification	Establish a transparent and standardized process for certifying the green nature of electricity sources	4	Certainty about electricity source enhances PtX's credibility and environmental impact	3	Collaboration required for certification standardization
Local Heavy Transportation	Diesel reliance for local transportation	Encourage Alternative Transportation	Incentivize the adoption of electric or hydrogen-powered vehicles to reduce diesel dependence	4	Reduced diesel usage leads to decreased emissions and improved air quality	3	Collaborative efforts needed for incentives and infrastructure
Local Industry Energy Usage	High energy consumption by local industries	Transition to Cleaner Energy Sources	Promote the use of PtX-generated hydrogen or other cleaner energy sources in local industries	4	Cleaner energy adoption reduces carbon footprint and enhances sustainability	3	Coordination needed for industry transition and resource allocation
WWTP Brine Disposal	Discharging concentrated brine into the sea	Innovative Brine Desalination Technologies	Research and implement desalination methods that reduce brine salinity for safe sea discharge	3	Reduced environmental impact from brine discharge	4	Collaborative research and technology integration required

10.7. Legal Factors

There were twenty-seven factors identified, group into 7 categories: Regulatory and Policy Landscape, Government Support and Funding, Environmental and Sustainability Regulations, Land and Space Usage, Economic and Financial Factors, Community Engagement and Local Impact, and Technical and Operational Challenges. The interrelationships and potential effects of these factors are explored to provide a comprehensive understanding of their implications.

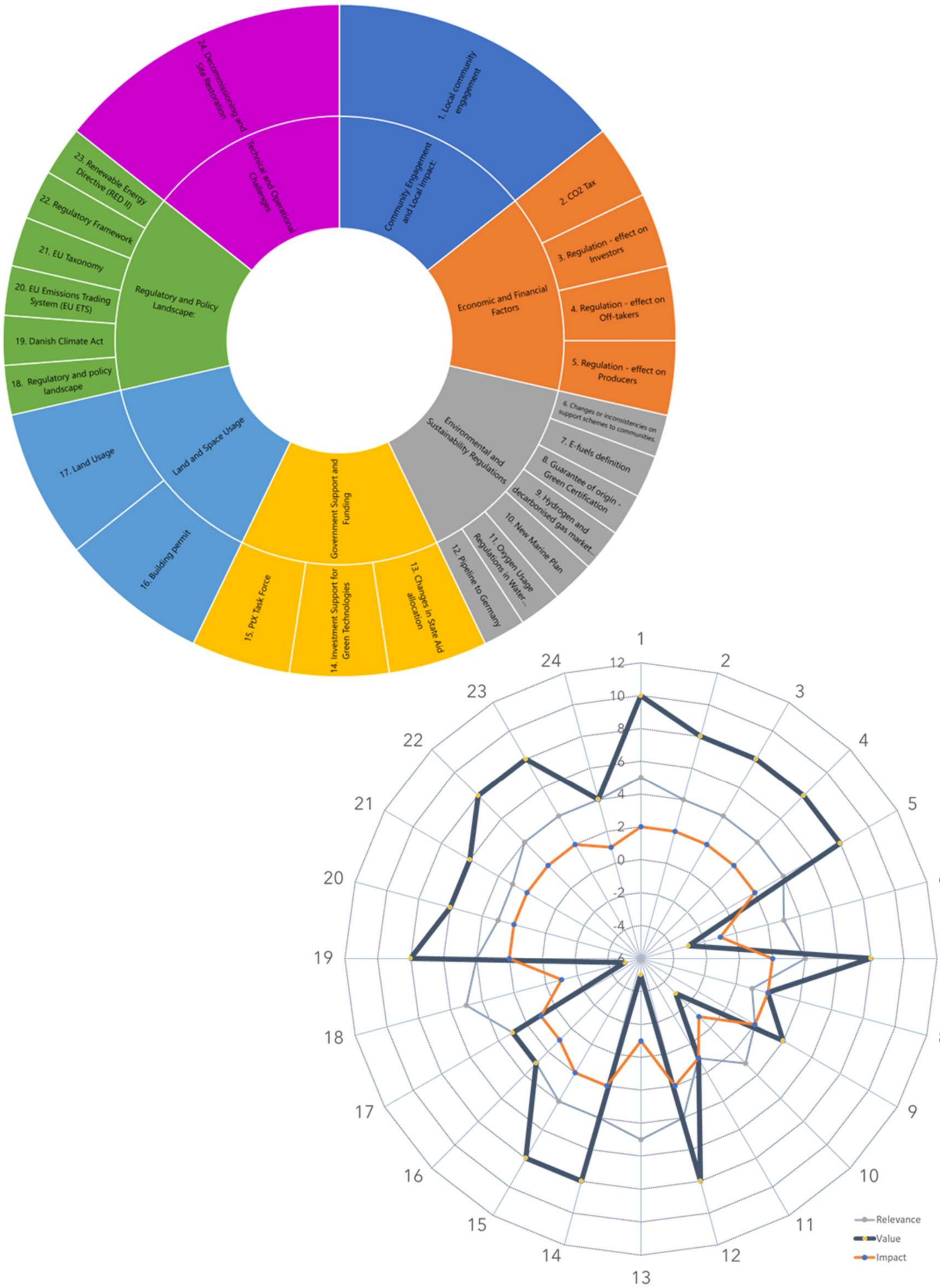

Figure 72. Legal Factors Classification and Value

10.7.1. Regulatory and Policy Landscape
The regulatory and policy landscape significantly influences the PtX market in Bornholm. Government initiatives, such as CO2 taxes and emission reduction targets, drive the transition towards green fuels. The inclusion of road transportation and buildings in the EU Emission Trading System (ETS) and the establishment of carbon pricing mechanisms impact fuel prices and incentivize the adoption of low-carbon alternatives. The Danish Climate Act, which sets binding emission reduction targets, further propels the shift towards sustainable energy solutions.

10.7.2. Government Support and Funding
Government support and funding play a pivotal role in PtX projects. The allocation of state aid for offshore wind farms is subject to limitations, impacting the financial viability of the projects. Negotiations with the EURopean Commission for investment support reflect the government's commitment to fostering green technologies. The PtX Task Force's coordination efforts are anticipated to streamline regulatory barriers and support the growth of the sector.

10.7.3. Environmental and Sustainability Regulations
Environmental and sustainability regulations significantly impact PtX projects. Definitions of e-fuels and support schemes for communities can influence the market landscape. The adoption of the EU Taxonomy aims to facilitate sustainable investment setting stringent criteria for green fuels. The proposed Hydrogen and Decarbonized Gas Market Package aims to integrate renewable and low-carbon gases into the gas network, affecting PtX projects' viability and regulatory compliance.

10.7.4. Land and Space Usage
Land and space usage are crucial aspects of PtX projects. Building permits, land optimization, and space requirements for different PtX technologies must be considered. While building permits are necessary for construction, optimizing land use and considering additional facilities atop hydrogen storage might be viable solutions.

10.7.5. Economic and Financial Factors
Economic and financial factors are intertwined with regulatory measures. CO2 taxes and the inclusion of road transportation in the EU ETS impact industries and transportation, potentially making green fuels more competitive. Regulations aligning with EU criteria can affect investors, off-takers, and producers, shaping the market landscape and incentivizing the production of sustainable alternative fuels.

10.7.6. Community Engagement and Local Impact
Community engagement plays a pivotal role in PtX projects. Open dialogue and engagement foster trust, address concerns, and ensure the project brings positive benefits to local areas..

Key considerations include:

- Transparency: Engaging the local community fosters transparency, enabling them to grasp the project's objectives, advantages, and potential ramifications.
- Cultivating Trust: An open exchange and engagement establish trust between project developers and the community, minimizing the likelihood of conflicts or opposition.
- Resolving Concerns: Community members might express reservations about noise, visual impact, environment, or safety. Engagement offers a platform to acknowledge these concerns and collaboratively devise solutions.
- Shared Benefits: Through community involvement, developers can identify avenues to ensure that the project yields positive economic, social, or environmental outcomes for the local region.
- Alleviating Opposition: Early engagement in the project's lifecycle aids in recognizing and mitigating potential opposition, leading to smoother regulatory approvals and project execution.

10.7.7. Technical and Operational Challenges

Technical and operational challenges encompass decommissioning, site restoration, and safety regulations. These challenges have implications for costs, environmental risks, technical complexities, regulatory compliance, liability, community concerns, and land use restrictions. While not considered within the project scope, addressing these challenges is crucial for future PtX projects.

10.7.8. Proposed Impact Effort Table

Table 22. Legal Factors - Proposed Impact Effort Table

Factor Name	Challenge	Solution	Impact Score	Explanation of Impact Score	Effort Score	Explanation of Effort Score
Regulatory and Policy Landscape	Regulatory complexity and evolving definitions	Regulatory compliance team	3	Moderate impact; regulatory uncertainty can hinder progress	2	Reasonable effort required to establish a dedicated team
Government Support and Funding	Insufficient state aid allocation	Diversification of funding sources	3	Moderate impact; limited funds jeopardize project viability	3	Significant effort; requires engaging investors and exploring bonds
Land and Space Usage	Spatial optimization challenges	Urban planning expertise	4	Substantial impact; space constraints affect project scalability	3	Significant effort; strategic planning and coordination needed
Environmental and Sustainability Regulations	Shifting support schemes and ownership models	Cross-functional monitoring and contingency planning	2	Moderate impact; changing regulations introduce uncertainty	2	Reasonable effort; proactive monitoring and planning required
Technical and Operational Challenges	Decommissioning and site restoration complexities	Comprehensive plan with environmental consultants	3	Moderate impact; inadequate planning may lead to liabilities	3	Significant effort; collaboration with experts for meticulous planning
Community Engagement and Local Impact	Ensuring effective community engagement	Transparent communication and engagement strategies	4	Substantial impact; community opposition can delay or halt the project	4	Significant effort; requires continuous dialogue and community involvement
Economic and Financial Factors	Adapting to evolving economic conditions	Scenario planning and risk management	2	Moderate impact; economic changes can affect project viability	2	Reasonable effort; proactive financial analysis and contingency planning

11. CONCLUSIONS AND RECOMMENDATIONS

11.1. Political

In evaluating the feasibility of establishing a Power-to-X (PtX) plant in Bornholm, we find numerous political factors at play, both positive and negative. Denmark's strong commitment to renewable energy and PtX technologies aligns well with national and European sustainability goals.

The country's participation in regional collaborations, such as the Ostend and Esbjerg Declarations, in a addition to the plans to make Bornholm an energy island, set the island as prime candidate for PtX development.

Efforts to reduce reliance on imported fossil fuels and contribute to European energy independence are commendable, albeit with the challenge of geopolitical risks that require diligent risk assessment strategies.

The generation of jobs and innovative funding mechanisms ensure financial viability and private sector support. Exploring additional funding avenues and active private sector engagement can enhance this aspect.

Denmark's commitment to expanding electrolysis capacity and cross-border infrastructure positions it as a key player in the green hydrogen market. Close collaboration with regulatory authorities and adaptive strategies in response to offshore wind scheme changes are essential for project stability.

Despite these positive factors, challenges exist. Changes in offshore wind schemes affecting power supply have a significant impact. Addressing this challenge requires diversifying energy sources, enhancing the grid, and planning for flexible capacity.

Uncertain policy landscapes can also impact project stability. Close regulatory collaboration and continuous monitoring are essential to ensure policy alignment and adaptability.

11.2. Economical

The feasibility of establishing a Power-to-X (PtX) plant in Bornholm is influenced by a multitude of factors, both positive and negative, with significant implications for the project's profitability and sustainability.

Positive factors include the strategic location of Bornholm in the Baltic Sea, which sees a high volume of vessel traffic. This presents an excellent opportunity for PtX technology adoption, potential fuel sales and international trade and cooperation. Moreover, Bornholm is actively exploring options to replace traditional fossil fuels with greener alternatives, aligning with the island's commitment to reducing carbon emissions and complying with EU regulations. These shifts in energy demand and the island's efforts to transition to green alternatives create a robust market for PtX products.

Bornholm's ample renewable energy potential, reliable water supply, and the availability of biogenic CO2 further enhance the feasibility of a PtX plant. A very important point is that potable sources of water will not be required, and the project can safely rely in wastewater, having a positive impact the island circular economy and the Baltic Sea environment.

In addition, government initiatives such as CO2 taxes, geographically differentiated tariffs, and green transition drivers offer a favorable environment for the adoption of PtX technology. Investment support, including funding secured from the REACT-EU initiative, provides potential financial backing to accelerate the project.

However, there are challenges to be addressed. Production costs, while competitive, must navigate uncertainties in factors like technology advancements, electricity prices, and regulatory conditions. Uncertainties in future grid prices and renewable fuel certification could pose challenges for the project's competitiveness and market access. Moreover, the project's budget and funding are exposed to fluctuations in resource and product prices, interest rates, and state aid reductions.

Market price fluctuations for feedstock and products also present a significant revenue and profitability risk for the PtX plant. Exporting hydrogen to Germany introduces additional complexity, with uncertain transport costs.

To enhance the feasibility of the PtX plant in Bornholm, several actions are recommended. These include focusing on adopting and optimizing Solid Oxide Electrolysis Cell (SOEC) technology, diversifying PtX product offerings, developing comprehensive risk management strategies, evaluate international cooperation to make hydrogen pipeline to mainland Europe a reality, optimizing resource usage, and collaborating closely with government bodies.

11.3. Social

One of the most critical aspects is community involvement and acceptance. Early engagement with local authorities and the community is essential to establish a cooperative environment. Transparent processes and ongoing communication channels can help build trust and confidence among stakeholders. Implementing ownership models, such as RE-bonus schemes and loss of value schemes, can incentivize residents and municipalities, aligning interests and fostering acceptance. However, it is imperative to ensure transparency in decision-making to address the concerns of residents fully.

Bornholm's unique cultural and historical identity must be respected and preserved during the development of the PtX plant. Balancing modern developments with the island's aesthetics and cultural values is crucial to maintain harmony between innovation and heritage. Additionally, careful planning is necessary to manage potential tourism influx without straining local resources and impacting the island's cultural heritage.

Utilizing brownfield and existing industrial areas for the PtX plant location can provide economic benefits and synergies. Compensation mechanisms like the loss of value scheme and the option-to-sell scheme address concerns over property value depreciation and offer an exit strategy for affected residents. However, balancing industrial growth with agricultural sustainability and managing increased tourism sustainably are challenges that need to be addressed.

The PtX project presents significant employment opportunities, including roles related to offshore wind service, plant construction and operation, and other aspects of the energy transition. Partnering with local educational institutions to design training programs and collaborating with local businesses can help bridge skill gaps and facilitate job placements. Continuous learning and networking in the PtX industry are essential for workforce competence and career growth.

Educational efforts and awareness campaigns are crucial for garnering support for the project and dispelling misconceptions, helping authorities and citizens to understand the real risks associated with the technology and the products created. This analysis must also include a thorough terrorism risk assessment which is vital to ensure the safety of the PtX project on Bornholm and as well as the wellbeing and peace of mind of the habitants. Developers should evaluate vulnerabilities and potential threats, design effective security measures, and share their approach to demonstrate a commitment to safety and overall island resilience.

11.4. Technology

Firstly, it's evident from the PESTEL analysis that optimizing costs in critical areas such as the Offshore Wind Farm (OWF) and electrolyzer production is paramount to the economic viability of the PtX plant. Advanced technologies, streamlined processes, and efficient supply chain management should be pursued to reduce expenses in these components.

The production of ammonia introduces complexity and additional costs, in addition to the need for land but developments in the maritime industry will possibly make ammonia more attractive in the future.

Wind power, as a renewable energy source, is essential for the project's success. Bornholm boasts varying capacities of offshore and onshore wind power, but the inherent variability of wind power must be accounted for in project design and energy management strategies.

The availability of water sources, particularly wastewater treatment plants and seawater, seems adequate for PtX production. However, precautions must be taken to reserve drinking water resources for employees and contingency use. Additionally, plans to increase biogas production and separate CO2 from methane could provide a reliable source of biogenic CO2.

Infrastructure and setup choices, such as behind-the-meter setups and capacity factors, have implications for operational efficiency and costs. Careful consideration of these factors is crucial in project planning.

Market trends in the local industry indicate a strong push towards decarbonization and the adoption of alternative fuels, including hydrogen and ammonia. This presents an opportunity for PtX production to meet the increasing demand for these fuels.

Location, transport, and storage considerations highlight the need for efficient land utilization, especially for hydrogen production systems. Transporting products, safety, and storage solutions such as underground storage must be carefully evaluated and integrated into the project plan.

Operational performance is critical for the longevity and efficiency of the electrolyzer system. Strategies to minimize start/stop cycles, grid connection for stability, and portfolio configuration for flexibility are key elements to consider.

It is possible to build a PtX plant in Bornholm, given the island's renewable energy resources and the local industry's transition towards cleaner fuels. However, the economic feasibility will depend on meticulous cost optimization, technology advancements, and strategic planning. To increase the positive factors, the project should focus on maximizing cost-efficiency, leveraging wind power, and capitalizing on the local industry's shift towards cleaner fuels. Additionally, addressing the challenges related to ammonia production and CO2 sourcing is essential.

11.5. Environmental

The environmental benefits of PtX systems are apparent, aligning with the global push to decarbonize industries. The potential to minimize air pollution and greenhouse gas emissions by utilizing renewable energy sources, such as offshore wind farms, is a compelling advantage.

Energy consumption and sources in the local context represent a mixed bag of challenges and opportunities. On one hand, heavy reliance on diesel fuel and LPG for transportation and industrial processes highlights the urgency of optimizing energy sources to reduce emissions. On the other hand, this situation provides a platform for PtX implementation to make a substantial impact by transitioning these sectors towards cleaner energy alternatives.

The environmental impact of PtX plants and its products, particularly in terms of ammonia and air and water pollution, necessitates a proactive approach to safeguarding nearby ecosystems and agricultural areas. Strict environmental screening and monitoring, along with waste management practices, are essential to mitigate these effects.

Infrastructure and planning pose significant challenges, with land area estimates varying considerably. Efficient plot optimization and standardized designs will be crucial to maximize space utilization for PtX facilities, minimizing potential bottlenecks in the project development phase.

The Seveso Directive mandates stringent safety protocols for industrial facilities, including PtX plants, highlighting the importance of safety compliance and risk management in the project's execution.

Resource availability and usage present a promising outlook, with increasing CO2 availability due to biogas plant expansion and convenient transportation options. The use of non-potable water sources further contributes positively to resource efficiency.

11.6. Legal

The regulatory and policy landscape in Denmark and the broader European context presents a favorable environment for PtX projects. Government initiatives aimed at reducing CO2 emissions, such as CO2 taxes and emission reduction targets, create a strong incentive for the transition to green fuels. The inclusion of road transportation and buildings in the EU Emission Trading System (ETS) and the establishment of carbon pricing mechanisms further enhance the attractiveness of low-carbon alternatives. The Danish Climate Act, with its binding emission reduction targets, provides a clear roadmap for sustainable energy solutions.

Government support and funding mechanisms play a pivotal role in PtX projects, and the commitment of the Bornholm government to secure investment support from the European Commission is a positive sign. The efforts of the PtX Task Force to streamline regulatory barriers are also encouraging, as they are expected to facilitate project development.

However, challenges exist in the form of environmental and sustainability regulations. The definitions of e-fuels and support schemes for communities can have an impact on the market landscape. The proposed Hydrogen and Decarbonized Gas Market Package may introduce additional regulatory complexities that need to be carefully navigated.

Land and space usage present logistical challenges. While building permits are necessary, optimizing land use and considering additional facilities atop hydrogen storage could help mitigate these issues but still require careful planning.

While not within the initial project scope, keep an eye on technical and operational challenges related to decommissioning, site restoration, and safety regulations. Addressing these challenges effectively is crucial for the long-term sustainability and profitability of PtX projects.

12. ABBREVIATIONS

Acronyms	Definition
AEC	Alkaline Electrolysis
aFRR	automatic Frequency Restoration Reserve
BTM	Behind-the-meter
CAPEX	Capital expenditure - money invested by a company to acquire or upgrade fixed, physical or non-consumable assets.
CHP	Central Heat and Powerplant
CIP	Copenhagen Infrastructure Partners (https://www.cip.com/)
CO2	Carbon dioxide
ETS	The Emission Trading System (ETS). It is a market-based approach to reducing greenhouse gas emissions.
LCOE	Levelized Cost of Electricity. It is a metric used to assess and compare the cost of generating electricity from different sources over the lifetime of a power plant. The LCOE takes into account all the costs associated with building, operating, and maintaining a power plant, as well as the total amount of electricity it is expected to generate over its operational lifetime.
LPG	Liquefied petroleum gas
mFRR	mandatory Frequency Restoration Reserve
MGO	Marine Gas Oil
MWh	Megawatt hour.
OPEX	Operational expenditure - the money a company or organization spends on an ongoing, day-to-day basis to run its business.
P2X	Power-to-X
PEM	Proton Exchange Membrane
Power-to-X	Power-to-X (PtX) covers several technologies, all of which are based on electricity used to produce hydrogen. In Denmark, they talk about Power-to-X, while abroad they call it green hydrogen or e-fuels. Both terms describe the process where electricity and water are converted into hydrogen through electrolysis. The hydrogen can be used directly in e.g. trucks, ferries or industry, but it can also be further converted into other fuels.
PPA	Power Purchase Agreement
PtX / PTX	Power-to-X
RFNBO	Renewable Fuel of Non-Biological Origin
SOEC	Solid Oxide Electrolysis Cell
WWTP	Wastewater treatment plants
GW	Gigawatt . Unit of power equal to one billion watts.
MW	Megawatt . Unit of power equal to one million watts.
°C	Degrees Celsius. Unit of temperature measurement.

13. REFERENCES

[1] Ministry of Climate, Energy and Utilities. "Climate Act" (2020). File no. 2019-2855. https://en.kefm.dk/Media/1/B/Climate%20Act_Denmark%20-%20WEBTILG%C3%86NGELIG-A.pdf

[2] Durakovic, A. (2022) Denmark accelerates power-to-X push with DKK 1.25 billion subsidy scheme, Offshore Wind. https://www.offshorewind.biz/2022/03/15/denmark-accelerates-power-to-x-push-with-dkk-1-25-billion-subsidy-scheme/.

[3] Denmark proposes the first outline of the new power-to-X strategy (2022) Invest in Denmark. https://investindk.com/insights/denmark-proposes-the-first-outline-of-the-new-power-to-x-strategy.

[4] Feasibility Study for power-to-X production on Bornholm. Udvikling i Danmark. Available at: https://udviklingidanmark.erhvervsstyrelsen.dk/feasibility-study-power-x-production-bornholm.

[5] Hvad er power-to-X? (2023) Energistyrelsen. https://ens.dk/ansvarsomraader/power-x-og-groen-brint/hvad-er-power-x

[6] What exactly is power-to-X? (2019). H2. https://www.h2-international.com/2019/06/03/what-exactly-is-power-to-x/

[7] Wulf, C., Zapp, P. and Schreiber, A. (2020) Review of power-to-X demonstration projects in Europe, Frontiers. Available at: https://www.frontiersin.org/articles/10.3389/fenrg.2020.00191/full (Accessed: 18 July 2023).

[8] Wulf, C., Zapp, P. and Schreiber, A. (2020) Review of power-to-X demonstration projects in Europe, Frontiers. Available at: https://www.frontiersin.org/articles/10.3389/fenrg.2020.00191/full (Accessed: 18 July 2023).

[9] Hydrogen Production: Electrolysis | Department of Energy</i>. (n.d.). https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis

[10] How to develop high performance electrodes for Power-to-X-electrolysis</i>. (n.d.). https://forcetechnology.com/en/articles/how-to-develop-high-performance-electrodes-for-power-to-x-electrolysis

[11] Hussy, C. (n.d.). Water electrolysis explained – the basis for most Power-to-X processes - PtX Hub. https://ptx-hub.org/water-electrolysis-explained

[12] What are Power-to-X solutions? (n.d.). https://as-schneider.blog/2022/03/02/what-are-power-to-x-solutions

[13] Decourt, B. (2019). Weaknesses and drivers for power-to-X diffusion in Europe. Insights from technological innovation system analysis. International Journal of Hydrogen Energy, 17411–17430. https://doi.org/10.1016/J.IJHYDENE.2019.05.149</div>

[14] ACS Energy Lett. 2020, 5, 12, 3843–3847. (2020). https://doi.org/10.1021/acsenergylett.0c02249. Copyright © 2020 American Chemical Society

[15] Araya, S., Cui, S.;, Li, X. ;, Liso, N. ;, Sahlin, V. ;, & Lennart, S. (2023). Aalborg Universitet Power-to-X Technology overview, possibilities and challenges. In *Downloaded from vbn.aau.dk on*.

[16] Rego de Vasconcelos B, Lavoie JM. Recent Advances in Power-to-X Technology for the Production of Fuels and Chemicals. Front Chem. 2019 Jun 5; 7:392. doi: 10.3389/fchem.2019.00392. PMID: 31231632; PMCID: PMC6560054.

[17] Power-to-gas: Fix for all problems or simply too expensive? | Clean Energy Wire. (2018). https://www.cleanenergywire.org/factsheets/power-gas-fix-all-problems-or-simply-too-expensive.

[18] Buljan, A. (2022). Denmark working on world's first Power-to-X tender - Offshore Energy. https://www.offshore-energy.biz/denmark-working-on-worlds-first-power-to-x-tender/

[19] Denmark reaches agreement on tenders for 9 GW of offshore wind capacity | Enerdata. (2023). https://www.enerdata.net/publications/daily-energy-news/denmark-reaches-agreement-tenders-9-gw-offshore-wind-capacity.html

[20] Brintprojekter i Danmark - Brintbranchen</i>. (n.d.). https://brintbranchen.dk/brintprojekter-i-danmark

[21] Bornholms Energistrategi 2040 (2020). Bornholms Regionskommune. https://www.brk.dk/Indflydelse-Politik/Politikker/Documents/Energistrategi%202040%20Bornholms%20Regionskommune.pdf.

[22] Jacobsen, C. et al. Work Package 1-Feasibility Study for Power-to-X Production on Bornholm (2022). Bornholms Energi & Forsyning A/S (BEOF).

[23] Ansøgning om Forundersøgelsestilladelse - Bornholm Bassin Syd | Copenhagen Infrastructure Partners. (2022). https://dagsordener.brk.dk/vis/pdf/bilag/b6d1667e-9cc0-4308-ad32-57d970ab820b/?redirectDirectlyToPdf=false

[24] Ansøgning om Forundersøgelsestilladelse - Bornholm Bassin Øst | Copenhagen Infrastructure Partners. (2022). https://ens.dk/sites/ens.dk/files/Vindenergi/ansoegning_om_forundersoegelsestilladelse_bornholm_bassin_oest_-_aaben_doer_ansoegning_final_revised_20220622.pdf

[25] Energy Island Bornholm: Technical Report – Maritime Traffic and Navigational Safety (2022). Ramboll. https://ens.dk/sites/ens.dk/files/Energioer/technical_report_-_maritime_traffic_and_navigational_safety.pdf

[26] Guarantees of origin. (n.d.). Energinet EN. https://en.energinet.dk/energy-data/guarantees-of-origin-el-gas-hydrogen/

[27] European Hydrogen Backbone - A European Hydrogen Infrastructure Vision covering 28 countries. - April 2022 https: // ehb. eu/ files/ downloads/ ehb-report-220428-17h00-interactive-1. pdf.

[28] Bendtsen, M.F. REACTRF-22-0054 - Work Package 3: Market for products (2023). Rønne Havn A/S.

[29] Emissions from Baltic Sea shipping in 2006 – 2020 https://portal.helcom.fi/meetings/MARITIME%2021-2021-939/MeetingDocuments/4-2%20Emissions%20from%20Baltic%20Sea%20shipping%20in%202006%20-%202020.pdf

[30] Maritime Decarbonization Strategy 2022 https://www.zerocarbonshipping.com/publications/maritime-decarbonization-strategy/

[31] Maritime Forecast to 2050. DNV. https://www.dnv.com/maritime/publications/maritime-forecast-2022/digitalization.html.

[32] Innovation Outlook: Renewable ammonia (2022). IRENA. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf.

[33] Edström, J. T3.5 Market for waste heat (2023) Supplementary report to REACTRF22-0054-WP3. Bornholms Energi & Forsyning A/S (BEOF).

[34] EU Emissions Trading System (EU ETS) (n.d.) European Commision. Website. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en.

[35] Fuel EU Maritime - Sustainable maritime fuels, In "A European Green Deal" https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/file-fuel-eu-maritime.

[36] You, S. REACTRF-22-0054 - Work Package 4: Integration into energy systems (2023). DTU Wind and Energy Systems.

[37] Techno-economic analysis of 1GW electrolyzer portfolio for Energy Island Bornholm, Sergio Chen, June 2023

[38] Y. Zheng, C. Huang, J. Tan, S. You, Y. Zong, C. Træholt, "Off-grid Wind/hydrogen Systems with Multi-electrolyzers: Optimized Operational Strategies", Energy Conversion and Management, 2023 (Under review).

[39] Stigsen, B. REACTRF-22-0054_WP5 Location of Power-to-X Plant and Storage (2023). Bornholms Regionskommune. Work Package 5 Final Report.

[40] Etablering af PtX-anlæg på land(n.d.). Energistyrelsen https://veprojekter.dk/anlaeg/ptxanleag.

[41] Maritime spatial plan (2023). Danish Maritime Authority. https://dma.dk/growth-and-framework-conditions/maritime-spatial-plan.

[42] Durakovic, A. Denmark Kills Off Open Door Offshore Wind Scheme, 24 Projects Cancelled

[43] Energy Technology Perspectives 2023 (2023). International Energy Agency (IEA). https://iea.blob.core.windows.net/assets/a86b480e-2b03-4e25-bae1-da1395e0b620/EnergyTechnologyPerspectives2023.pdf

[44] Garcia Marín, D., Busch-Knudsen, J.F., Letoffet, A., Campion, N. & Münster, M. REACTRF-22-0054 - Work Package 2: Modelling of scenarios for Power-to-X production in Bornholm (2023). Technical University of Denmark, Department oof Technology, Management and Economics.

[45] IEA (2022), Global Energy and Climate Model, IEA, Paris https://www.iea.org/reports/global-energy-and-climate-model, License: CC BY 4.0

[46] Hydrogen Demand and Cost Dynamics (2021). World Energy Council. Working Paper. https://www.worldenergy.org/assets/downloads/Working_Paper_-_Hydrogen_Demand_And_Cost_Dynamics_-_September_2021.pdf?v=1658324860

[47] Wan, L., Butterworth, P. Energy from green hydrogen will be expensive, even in 2050 (2023). CRU International Limited. https://sustainability.crugroup.com/article/energy-from-green-hydrogen-will-be-expensive-even-in-2050?fbclid=IwAR3gQVvaCikBTXRUA6-XlW7eBI1YUFsSKUlx-X0FX0TAl8_zttmM4_yYSmY

[48] IRENA (2021), Making the breakthrough: green hydrogen policies and technology costs, International Renewable Energy Agency, Abu Dhabi.

[49] IEA (2021), Ammonia Technology Roadmap, IEA, Paris https://www.iea.org/reports/ammonia-technology-

[50] Castro, K. Digital platform til terrorsikring. Website. https://www.terrorsikring.nu/Risikovaerktoj/

14. APPENDIX

14.1. PESTEL Analysis Matrix

Link to website

14.2. WP1 Report

Link to website

14.3. WP2 - Modelling of scenarios for Power-to-X production in Bornholm

Link to website

14.4. WP2 App User Guide

Link to website

14.5. WP3 report

Link to website

14.6. WP4 Report

Link to website

14.7. WP4 App User Guide

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14.8. WP5 Report

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