Baltic Sea Oxygenation and the Super-Green Hydrogen Economy (BOxHy)

Project Report

November 2024

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Foreword

The Baltic Sea Oxygenation and the Super-Green Hydrogen Economy (BOxHy) project was carried out as a collaborative effort between Flexens Oy Ab (Flexens), Lhyfe SA and Lhyfe Sweden Ab (Lhyfe), and Stockholm University's Department of Ecology, Environment, and Plant Sciences (DEEP). The main objective of the project was to investigate tackling the problems of anoxia and hypoxia in the Baltic Sea by injecting oxygen into the sea via existing Pure Oxygen Injection (POI) technology. Sourcing oxygen for POI from renewable energy source water electrolysis producing hydrogen and oxygen by-product was also evaluated. The project is an extension of the previous work conducted by Vahanen Environment Oy (Finland) and Jacobs Engineering Group Inc. (USA and Stockholm) in their BSAP-funded study "**Combining green hydrogen production and deep injection of pure oxygen gas to recover the Baltic Sea**."

The key experts on the project team included Szilvia Haide, Dr Patricia Handmann, Dr Jakob Walve, Dr Anna Canning, Frédéric Lourties, Hanna Nordlund and Sandra Sonneborn. Supporting team members included Baptiste Merlet, Baptiste Boillot, Edvard Nordlund, and Mikko Jantunen.

The project also received in-kind contributions from the Science and Technology Advisory Committee for Oxygenation (STACO) and the offshore wind advisory (OWA) board. The STACO members included David Austin, Dr Paul Gantzer, Professor Dr John Little, Professor Dr Mark Beutel, Marc Mobley, Professor Dr Anders Stigebrandt, Lee Bryant and Dr Sunke Schmidtko. The OWA board members represented the following offshore wind developer companies: Eolus Offshore Finland Oy, RWE Renewables Sweden Ab, Ilmatar Offshore Ab and Ørsted Wind Power A/S. The project team would like to thank all the STACO and OWA board members for their time and valuable contributions to the project.

The study was co-financed by the Baltic Sea Action Plan (BSAP) Fund with Nordic Environment Finance Corporation (NEFCO) as fund manager. We thank the BSAP Fund and NEFCO for their support of our project. BOxHy was also endorsed as a project forming part of the United Nations Decade of Ocean Science for Sustainable Development 2021-2030 in Spring 2024. We thank the Executive Secretary of the Intergovernmental Oceanographic Commission (IOC) of UNESCO for this recognition. This report has been produced independently by the project team and the conclusions of the report do not necessarily represent the views of NEFCO, UNESCO, the STACO or the OWA Board members.

Executive summary

Internal phosphorus loading in the Baltic Sea Proper and Gulf of Finland is caused by strong anoxia below the halocline. Since 1992, external nutrient loading has decreased and is now surpassed by internal loading, caused by a legacy of past nutrient loads (Forth, Liljebladh, Stigebrandt, Hall, & Treusch, 2015) (Rantajärvi, et al., 2012). This report details the findings of the BOxHy project, which takes a multi-phase approach to evaluating the feasibility of injecting by-product oxygen from electrolysis as a service for managing internal nutrient reserves and combating anoxia and hypoxia in the Baltic Sea. Through a detailed scientific investigation including a literature review and risk assessment, two Swedish sites (Säbyviken and Skärpösundet) are identified as potential for conducting a POI pilot in a marine environment. The pilot project is estimated to take six years and require 5-6 million Euros.

In parallel to planning the pilot project, the next phase for achieving the long-term ambition of combatting anoxia and hypoxia on a Baltic-sea wide scale is explored. With the emerging production of offshore wind energy and growing demand for renewable hydrogen, the development of offshore electrolysers for co-production of hydrogen and oxygen is deemed feasible. Our desktop study concludes that the installation of nearly 20 GW of offshore electrolysis capacity would be required to meet the Baltic Sea's total calculated oxygen injection demand of 57.16 +- 25.261 kilotonnes O_2/day to increase oxygen concentrations to 10 mg/l on the sub-basin and basin scales. Methods for sourcing electricity from offshore wind parks and transporting hydrogen to final offtakers are investigated. It is concluded that there is theoretically sufficient offshore wind capacity under development in the Baltic Sea to meet electricity demands, but further discussions with wind developers and coordination of project timelines is needed. Establishing intermediate pipeline connections from offshore electrolysis platforms to the planned Baltic Sea Hydrogen collector is deemed the most feasible method for transporting hydrogen to offtakers, contingent upon routing and further techno-economic studies.

The project investigates the conceptual design of a 400 MW capacity offshore electrolyser platform integrated with POI. The additional costs for producing oxygen for POI and integrating POI with such a platform are 79 million Euros in capital expenditure and 2.17-2.73 million Euros per year in operational expenditure (depening on production rate). The resultant annual cost for providing reoxygenation as a service to the entire Baltic Sea is 367-612 million Euros, which compared to the current estimated annual economic loss of 5.6 billion Euros from direct and indirect losses due to the poor state of the Baltic Sea is a small price to pay. As the continuation to the BOxHy project, the BOxIn project is proposed to pilot POI in a marine environment at one of the identified sites, take steps towards pilotting an offshore electrolysis platform integrated with POI, and continue engagements with a wide array of stakeholders in the Baltic Sea region.

Abbreviations

Abbreviation	Description
barg	a unit of gauge pressure, i.e. pressure in bars above ambient or atmospheric pressure
BFD	Block flow diagram
BHC	Baltic Sea Hydrogen Collector
BOxHy	Baltic Sea Oxygenation and the Super-Green Hydrogen Economy
BOxIn	Baltic Sea Pilot for Pure Oxygen Injection
BSAP	Baltic Sea Action Plan
CAPEX	capital expenditure
COD	Commercial Operations Date
DEEP	Department of Ecology, Environment, and Plant Sciences (Stockholm University)
deoxo	deoxidation
DI	deionised
DR 7	DR 7.0 is a pipe class. The DR 7.0 (also called SDR 7.0) is the commercial HDPE piping class than can withstand the biggest pressure range (thickness)
EGU	European Geosciences Union
EHB	European Hydrogen Bank
EHS	Environment, Health and Safety
ELZ	electrolyser
EU	European Union
FID	Final Investment Decision
GOOD	Global Ocean Oxygen Decade
GoR	Gulf of Riga
GW	gigawatt
H2	Hydrogen
HAZID	Hazard Identification study
HDPE	high density polyethylene
HELCOM	The Baltic Marine Environment Protection Commission – also known as the Helsinki Commission (HELCOM) – is an intergovernmental organisation (IGO) and a regional sea convention in the Baltic Sea area
HOPE	Hydrogen Offshore Production for Europe
HSE	Health, Safety and Environment
HV	high voltage
HVAC	Heating, Ventilation, and Air Conditioning
IOC-UNESCO	Intergovernmental Oceanographic Commission of UNESCO
ISBL	inside battery limits
LCOE	Levelised cost of electricity
LF	location factor
MLD	Mixed layer depth
MW	megawatt
NEFCO	Nordic Environment Finance Corporation
NORCE	Norwegian Research Centre
O2	Oxygen
OEM	original equipment manufacturer
OPEX	operational expenditure
OSBL	outside battery limits

OWA	Offshore Wind Advisory
PCI	Project of Common Interest
PEM	Proton Exchange Membrane
POI	Pure oxygen injection
psu	practical salinity unit; unit of measurement. Salinity in the ocean is defined as the grams of salt per 1000 grams of water, wherein one gram of salt per 1000 grams of water is defined as one practical salinity unit or one psu
Ro-pax	roll-on/roll-off passenger vessel
SAF	sustainable aviation fuel
SDG	Sustainable Development Goal
SGU	Sveriges geologiska undersökning (in English: Geological Survey of Sweden)
SKVVF	Svealands kustvattenvårdsförbund (in English: Svealand's Coastal Water Conservation Association)
SMHI	Swedish Meteorological and Hydrological Institute
STACO	Science and Technology Advisory Committee for Oxygenation
SVOA	Stockhom vatten och Avfall (in English: Stockholm provider of drinking water and sewer services)
TRL	technology readiness level
TSO	Transmission System Operator
UN	United Nations
WP	Work Package
WW1	World War I
WW2	World War II

1 Introduction

This section presents the Baltic Sea Oxygenation and the Super-Green Hydrogen Economy (in short "BOxHy") project background, partners and funding, objectives and scope of work.

1.1 Background

Low oxygen conditions increasingly threaten marine ecosystems by reducing habitat and biodiversity, altering biogeochemical processes in water and sediment, influencing greenhouse gas emissions, and contributing to toxic algae blooms by increased phosphorus recycling (Gregoire, et al., 2023). As a result, ocean deoxygenation can have a significant impact on regional economies costing billions of dollars and affecting thousands of jobs (Pitcher, et al., 2021) (Dewar, Landers, & Ridlington, 2009). It has been linked to human activities leading to eutrophication and ocean warming since the 1950s (Breitburg, et al., 2018). Low oxygen zones exist in the open ocean, over continental shelves, and in coastal seas, and are expected to expand in the future due to warming and increasing nutrient pollution. Low oxygen zones include hypoxic environments (oxygen concentrations between 2 ml/l O_2 and 0 ml/l O_2) and anoxic environments (have zero oxygen or even contain hydrogen sulphides) (Hofmann, Peltzer, Walz, & Brewer, 2011). Despite this increasing threat to the marine ecosystem, current conservation measures do not effectively address the impacts of reduced oxygen or feature large time lags in implementation or projected outcomes (Scientific and Technical Advisory Committee (STAC), 2023) (Baltic Marine Environment Protection Commission - Helsinki Commission, 2021).

While small-scale, pure oxygen injection (POI) has been used in freshwater lakes and in marine aquaculture settings, sub-basin and basin-scale implementations are non-existent. The use of marine renewable energy for green hydrogen production potentially presents a new opportunity to mitigate hypoxia or anoxia in the marine environment through POI. The oxygen by-product resulting from electrolytic hydrogen production could be used to mitigate anoxia, restore benthic habitat, reduce phosphorus loading, and hence suppress the vicious cycle of algal blooms. Constant POI could also help combat increasing hypoxia caused by circulation shifts, decreased deep mixing in autumn and winter and decreasing oxygen concentrations due to increasing water temperatures related to climate change (Wallace, Jutras, Nesbitt, Donaldson, & Tanhua, 2023). POI technologies that can scale up to oxygen demands estimated for marine applications are already common in USA reservoirs (Mobley, et al., 2019). The largest installation of freshwater POI can supply up to 350 tonnes of oxygen per day. Although ocean deoxygenation is an increasing threat, POI for the marine environment has received little attention, likely due to the current cost of oxygen and/or lack of science, infrastructure and awareness.

The BOxHy project is an innovative project focused on preparing a pilot study site for POI in the Baltic Sea environment, with the extended focus of upscaling the technology and science to basin-wide scales and conceptualizing POI integrated with electrolysis powered by offshore wind farms within the Baltic Sea. The concept would be to co-produce renewable hydrogen for the emerging renewable hydrogen economy and oxygen for injection to the sea via offshore electrolysis, creating a novel innovative technique that could be adapted to other anoxia-prone coastal environments with similar environmental challenges.

1.2 Project partners and funding

The project is a collaborative effort between Flexens Oy Ab, Lhyfe, and Stockholm University's Department of Ecology, Environment, and Plant Sciences (DEEP). A brief description of each of the partners is provided below.

Flexens is the ideal partner for communities, industries, and investors seeking renewable Power-to-X solutions. We develop large-scale, clean, and sustainable hydrogen projects to accelerate the energy transition. Flexens was founded in 2018 to capitalise on the skills and capabilities created in building the world-leading RES testbed and demo, Smart Energy Åland, to capture the rapidly growing demand for renewable energy systems. www.flexens.com

Lhyfe is a European group devoted to energy transition, and a producer and supplier of green and renewable hydrogen. Its production sites and portfolio of projects intend to provide access to green and renewable hydrogen in industrial quantities and enable the creation of a virtuous energy model capable of decarbonising entire sectors of industry and transport.

In 2021, Lhyfe inaugurated the first industrial-scale green hydrogen production plant in the world to be interconnected with a wind farm. In 2022, the company inaugurated the first offshore green hydrogen production pilot platform in the world. In 2023, it inaugurated its second and third sites, and currently has several sites under construction or expansion across Europe. Lhyfe is represented in 12 European countries and had 195 staff at the end of December 2023. The company is listed on the Euronext market in Paris (ISIN: FR0014009YQ1 – LHYFE). Lhyfe.com

Lhyfe Sweden AB, a limited liability company incorporated and existing under the laws of Sweden, having its registered office located at Klarabergsgatan 60, 111 21 Stockholm, Sweden, with registration number 559334-3857.

Stockholm University (SU) department of Ecology, Environment and Plants Sciences (DEEP) has 140 employees, including 35 teachers and researchers and ca. 50 PhD students. The research and education at DEEP include ecology and evolution, ecotoxicology, marine biology, plant physiology and plant systematics. The research has partly direct environment and society relevance and is often interdisciplinary. DEEP has a long tradition of Baltic Sea research including environmental monitoring of the Baltic Sea as an integrated part of the research. This links to the strategic focus on the Baltic Sea of Stockholm University and the work at Stockholm University Baltic Sea Centre.
https://www.su.se/department-of-ecology-environment-and-plant-sciences/

The **Baltic Sea Action Plan (BSAP) Fund** is funding the project. Read more about the Baltic Sea Action Plan Fund: https://www.nefco.int/financing/other-regions/baltic-sea-action-plan-fund/

1.3 Objectives

The main objective of the project is to tackle the problems of anoxia and hypoxia in the Baltic Sea by evaluating injecting oxygen into the sea via POI. The BOxHy project aims to build upon the work conducted by Vahanen Environment Oy and Jacobs Engineering Group Inc. in their 2021 BSAP-funded project on "Combining green hydrogen production and deep injection of pure oxygen gas to recover the Baltic Sea" (Vahanen; Jacobs, 2022).

The BOxHy project evaluates suitable onshore locations in the Baltic Sea for conducting a POI pilot study and begins preparations for launching a pilot POI site, including stakeholder engagement, project planning and identifying potential funding sources. In parallel, the project investigates the feasibility of sector coupling opportunities with renewable hydrogen production to meet forecasted regional hydrogen demands and sector coupling with ongoing offshore wind development in the Baltic Sea.

The project contributes to the following United Nations Sustainable Development Goals (UN SDGs):

Goal Nr 3 "Ensure healthy lives and promote well-being for all at all ages"*: Improving the water quality in the Baltics allows access to ecosystem services for young to old and allows people to strengthen their relation to nature.*

Goal Nr 7 "Affordable and clean energy"*: This goal is connected to the production of renewable energy i.e., wind power. It is the main source of energy for the proposed electrolyser technology.*

Goal Nr 13 "Climate change"*: Climate change is expected to gradually warm up the top layer of the Baltic Sea. This would also warm the bottom layers when they are mixed a few times a year. The proposed pure oxygen technology would not warm deep water through vertical mixing like aeration of downflow mixing technologies, preserving thermal and saline stratification. Offshore hydrogen has the potential to replace i.e., diesel in maritime applications and reduce large amounts of* CO_2 *emissions.*

Goal Nr 14 "Life below water"*: Decreasing the internal loading of phosphorus would reduce algae production in total and the frequency and intensity of algal blooms (of toxic blue-green algae). It would also have significant positive impacts on fisheries and fish catches in the southern and central parts of the Baltic Proper as well as in the Gulf of Finland. Reproduction of cod would be possible in much wider areas than today towards a level that was prevailing before the 1940s.*

Goal Nr 17 "Partnerships for the goals"*: This goal must be fulfilled if the proposed technology will be applied in the large and deep offshore oxygen deficit areas such as deep areas near Bornholm Island and Gotland (Gotland Deep, Landsort Deep and Fårö Deep located in the east, northeast and northwest of Gotland respectively). International cooperation is required to restore deep water quality and shrink the oxygen deficit bottoms back to what they used to be before the 1930s when the water quality was closer to the natural state of the sea. HELCOM is a natural and most suitable forum to continue the protection and restoration of the Baltic Sea.*

1.4 Scope of work

The project work was divided into four work packages (WPs), which were carried out in parallel from the project start in October 2023 to the project end in October 2024. The work packages are summarised below.

WP1: Site screening and preparations for an onshore marine POI pilot project, including a literature review of anoxia induced greenhouse effects, risk assessment of the linear diffuser oxygenation equipment in a marine environment, criteria development for evaluating the sites, stakeholder engagement and planning of next steps.

WP2: High-level mapping and investigation of potential locations in the Baltic Sea for POI integrated with large scale electrolysis to simultaneously combat sub-basin and basin scale anoxia/hypoxia as well as supply hydrogen to the emerging renewable hydrogen economy.

WP3: Early-stage concept design of an offshore hydrogen production platform integrated with POI, including determination of technical modifications and additional equipment requirements for POI integration, corresponding economic impacts, infrastructure requirements and EHS (environment, health and safety) risks and mitigation measures.

WP4: Coalition building and knowledge sharing, including the formation of two advisory boards to support the project work (a Science and Technology Advisory Committee and an Offshore Wind Advisory Board), participation in relevant conferences and communities, and coordination of information sessions and project results dissemination.

The project was conducted primarily as a desktop study based on publicly available data sources. The communications with stakeholders were carried out mainly via email or video calls. There were, however, a few face-to-face engagements with stakeholders and at knowledge-sharing events which are further elaborated in section 7.

The geographical scope of the study is the Baltic Sea region. For the POI pilot site, mainly the Stockholm archipelago and Åland Islands regions were evaluated due to limitations further elaborated in section 4.3.1. However, since anoxia is a growing global challenge with over 900 coastal hypoxic and anoxic sites worldwide, the learnings and insights from this study can also be considered in other oxygen depleted marine regions outside of the Baltic Sea region (Breitburg, et al., 2018).

1.5 Report structure

Following this introduction, sections 2 and 3 provide further background knowledge on anoxia/hypoxia impacts and potential risks associated with combatting such anoxia/hypoxia via POI. Sections 4-7 are divided according to the project WPs 1-4, respectively, detailing the key methods and findings for each WP. The report concludes with the overall key findings. To limit the report length, most of the numerical data and detailed analyses are left to the Appendices and only referenced in the main Report.

2 Literature Review of anoxia-induced greenhouse gas effects

A thorough literature review was conducted on anoxia-induced greenhouse gas effects to create a foundation of understanding on how anoxia and hypoxia impact aquatic environments. The literature review can be found in Appendix 1.

3 Risk Assessment for BOxHy

In addition to the literature review, a detailed preliminary risk assessment was conducted to evaluate the potential impacts of POI on marine environments, with particular focus on the Baltic Sea. The risk assessment included analyses of environmental, technical and socio-economic risks and planned mitigation measures. The risk assessment can be found in Appendix 2.

4 Identification of potential sites for piloting reoxygenation

This section details the findings from WP1. The aim of WP1 was to identify a site or sites that are feasible for piloting the POI equipment in a marine environment. First, we provide a brief background on previous studies that have investigated methods for mitigating anoxia/hypoxia in the Baltic Sea (section 4.1). Next, the criteria building up a decision matrix for choosing the best POI pilot site are presented in section 4.2. This methodology is crucial to define and select the most promising sites for a POI pilot. Based on these criteria and the scope limitations of the study, 19 potential sites were identified in the preliminary screening (section 4.3). Through more detailed analyses and discussions with local stakeholders, these sites were narrowed down to three possible site candidates: Byfjorden, Säbyviken and Skarpösundet (section 4.4). Discussions with all three sites are still ongoing at the time of writing the report. The envisioned next steps for realising the pilot project, including the project plan, preliminary budget, permitting requirements and financing opportunities are detailed in section 4.6.

4.1 Background on previous studies

Previous studies and pilot projects have already been conducted to test other methods than POI for combatting anoxia and hypoxia in the Baltic Sea region. These studies include, but are not necessarily limited to, the ones described below.

4.1.1 PROPPEN, BOX and BOX-WIN projects

Prior to BOxHy, there were two projects carried out in three fjords of the Baltic Sea between 2010-2012: BOX project (Byfjord) (Forth, Liljebladh, Stigebrandt, Hall, & Treusch, 2015) and the PROPPEN project (Rantajärvi, et al., 2012) (Lännerstasundet and Sandofjärden). These projects focused on pumping oxygen-rich surface waters into deeper layers, breaking the stratification of the water column which further facilitates the wind induced mixing and hence, oxygenating bottom anoxic waters. The BOX project has led to a community-induced follow up project (start 05/2024) within the Byfjord for reoxygenation through pumping surface waters to depth (Stiftelsen Byfjordens framtid, n.d.). Additionally, a theoretical study, BOX-WIN, was performed in 2013 exploring different economic, technical and ecological aspects of reoxygenation of the Bornholm basin using wind powered pumping systems. However, for larger scale applications, the pumping of oxygenated surface water is considered too expensive and further work is needed on the stratification modifications it causes (Ollikainen, et al., 2016).

4.1.2 OX2 and SMHI’s reoxygenation project

On February 15, 2024, renewable energy solutions developer, OX2, the Swedish Meteorological and Hydrological Institute (SMHI), Stockholm University and the Norwegian Research Centre (NORCE) announced their plans to research artificial oxygenation in the Baltic Sea in combination with hydrogen production by OX2’s planned offshore energy parks “Neptunus” in south of Sweden and “Pleione” located east of Gotland. The project “BaltVent” was approved a research grant by the Swedish Environmental Protection Agency and from the Norwegian Sea and Water Authority for a duration from 2024 to 2027. OX2 is also collaborating with Uppsala University and Baltic Waters to investigate how oxygenation and the release of cod can strengthen cod stock in the Baltic Sea (Lind, 2024).

4.1.3 BSAP-funded project by Vahanen and Jacobs

The BSAP-funded pre-feasibility study conducted by Vahanen and Jacobs in 2021 has already investigated combining Baltic Sea oxygenation with the emerging hydrogen economy through the production of oxygen for deep-water injection and "super-green hydrogen" via water electrolysis. The final technical report published on the project in October 2022 includes a detailed overview of eutrophication in the Baltic Sea, various oxygen injection technologies and an investigation of potential pilot sites in Finland and Sweden, among other topics.

In the Vahanen and Jacobs study, it was concluded that Lännerstasundet bay in Sweden could be an ideal piloting site. The estimated cost of a pilot project was 5-10 million Euros if sourcing liquid oxygen from a third party, and 25-30 million Euros if sourcing oxygen from electrolysis. It was recommended that as the next step, a study be conducted on the "super-green hydrogen economy", pilot preparation, funding models and further engagement of various stakeholders.

The present BOxHy study was launched as a continuation of the work of Vahanen and Jacobs. While there were a few adjustments to the scope of work such as re-evaluation of potential pilot sites with adjusted criteria, the goals and techno-economic considerations remained mostly the same. BOxHy continued to use the linear diffuser technology as a design basis for oxygen injection to the Baltic Sea, in both the pilot and future scale-up scenarios. The technology is shown in Figure 1 below.

Figure 1. Left picture: Linear diffusers towed into place with weights installed (Vahanen; Jacobs, 2022). Right picture: Linear diffusers positioned over the design location and sinking gradually from shore as the ballast pipe filled with water. Note the liquid oxygen supply tank photo insert (Vahanen; Jacobs, 2022).

The pilot site criteria and risks determined by Vahanen and Jacobs served as an excellent basis for the work carried out in BOxHy. While Lännerstasundet was further evaluated in BOxHy as a potential site for a POI pilot, it was not among the top candidates after our advanced site analysis due reasons such as high levels of contaminants, low levels of salinity in the deep water and limitations in space for the onshore installation. While neither Jacobs Engineering nor Vahanen (now acquired by AFRY) were project partners in BOxHy, Jacobs maintained an active role in the BOxHy project, including representation by David Austin in the Science and Technology Advisory Committee for Oxygenation (see section 7.1 for more information).

4.2 Pilot project criteria table

The pilot project criteria are a general collection of favourable conditions for preparation, permitting surveillance and implementation of a marine pilot site for POI. To keep the costs of this first pilot as low as possible, several technical, scientific and infrastructural boundary conditions play a crucial role in the site determination. Such boundary conditions include, for example, road access to the oxygenation site and an existing hydrographic and biogeochemical observation program of the concerned water body including reoccurring ship-based observations, biogeochemical probing of the water column and lab analysis of the probes and/or mooring installations. To keep track of the environmental impact and ecosystem reaction to POI on the concerned water body, a long-term scientific surveillance program is crucial and not negligible. At the same time, the bathymetry of the water body must be known to estimate the oxygen volume demand of the marine system and to correctly dimension the reoxygenation unit. Additional favourable criteria include local stakeholder interest in hosting a POI pilot site and established regulations and streamlined processes for obtaining permits for both land and water-based installations.

Using the criteria table from the Vahanen and Jacobs BSAP report as a reference, the criteria for locating the most suitable site(s) for piloting marine POI were determined (Vahanen; Jacobs, 2022). The criteria were divided into the following categories: (1) Technical and Operational, (2) Socio-economic, and (3) Regulatory. These criteria are detailed in Table 1 below.

Table 1. Updated pilot site criteria table from Vahanen and Jacobs BSAP report (Vahanen; Jacobs, 2022).

Technical and Operational Criteria		
Criteria Category	**Criteria**	**Further explanation**
Models and Surveys of Water body	Detailed Bathymetry available	For example: high-resolution bathymetric data (ETOPO2); digital data bases of seafloor and land elevations on a 2-minute latitude/longitude grid (1 minute of latitude =1 nautical mile or 1.15 statute mile)
	Regular/Continuous Hydrographic Data monitoring ongoing	For example: currents, mixed layer depth (MLD), depths profiles of T, S, O_2, H_2S, P, N, pH)
	Historic Hydrographic Data available	For example: currents, MLD, depths profiles of T, S, O_2, H_2S, P, N, pH)
	Ongoing Mooring/ship observations	If not ongoing, what is the added financial cost/personnel required to survey/monitor the pilot installation?
	Monitoring of pollutants in sediment and water column	e.g. WWI and WW2 munitions, etc.
Properties of oxygen concentration	Oxygen demand below the halocline is near or less than 10 tonnes O_2 per day	10 tonnes of O_2 are taken as an upper limit to restrict costs for pilot site oxygenation
	Persistent anoxia below the halocline (strongly preferred over seasonal summer-only anoxia)	Strongly preferred. Seasonal summer-only anoxia below the thermocline is the second-best option.
	Reasonable depth below pycnocline and bottom.	Sufficient depth is needed for oxygen to dissolve in the deep water
Site location	Bathymetrically confined sub-basin	A confined basin with isolated deep water with anoxia will facilitate the efforts for monitoring of the follow-up of effects of POI.
	Available land area for onsite infrastructure and construction phase	Minimum requirements are roughly 15 m x 20 m land area to fit the oxygen storage tank, vaporizers and piping to the water body
	Access to oxygen supply	If oxygen is sourced from a third-party: • Source within approximately 50 km of installation to keep the delivery costs low • Available road access for large oxygen delivery truck (about 20 t capacity or greater/adapted to site necessity)
		If oxygen is generated via a new-build electrolyser: • Available Electrical supply to site per electrolyser demand • Identified hydrogen off-taker(s) for hydrogen product

		• Available land area for electrolyser construction and operation
	Pipe access to water body from oxygen source	Needed to install the linear diffuser system.
	Underwater oxygen supply pipe access to anoxic water volume	
	Site security to protect oxygen supply and in-water monitoring probes	
	Electricity supply availability	Required during construction phase. During operation, vaporisers can be run on solar power from a small onsite solar panel
Socio-economic criteria		
Criteria Category	**Criteria**	**Further explanation**
Support for the project	Stakeholder support for the project	Including local communities, local government, scientists, public officials, etc. Increased stakeholder support lowers risks of project delays
Location	No barriers to installation due to local activities. What are local activities at the site?	E.g., maritime transport, fishing, swimming, public beaches, recreation
	Accessible for public viewing	To support citizen engagement activities throughout the pilot project through an "open view" on the installation.
Ecological	Has the local ecosystem has been affected by low oxygen concentrations?	E.g., disruptions in fish species in local waters, presence of algal blooms
Economic	Available project funding and financing mechanisms	E.g., public funding, interested private investors
Regulatory criteria		
Criteria Category	**Criteria**	**Further explanation**
Safety	Well-defined safety regulations for installation and execution of the pilot	A solid existing framework ensures that the pilot project can be executed in a safe manner
Environmental	Well-defined environmental regulations for installation and execution of the pilot	A solid existing framework ensures that no harm is done to the environment
Permitting	Well-defined permit requirements	It should be rather easy to understand what permits need to be required and how to complete the applications.
	Reasonable timelines and procedures for obtaining the permit	Minimised delays in starting the project
	Support from permitting authorities	On local, national and regional levels, including, e.g., HELCOM and the EU

4.3 Mapping of anoxic locations based on identified criteria

Based on the identified criteria, potential pilot sites were evaluated. The evaluation was conducted in multiple stages. The methodology and results of the multi-stage evaluation are detailed in this section.

4.3.1 Methodology for first-phase screening

Due to limitations in data, time and resources, the entire Baltic Sea region could not be screened within the scope of this study. Therefore, the first-phase screening was limited to the Stockholm archipelago, the Åland Islands sub-regions and the Byfjord on the west coast of Sweden. These sub-regions were selected based on the project team's previous knowledge and experiences within these regions of the Baltic Sea and in the case of Byfjord, due to possible cooperation with the on-going restoration project that is a follow-up to the BOX project.

The first-phase screening focused primarily on finding locations that met, first and foremost, the technical and operational criteria. In particular, the bathymetry, occurrence of anoxia, the infrastructure availability and the availability of monitoring and modelling data were evaluated in this phase as they are the most critical criteria for the implementation of a pilot. These criteria are described in more detail in the sub-sections below.

Data from the monitoring program of Svealands kustvattenvårdsförbund (SKVVF) from July-August 2010-2023 was used to screen for potential pilot areas in the Svealand coastal areas. Additional data from the control program of Stockholm's water and waste company, Stockhom vatten och Avfall (SVOA), complemented the SKVVF data set. For the Åland Islands region, we used data obtained from the monitoring program of the Åland government, Ålands landskapsregering in Swedish, (data from August 2000-2022).

Based on this first-stage screening, we identified 19 sites with regular summer hypoxia in a confined basin, potentially interesting to be used as pilot sites for POI. Ideally, the site should have persistent anoxia year-round. However, due to data limitations, this criterion could be evaluated for only some of the sites. It appears that for some sites there may be persistent anoxia in some years but in other years there is complete mixing of the water column depending on the specific environmental conditions. All sites are shown in Figure 2 and are further elaborated upon in Appendix 3.

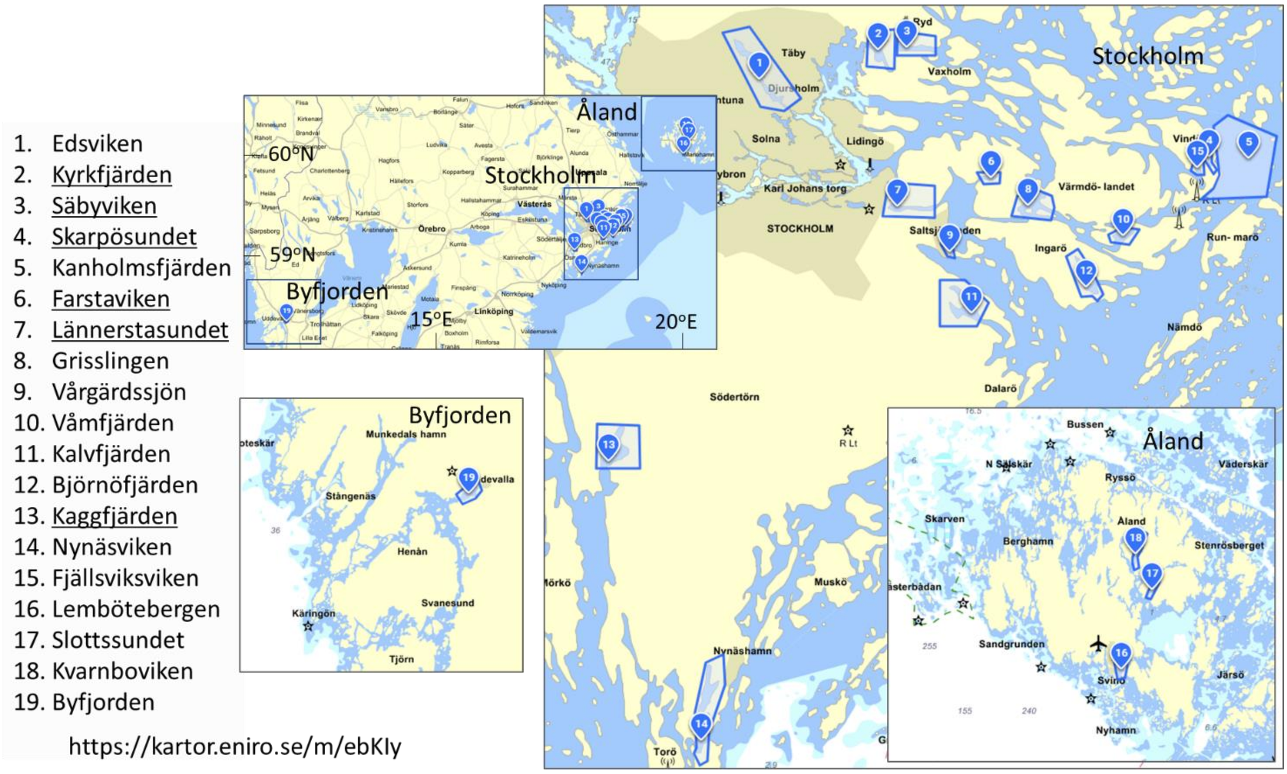

Figure 2. Map of potential pilot sites identified via the first screening. The map can be accessed here.

4.3.1.1 Bathymetry

High resolution bathymetry is needed to calculate the volumes of different water layers and sub-areas, as well as to plan the location of the oxygen diffusers for the pilot. The availability of detailed bathymetry is limited in all areas. The Swedish Maritime Administration, Sjöfartsverket in Swedish, has a website which shows the quality of existing depth information. An example is provided in Figure 3. The turquoise-coloured areas are charted with modern technology and fulfil the FSIS-44 quality; here high-resolution depth charts can normally not be produced. The red areas are not measured with modern technology; they may be hand charted with long distances between data points and not-so-reliable data sources. Most of the identified anoxic areas are in isolated bays with poor depth information.

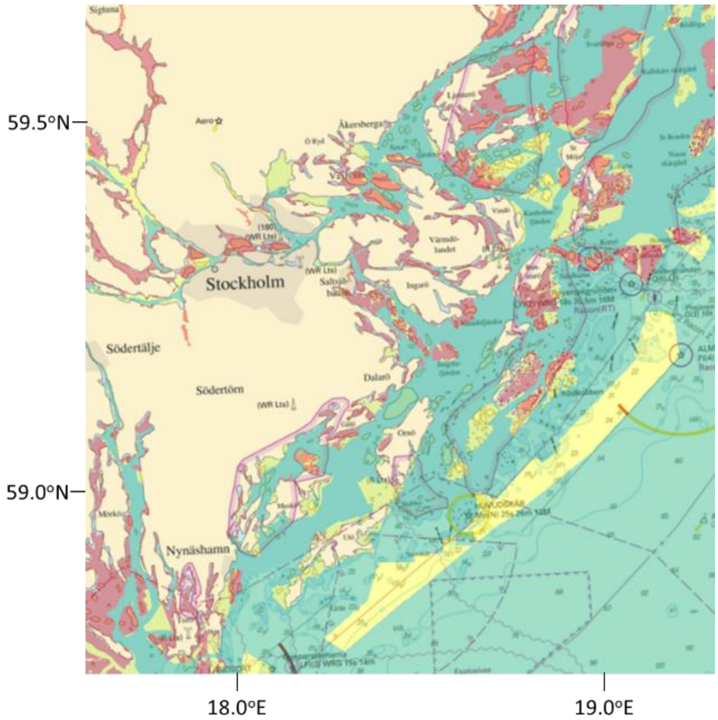

Figure 3. Example depth chart from the Stockholm Archipelago region used to evaluate bathymetry data for various potential pilot sites (Sjöfartsverket, 2023).

4.3.1.2 Monitoring and occurrence of anoxia

Most of the 19 areas we analysed are at least twice per summer (July and August) subject to regular monitoring. For some areas, there are more intense sampling programmes, up to ten times per year. An existing and ongoing monitoring programme is crucial to evaluate and follow up on the effects of a pilot experiment on a wide variety of environmental properties in the area. Existing historical data is needed to evaluate the long-term variability of anoxia and, if sufficiently detailed, can be used to estimate oxygen consumption rates to dimension the oxygenation system of the POI installation. Even if water bodies are monitored twice in summer, it is not possible to calculate oxygen consumption rates if profiles of the hydrogen sulphide are missing and if anoxia has already developed before the first data acquisition. For these sites rough estimates were made using the volume of hypoxic water and the assumption that 10 mg/l O_2 would have to be added over a period of two months to either prevent seasonal anoxia from developing or increase the oxygen concentration in a permanently anoxic area. The description of calculations of oxygen consumption rates based on monitoring data are included in the site descriptions in Appendix 3.

4.3.1.3 Models

The SMHI oceanographic coastal zone model S-HYPE includes the Swedish areas that are official water bodies. However, this is a one-dimensional model for each waterbody, ignoring the spatial variability within waterbodies, i.e. each model basin has many depth layers but each layer is assumed to be horizontally mixed. The models can help describe vertical mixing and water exchange with surrounding water bodies, but validation of model results is deemed necessary. Some model results can be downloaded from here (model data per area).

4.3.1.4 Infrastructure:

Infrastructure requirements include, among other criteria, sufficient available space for the safe installation of the oxygen tank on land, sufficiently large oxygen transport truck access roads to replace or refill the oxygen tank and access to the electricity grid and/or onsite renewable energy generation (in the case of coupling with renewable hydrogen production). Online satellite maps and a few site visits were used to evaluate infrastructure possibilities and limitations.

4.3.2 Second-phase screening:

In the second-phase screening, the remaining technical and operational criteria and the socio-economic and regulatory criteria were evaluated. The findings are summarised in Table 2 and are detailed in the sub-sections below.

Table 2. Results of second-phase screening. Critical aspects graded as following: green = acceptable, yellow = problematic/questionable, orange = not acceptable. Recommended pilot sites are 3, 4 and 19. Abbreviations: No or less anoxia in July (J), (sometimes) only very deep anoxia (D), or some years without anoxia (O).

Site no.	Name	Municipality	Mean depth bottom-to pycnocline	Consistent Anoxia in summer	Typical Salinity Deep water	O_2 demand ton/day (adding 0-10mg/l 2 months)	O_2 demand ton/day (data O_2 consumption)	Contaminants	Potential installation site and access	Other aspect
1	Edsviken	Sollentuna/Danderyd	5	O	3	0.8			Small marina	P precipitation planned
2	Kyrkfjärden	Österåker	5	Yes	3.5	0.5	0.5-1		Small marina	
3	**Säbyviken**	**Österåker**	**7/8**	**Yes**	**5.1**	**1.0/0.7**			**Marina**	
4	**Skarpösundet**	**Värmdö**	**12**	**Yes**	**5.9**	**0.1**	**0.05**		**Small Marina**	
5	Kanholmsfjärden	Värmdö	27	D, O	8.5	58	6 (-3-17) (Jul-Aug)		Limited	
6	Farstaviken	Värmdö	5	Yes	5.5	0.13		High	Marina	
7	Lännerstasundet	Nacka	9	Yes	4	0.8 (Western area)	2-3 (Western area, Apr-Aug)	High	Small marina	
8	Grisslingen	Värmdö	5	J, D	5.5	0.7			Marina	
9	Vårgärdssjön	Nacka	3	Yes	5.4	0.05			Very limited	

	Våmfjärden	Värmdö	8	D	5.4	0.3			Very limited	
11	Kalvfjärden	Tyresö	9	J, D	5.5	1.7			Marina 1.5 km	
12	Björnöfjärden	Värmdö	n/a	Yes	5.5	<10			Marina 1.5 km	P precipitation done
13	Kaggfjärden	Botkyrka	10	J, D	6.4	2.8			Marina	
14	Nynäsviken	Nynäshamn	8	Mostly O	5.9	2	0.6-1.6 (Jul-Aug)		Very limited	
15	Fjällsviksviken	Värmdö	n/a	Yes	4.9				Very limited	
16	Lembötebergen	Åland	n/a	D, O	6	ca 0.2			Small marina >1.5km	
17	Slottssundet	Åland	n/a	Yes	5.6	ca 0.1			Limited	
18	Kvarnboviken	Åland	n/a	D	5.3	ca 0.25			Limited	
19	**Byfjorden**	**Uddevalla**	**>20**	**Yes**	**32**	**9**	**2.5***		**Port**	**Ongoing oxygenation by pumping**

* No or less anoxia in July (J) , (sometimes) only very deep anoxia (D), or some years without anoxia (O).

* Stigebrandt pers. Comm.

4.3.2.1 Evaluation of the remaining technical and operational criteria

The results of the evaluation of the remaining technical and operational criteria are summarised in Table 3.

Table 3. Results based on the analysis of the remaining technical and operational criteria. The findings for the most potential pilot sites are detailed in section 4.5.

Criteria	Short description of findings
Anoxic Conditions	Although some areas can have persistent anoxia for some years (Lännerstasundet, Kanholmsfjärden, Säbyviken, Skarpösundet, and Byfjorden), natural ventilation can occur in the autumn to spring period, thereby re-oxygenating the bottom water. Thus, any area chosen for a POI project would have to be closely monitored for deep-water ventilation, especially in autumn, winter and spring. Consistent development of summer anoxia (also in years with oxic conditions in spring) i.e., without oxygenation there is always summer anoxia, will however facilitate the evaluation of POI. Sites with sufficient anoxic conditions to be interesting for the POI pilot are: Kyrkfjärden, Säbyviken, Skarpösundet, Farstaviken, Lännerstasundet, Björnöfjärden, Fjällsviksviken and Slottsundet.
Oxygen Demand	Based on the simple estimate to increase the oxygen concentrations in the anoxic volume to 10 mg/l in two months. All 19 areas except Kanholmsfjärden have an estimated oxygen demand lower than 10 tons per day and therefore fulfil the criteria.
Mean depth of the hypoxic water volume	The water column must be sufficiently deep so the small oxygen bubbles can dissolve and do not disrupt the stratification. The depth difference between the pycnocline depth and the bottom, where the diffuser will be installed needs to be sufficiently large for the oxygen bubbles to dissolve. All areas except Kanholmsfjärden and Byfjorden are relatively shallow. Säbyviken, Skarpösundet, Lännerstasundet, Våmfjärden, Kalvfjärden, Kaggfjärden and Nynäsviken have a depth distance between the pycnocline and the bottom of around 8 m which is still sufficient for POI.
Salinity of the deep water	To be representative of brackish water conditions (6-8 psu) of the Baltic Sea and the biogeochemical conditions associated with this, the salinity should not be too low. Edsviken, Kyrkfjärden and Lännerstasundet have relatively low salinities, below 5 psu.
Available land area for pilot infrastructure	Judging from maps, there is the best availability of land area, mainly in existing marinas, at the following sites: Säbyviken, Skarpösundet, Farstaviken, Grisslingen, Kaggfjärden, Björnöfjärden and Byfjorden. However, landowners’ permission and other restrictions may apply and must be investigated. A first visit and discussion with the landowner of the building hardware store and small marina of Skarpösundet has been done. Skarpösundet would be advantageous because of a small land area available about 6 meters from the shore, next to a sufficiently large parking space. This area could be a potential location for the oxygen storage tank.
Access to oxygen supply	The access to oxygen supply was evaluated from three potential sources: 1. The co-production of hydrogen and oxygen via small-scale electrolysis, 2. The sourcing of oxygen from planned

	electrolyser projects within the vicinity of the potential pilot sites and 3. sourcing oxygen from a third-party and storing onsite in a storage tank. We conclude that to achieve the main objectives of the POI pilot and minimise project risks and costs, option 3 as recommended in (Vahanen; Jacobs, 2022), is the most techno-economically feasible solution. Therefore, the primary focus for evaluating access to oxygen supply was evaluating the potential to source from a third party and store onsite.

4.3.2.2 Evaluation of socio-economic criteria

The socio-economic criteria were primarily evaluated through hosting a virtual information and Q&A session for relevant stakeholders at the identified potential pilot sites. The information session is described in more detail in section 7.3. Additional follow-up discussions were also held with stakeholders interested in hosting a POI pilot project.

For the Skarpösundet site, discussions were held with Jenni Brink Bylund, from Värmdö municipality. A site visit was also made, meeting the landowner and CEO of Vindö byggvaror, Daniel Kristiansen. For the Säbyviken area, discussions were held with Markus Andersson, from Österåkers municipality. For the Byfjorden area, discussions were held with the local Byfjordens group conducting the follow-up project to BOX to understand their strategy to obtain stakeholder acceptance and engagement. Additionally, some of the Byfjordens' connections and previous experience (such as in the BOX project in the same location) gave us a deeper understanding of the official permitting processes. Meetings with the BOxHy team, Byfjordens and different local authorities, such as the sea and water authority of the county, were planned. However, these meetings have been postponed until the financial opportunity of the pilot is clarified. In this regard, a screening of potential financing opportunities for the pilot was also conducted. The results are described in section 4.6.3.

4.3.2.3 Evaluation of regulatory criteria

The regulatory criteria primarily focused on permitting aspects. Discussions were held with local authorities to clarify permitting requirements for the pilot site. Permitting of the selected potential pilot sites is further described in section 4.6.2.

The safety of oxygen storage was also evaluated. Oxygen needs to be stored in a well-ventilated area. The oxygen tank of our POI pilot site will be located outside, hence, in case of leakage, the oxygen will be vented to the atmosphere. It is, however, highly important not to have any open flames or sparks near the storage tank, as the presence of oxygen could provoke an explosion.

Since the available land area at Skarpösundet is next to a parking space, it would be of interest to consider a fence or some other protective shield between the vehicles and the oxygen tank if a long enough safety distance cannot be obtained. It is also important to keep the tank free from oil, grease, and dust or other particles that potentially could ignite (Air Liquide, 2024).

Within the scope of this project, the oxygen would be stored as a liquid that later evaporates in a vaporiser before it reaches the diffuser. For liquid oxygen, the same safety regulations apply as for gaseous oxygen, with the addition that personal safety equipment such as eye protection and cold insulating gloves must be worn at all times when handling the liquid oxygen.

4.4 Selection of most potential pilot sites

The most potential pilot sites were narrowed down to the following three sites:

- Byfjorden, Uddevalla, Sweden
- Säbyviken, Stockholm, Sweden
- Skarpösundet, Stockholm, Sweden

The three sites are compared in Table 4. For all three potential pilot sites, Linde plc has been identified as a possible oxygen supplier, as they have multiple selling points near all sites. Synergies with hydrogen production were also evaluated and are detailed in section 4.5.

Table 4. Comparison between the three potential pilot sites. Sub-basins are defined in section 5.1.

	Byfjorden	Säbyviken	Skarpösundet
Municipality	Uddevalla	Österåker	Värmdö
Sub-basin	KT_DS	BY_31	BY_31
Electricity zone	SE3	SE3	SE3
O_2 demand/day	2.5 tonnes*	1 tonne	100 kg
Electricity supplier	Vattenfall & Uddevalla Energi	EON	Vattenfall
O_2 suppliers	Linde	Linde	Linde
Accessible with truck	Yes	Yes	Yes

* Stigebrandt, A., and Andersson, A., 2022: Improving oxygen conditions in periodically stagnant basins using sea-based measures - Illustrated by hypothetical applications to the By Fjord, Sweden. Continental shelf Research. 244, 104806, https://doi.org/10.1016/j.csr.2022.104806

4.4.1 Byfjorden

Byfjorden was selected due to multiple reasons, including data availability and synergies resulting from the current on-going project for reoxygenation, its previous utilisation for the BOX project, and an established continuous monitoring program in the region. It is also the only Swedish fjord that has long-term anoxia in its bottom water like the Baltic proper, with anoxic conditions under 30m, only interrupted every 2-3 years where oxygen levels rise to hypoxic conditions.

The project with the Byfjordens Framtid Foundation brought together a wealth of expertise, including Anders Stigebrandt, who has extensive experience in leading reoxygenation projects and is a member of the STACO for the BOxHy project. The initiative also featured a well-established setup, strong stakeholder collaboration, and comprehensive knowledge of permitting processes for a reoxygenation project.

There were multiple discussions between the BOxHy team and the Byfjorden project regarding the format of permitting, a potential collaboration, the logistics for a joint project, and possible limitations of the Byfjord. However, due to a discrepancy in project initiation timeline, potential complications with permits, and the differing techniques (aeration through a full lift system and POI) that could skew the results, we decided not to proceed with this location during the timeframe of the ongoing experiment (2024-2027). As POI is still under-explored, maintaining communication between projects is of importance to ensure the responsible, sustainable and successful development of reoxygenation techniques.

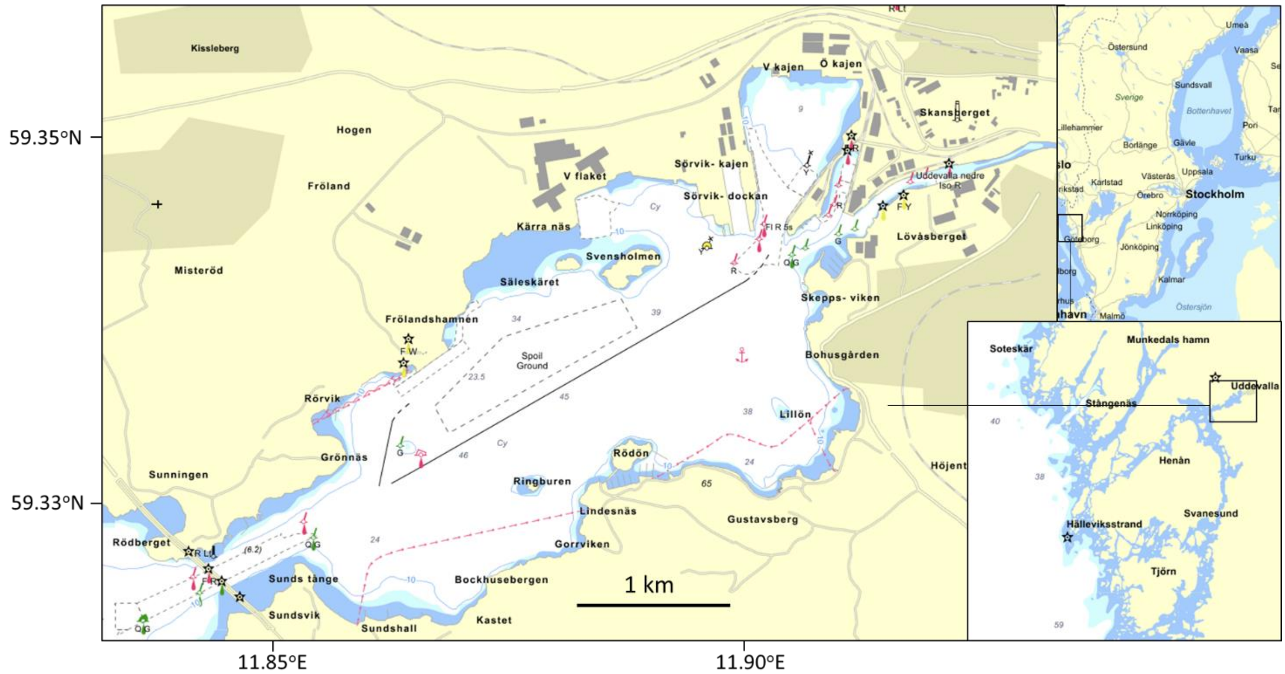

Figure 4. Close-up map of the Byfjorden site.

4.4.2 Säbyviken

Säbyviken is an elongated bay near Stockholm, deepest (23m) in the inner part. The deep water is always anoxic in summer (SKVVF monitoring station S73, July and August 2010-2023). During winter and spring 2023 and 2024 hydrographic data showed permanent anoxia. However, it has previously been observed to be fully mixed in September. Probably, the observed inter-annual variation of hydrogen sulphide concentrations in summer depends on the presence of mixing in the autumn to spring period or not. Volumes and potential oxygen demand were estimated for the whole area and for the inner, western part separately. Säbyviken has suitable land area potentially available in the Säbyviken marina. Contacts have been taken with the owner of the marina who is also the landowner.

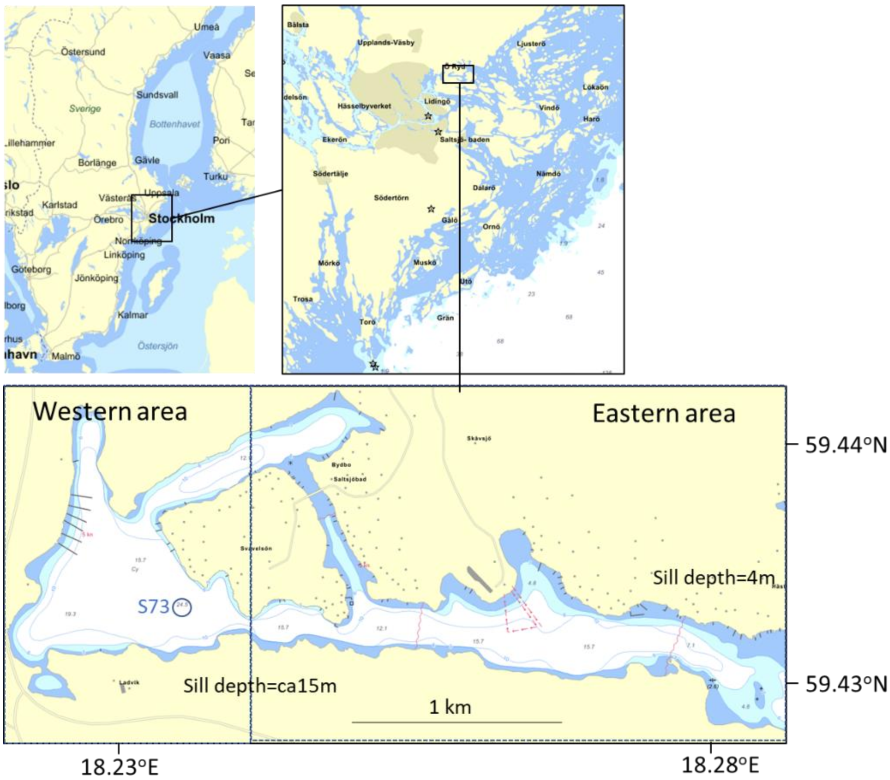

Figure 5. Location of Säbyviken bay in the Stockholm archipelago.

Figure 6. Säbyviken marina and available land area in relation to the bay (Screenshot from Google Maps). The road access to the marina yields potential for oxygen delivery to the site.

4.4.3 Skarpösundet

Skarpösundet is a small narrow bay in Värmdö municipality east of Stockholm. It has a deep central area (max depth 27 m), with consistent anoxia in summer at depths below 15 meters. It has been included in the SKVVF sampling program for a few years only (2012-2018). Unfortunately, no vertically resolved hydrogen sulphide data is currently available for this bay. For four years (2012-2015) Skarpösundet was sampled intensively in a research project (BalticSea2020), as reference area for the Björnöfjärden sediment Al-treatment (to precipitate phosphorus in Björnöfjärden). This data was used to estimate the oxygen consumption from the oxic conditions in late winter (three years, one year not mixed) until anoxia isdeveloped in early June. Due to the small volume of the deep water, the estimated oxygen consumption is one of the smallest of the investigated areas. It was estimated to be around 50 kg/day. A pontoon bridge stretches into the middle of the small bay, and there is sufficient depth for sampling vertical profiles of the water column. A site visit was made to the area and the landowner was met in April 2024 (Vindö Byggvaror, Daniel Christiansen, VD). Following this meeting a suitable site for an oxygen tank was identified in the area.

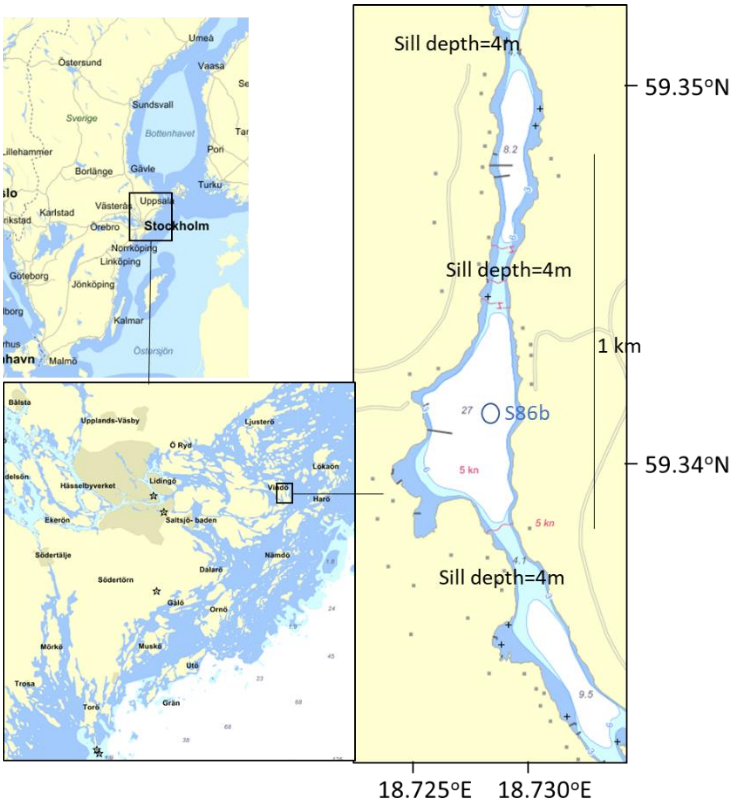

Figure 7. Location of Skarpösundet bay in the Stockholm archipelago.

Figure 8. Skarpösundet marina with potential location for oxygen storage tank. (eniro.se)

4.5 Potential synergies with hydrogen production

In the three identified sites, the synergies and limitations of coupling the POI pilot with hydrogen production through electrolysis were evaluated. The following options were evaluated: 1. sourcing oxygen from nearby electrolyser projects already under development and 2. co-production of hydrogen and oxygen via an on-site electrolyser. In option 2, the hydrogen would be produced for local off-takers and this feasibility of this was evaluated considering the following main parameters: (1) Access to grid connection, (2) Access to potential local hydrogen off-takers and (3) available land area. The findings are detailed in the sub-sections below.

4.5.1 Sourcing oxygen from local electrolyser projects

As part of WP2, a mapping of land-based electrolyser projects was conducted. This mapping is detailed in section 5.2.2. Based on this mapping, the nearest electrolyser projects to each of the three sites were identified and are detailed below.

4.5.1.1 Byfjorden

The nearest planned electrolyser project to the Byfjorden site is the 30 MW alkaline electrolyser that is part of the Project Air Methanol project being developed by Uniper and Perstorp Group in Stenungsund, Sweden (slightly over 40 km from Uddevalla municipality). The project is denoted as “S2” on the mapping of electrolyser projects in section 5.2.2. The project’s planned startup year is 2026, although the Final Investment Decision is still pending. Given the timeline, distance and size of the production plant, sourcing oxygen from this plant could potentially be feasible. However, further discussions would be required with the project developers and the additional cost of capturing and transporting oxygen to the pilot site would need to be evaluated.

4.5.1.2 Säbyviken

The nearest identified electrolyser project to Säbyviken is the HySkies 200 MW electrolyser project being co-developed by Vattenfall, SAS, Shell and LanzaTech in Forsmark, Sweden. The project is denoted as “S6” on the mapping of electrolyser projects in section 5.2.2. The planned start-up year is 2026-2027, which could potentially match up with the pilot timeline (refer to section 4.6.1). Nevertheless, the project is located roughly 130 km from the Säbyviken marina where the piloting is considered. Therefore, there would be significant transport costs involved for the small amount of oxygen required by the pilot. Hence sourcing oxygen from this plant is deemed unfeasible.

4.5.1.3 Skarpösundet

Since Skarpösundet is in relative proximity to Säbyviken, the same HySkies electrolyser project is the closest to this potential pilot site as well. However, the transport distance is over 170 km, even longer than to the Säbyviken site. Therefore, it is again concluded that it is too expensive and logistically unfeasible to source oxygen from this electrolyser project to the POI pilot.

4.5.2 Grid connection

The first criteria for evaluating co-production of electrolytic hydrogen and oxygen at the pilot site was accessible grid connection for supplying the electricity to the plant. The Swedish TSO (Svenska Kraftnät) has provided a map of the Swedish transmission grid, Figure 9 (Svenska Kraftnät, 2023). Grid access is available in all the relevant municipalities; however, a more detailed map would be needed to determine the actual connection capacity available near the potential pilot sites themselves. If a site would lack grid connection, the electrolyser and additional oxygen pumping equipment could be powered by solar panels, or a small wind turbine installed on-site. For this, however, sufficient land area and permits would be required.

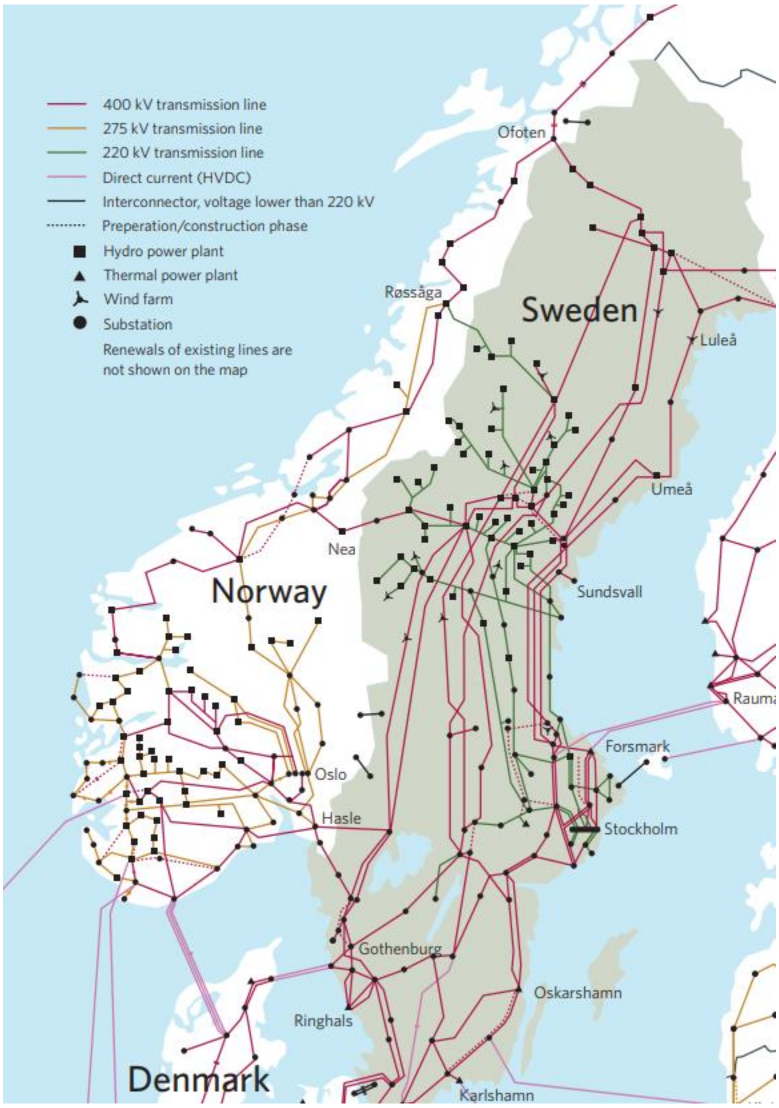

Figure 9. The Swedish transmission grid (Svenska Kraftnät, 2023).

4.5.2.1 Byfjorden

Byfjorden is located on the west coast of Sweden, about 90 km north of Gothenburg, and belongs to Uddevalla municipality. The fjord is adjacent to Uddevalla city in the north, east and south, and can, based on that, be assumed to have plenty of grid availability in the area. The electricity in Uddevalla is operated by Vattenfall and Uddevalla Energi. Byfjorden is, in theory, located just outside the borders of Kattegat and the Baltic Sea. However, as an experimental area with hypoxia, it is still interesting within the scope of this project.

4.5.2.2 Säbyviken

Säbyviken belongs to the Österåker municipality, northeast of Stockholm. The electricity in the municipality is operated by EON, but unfortunately, a detailed grid map has not been made available. Instead, a map of the municipality with marked height points was extracted from the municipal website and used as a reference for the grid availability (Figure 10). The height points marked with a red X are identified as electricity poles. Based on this method, grid connection seems to be available solely on the east side of Säbyviken. As interpreted from Google Maps, there is a building on the west side of Säbyviken, south of the marina. However, solar panels on the roof are visible, which could indicate an off-grid solution. In this case, on-site renewable electricity generation would most likely be needed to power electrolysis.

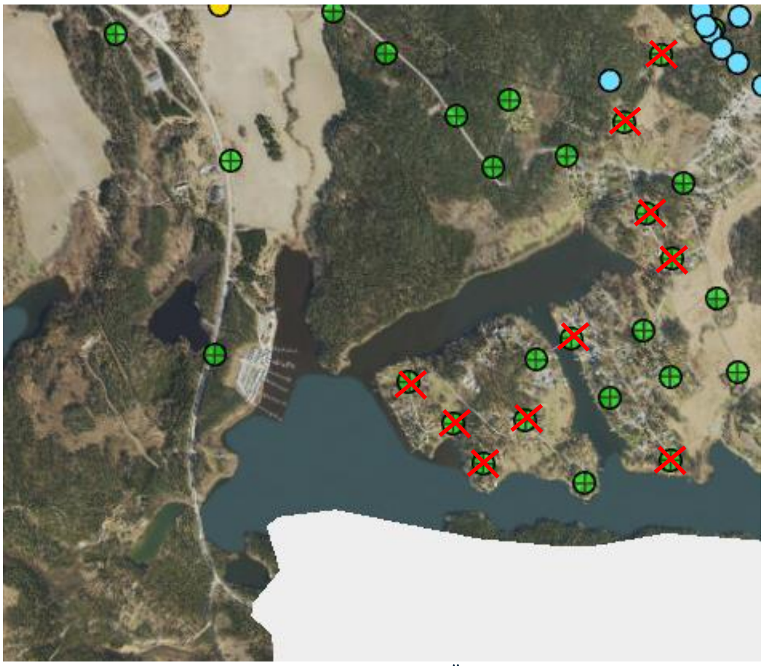

Figure 10. Height points around Säbyviken (Österåker, 2021).

4.5.2.3 Skarpösundet

Skarpösundet is located east of Stockholm in Värmdö municipality and belongs to the middle Stockholm archipelago. The electricity operator in Värmdö is Vattenfall and no detailed grid map is available. However, the site is surrounded by buildings which could indicate grid availability in the area.

4.5.3 Hydrogen off-take potential

To source oxygen from electrolysis, the produced hydrogen must also have off-taker(s) to justify the investment costs. Potential regional off-takers of hydrogen were explored for all three sites. The findings are detailed below.

4.5.3.1 Hydrogen supply to refuelling stations

Sweden has a handful of existing hydrogen refuelling stations and plenty more in the pipeline. There are three stations nearby Säbyviken and Skarpösundet (Figure 11). The green station is located at Arlanda airport and is already in operation, while the orange stations are to be built in the future. The closest station to Säbyviken is just outside Rosersberg, between Märsta and Upplands Väsby, while the distance from Skarpösundet is equally long to both orange stations.

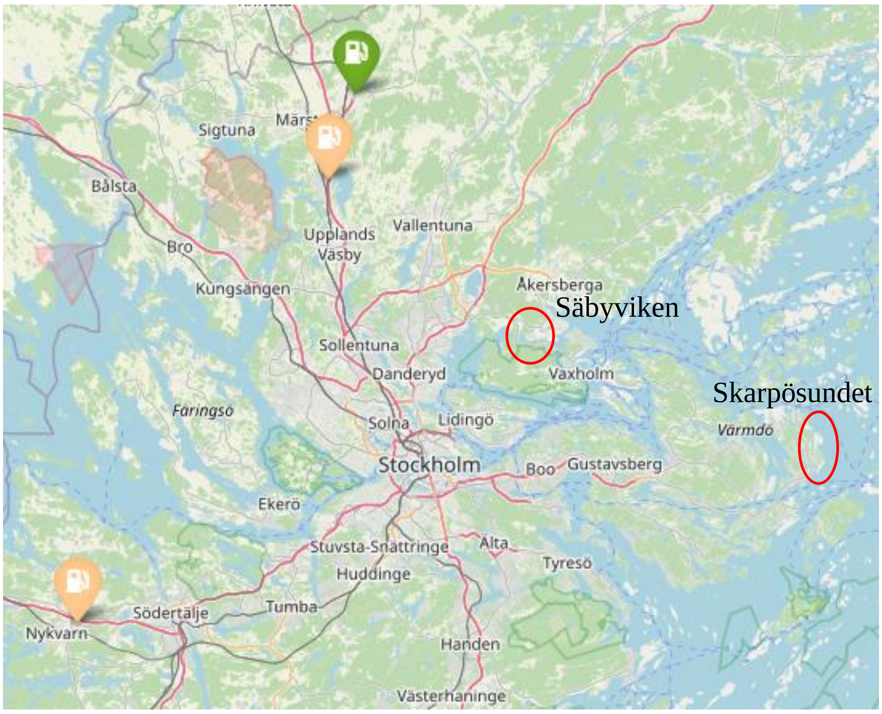

Figure 11. Hydrogen refuelling stations near Säbyviken and Skarpösundet (Luleå University of Technology, 2023).

For the Byfjorden site, there is a refuelling station planned in Uddevalla city, on the Northeast side of the fjord (Figure 12), which could be a potential hydrogen off-taker. The station is a part of the Nordic Hydrogen Corridor´s refuelling station network (Nordic Hydrogen Corridor, n.d.).

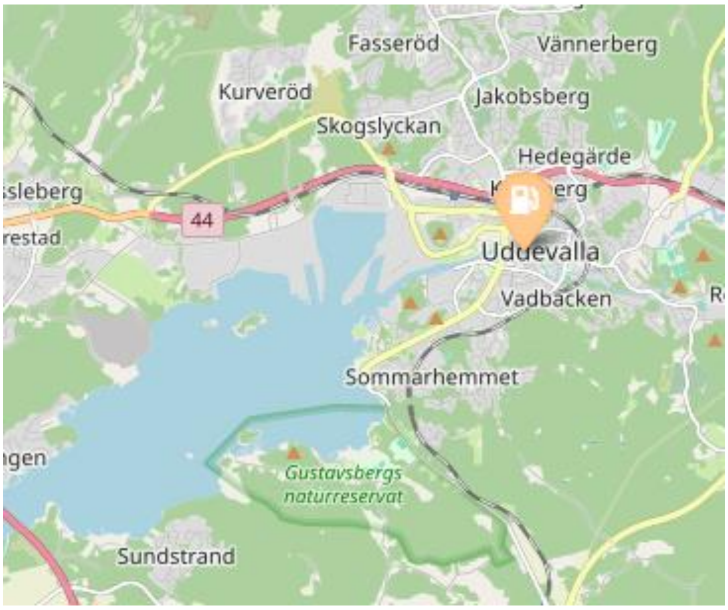

Figure 12. Hydrogen refuelling station near Byfjorden (Luleå University of Technology, 2023).

4.5.3.2 Hydrogen supply to local ferries

Another off-take alternative for renewable hydrogen is hydrogen-powered ferries by Green City Ferries. They are a part of Boatplan Stockholm 2025, which is based on the Stockholm region´s plans to climate-neutralize the Stockholm archipelago traffic. If carbon-fibre air supported vessel (ASV) hulls are used together with either electric or hydrogen propulsion, an 80 % emission reduction can be achieved compared to diesel-fuelled catamarans (Boatplan Stockholm 2025, 2020). The plan is built on four key suggestions: to utilise new technology, achieve optimal operation through a mixture of vessels, combine new technology and a new fleet, and lastly, new and external long-term financing

(Boatplan Stockholm 2025, 2020). The transition to new technologies of course holds multiple challenges, one major one being the ship operation during winter.

The new technologies include both electric ferries for short routes and hydrogen powered fuel-cell vessels for routes longer than 30 km, as batteries would become too heavy. For the moment (10/2024) the amount of hydrogen needed and the bunkering on the ships it is not clear and subject to further developments.

4.5.4 Land area availability

At all three evaluated pilot sites potential land area is available for a demonstration-scale electrolysis plant. However, given the proximity of the land areas to public areas, such as in the marinas, installation of an on-site electrolyser would require detailed safety analyses and extensive safety measures. Furthermore, the permitting of an electrolyser project is more complex than permitting of an oxygen storage tank.

4.5.5 Conclusions

In terms of sourcing oxygen from existing electrolyser projects under development, a potential synergy was identified between the Byfjorden pilot site and Project Air's alkaline electrolyser. It is recommended to discuss further with Uniper and Perstorp Group, the project developers, on whether oxygen capture could be considered in their plant if the Byfjorden site proceeds with POI piloting.

For the new-build, dedicated electrolyser for the pilot case, it is concluded that coupling the pilot site's oxygen production with hydrogen production through electrolysis is not feasible due to the lack of critical data availability at the sites. To consider electrolyser construction on site, more data would be required in terms of grid availability and potential hydrogen off-takers. Since detailed grid maps are unavailable online, discussions with the local electricity operators are needed. Regarding hydrogen off-takers, the identified projects have not yet reached a high enough maturity level to rely on, meaning that in-depth discussions regarding timelines would need to be held. Considering also the added complexities of more extensive site preparation, permitting, and safety requirements associated with electrolyser installation, and the foreseen financial costs and resources required for a procuring and commissioning the electrolysis plant, the costs are determined to outweigh the benefits at this stage of piloting.

The focus for the first-phase pilot is therefore shifted to the thorough investigation of linear diffuser technology operation in a marine environment and evaluation of corresponding reoxygenation effects, which has never been done before. For this purpose, it is concluded that importing oxygen from a local supplier such as Linde is the most techno-economically feasible option for the pilot. However, on sub-basin and basin wide scales, the integration of electrolysis with POI is determined to be not only technically feasible but also non-negotiable considering the scales of oxygen demand in the Baltic Sea. These points are further validated in sections 5 and 6.

4.6 Next steps and screening of financing opportunities

The final decision on the pilot site or sites will be made based on the progression of stakeholder discussions, permitting applications and availability of project financing. These three aspects are being advanced in parallel and continue beyond the publication of this report. While it is noted that conducting the pilot at multiple sites simultaneously would yield additional benefits for analysing the results, this option is limited by the availability of resources and project funding. Nevertheless, currently, all three potential sites are still candidates for the pilot project. However, due to the constraints posed by the ongoing pilot in the Byfjord, the project plan is developed with a focus on the other two sites. The next steps are briefly described in this section. More specifically, the preliminary pilot project plan, permitting requirements and potential financing opportunities are detailed. The pilot project is named the “Baltic Sea Pilot for Pure Oxygen Injection” or “BOxIn” in short.

4.6.1 BOxIn Preliminary Project Plan

The BOxIn pilot will be attached to shore, with an oxygen tank supplying the oxygenation to a linear diffuser as described in (Vahanen; Jacobs, 2022). Below is a simplified schematic.

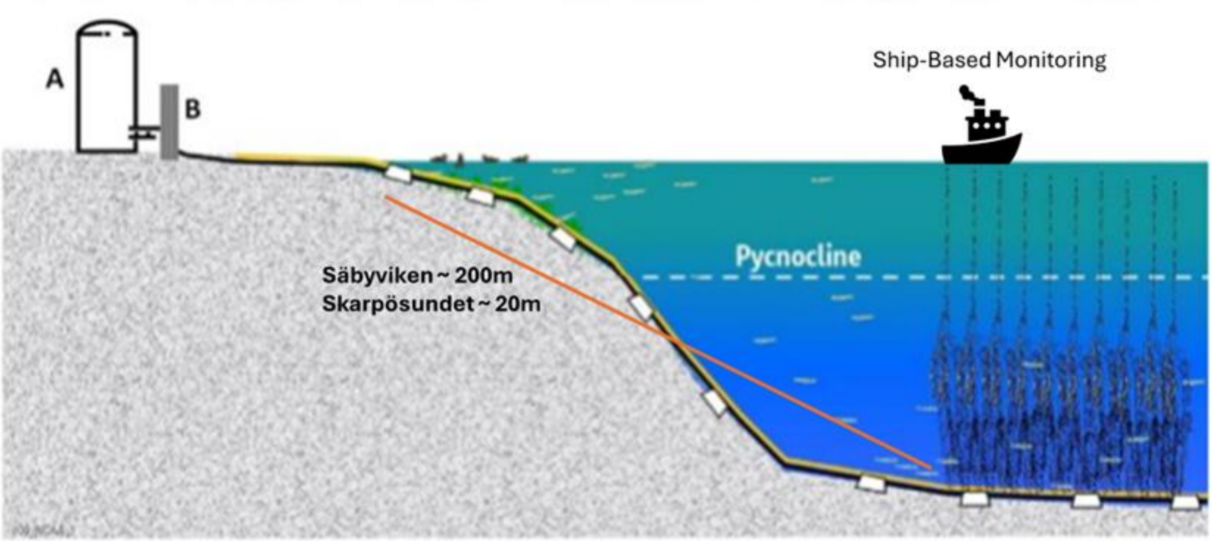

Figure 13. Conceptual schematic of a pure oxygen linear diffusion supply by a liquid oxygen tank (A) and vaporiser (B). The distance from shore to the imitation of the oxygenation is show (orange line) for each site in meters. Schematic: Modified from Jacobs Engineering.

A conservative preliminary implementation timeline for the project was elaborated (Figure 14). To fully evaluate all effects on the local environment, the project needs to be run over at least a five-year time period with one extra year allocated for obtaining the necessary permits, meaning six years in total. The oxygenation will be run over a course of three years, during which consistent monitoring will be conducted. Furthermore, additional monitoring will be conducted one year prior to the start of oxygenation and one year after the termination of oxygenation to determine the baseline conditions and after-effects, respectively.

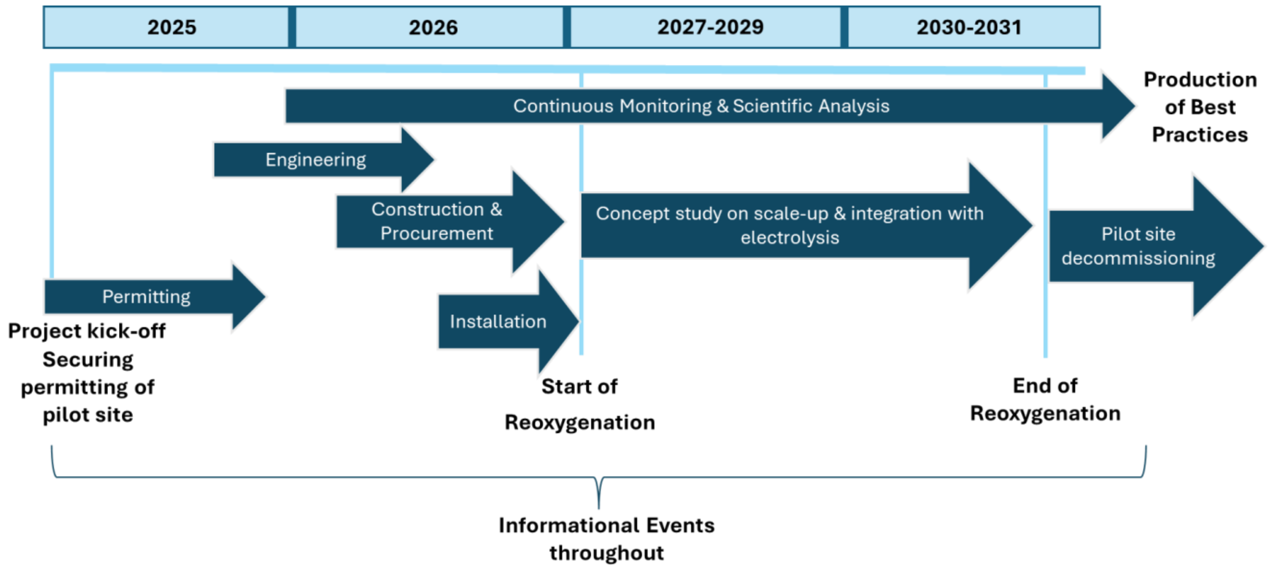

Figure 14. Preliminary six-year timeline for BOxIn development, denoting also key project tasks.

In addition to the development steps of the pilot (engineering, procurement, construction, installation, monitoring and decommissioning), the concept study on pilot scale-up and integration of reoxygenation with electrolysis will be further developed as well. The findings from the BOxHy project will be used as the starting point for this study.

4.6.1.1 Pilot objectives and main tasks

The breakdown of the project task outline is shown below. This comes from the breakdown of the needs for this project to answer the questions of our pilot, 'What are the impacts, changes, and best practices for oxygenation of anoxic regions in the Baltic Sea' with the goals, 1) understanding the biogeochemical and ecosystem changes during oxygenation, 2) understanding the changes in the ecosystem, 3) assessing and understanding the longer term effects and recovery time of anoxic regions, all with the practical outcomes of shutting down the internal phosphorus loading and restoring the habitat to 20th century levels:

- Ensuring baseline values to be able to track any changes
- Focus on research:
    - Data use for model calibration to track biogeochemical and ecosystem changes in Baltic Marine Models
    - The biogeochemical changes in the sediments and water column at varying times during and after oxygenation
    - Recovery of the system – both chemically and ecologically to ensure long-term sustainability, including what O_2 level is needed for this?
- Creation of Best Practices for re-oxygenation through POI.

As stated before, we will also continue investigating the implications for electrolyser incorporation, with the aim to have a follow up project after BOxIn to demonstrate offshore hydrogen production integrated with reoxygenation. Depending on funding, the project will be split into different work packages. Currently is it split into:

- Project Management
- Permitting
- Procurement and Commissioning

- Technical Studies (to ensure marine application)
- Stakeholder Engagement (to ensure open communication)
- Environmental Monitoring
- Scientific Exploration (following up the topics above)
- Follow Up Case Study (for electrolyser integration for the follow up project)
- Report Writing and Funding (for the follow up project of BOxIn)

4.6.1.2 Monitoring and sampling plans

Monitoring of parameters at the site will require an in-depth set-up due to the production of Best Practices and the trial transfer of the technique to a marine system. The sampling parameters that will be monitored are listed below:

Table 5. Sampling variables and quantities per year from the sampling stations. This includes both water and sediment samples, specified under Analyses.

Analyses	Samples per year	Variable
water	862	Total-Nitrogen and Total-Phosphorus
water	862	PO_4: Phosphate, NO_3: Nitrate, NH_4: Ammonium, SiO_4: Silicate
water	158	CTD (conductivity, temperature, depth):salinity/temperature/O_2
water	370	Hydrogen sulphide
water	224	chlorophyll
water	22	Particulate Organic Carbon / Nitrogen / Phosphorus 0-5/10m
water	254	Dissolved metals
water	22	phytoplankton
water	22	zooplankton
sediment	18	CNP (Carbon:Nitrogen:Phosphate stoichiometry)
sediment	18	metals
sediment	18	other pollutants

The proposed sampling schedule for Säbyviken and Skarpösundet includes 22 sampling excursions per year, varying between 1 to 3 times a month depending on seasonal variation. This sampling rate was considered when estimating the project budget, see section 4.6.1.3.

As an example, Figure 15 depicts a potential sampling location scheme for Säbyviken, depending on funding acquired. The sample sites will allow for dispersion rates to be analysed to understand the impacts of oxygenation.

Figure 15. Potential sampling spots for Säbyviken. Blue points as additional water sampling spots, orange points are current sampling spots, which will be continued throughout the monitoring program.

Throughout the project, monitoring of the oxygenation equipment will also be conducted to ensure proper equipment function while in anoxic conditions. This testing will be initiated during the monitoring stage, firstly in a lab and then in the field. This is due to the application design being based upon freshwater conditions; thus, with marine conditions, monitoring is advised.

4.6.1.3 Preliminary budget breakdown

Including the sampling and analysis costs, the estimated budget breakdown for piloting at the Säbyviken and Skarpösundet sites is shown in Table 6. This breakdown considers only the costs associated with the pilot development (from permitting to decommissioning) and does not include the costs associated with the scale-up and integration with electrolysis outside of the explorative case studies. As mentioned before, Byfjorden is still considered as a potential site, but has not been included in the project plan due to uncertainties with the timeline and constraints posed by the ongoing downflow experiment at the site.

Table 6. Preliminary budget breakdown for the BOxIn pilot.

Task	**Cost (€)**
O_2 Tank, Transport and O_2 Required (2022 quote)	644 891,00
Säbyviken	
Sampling Cost Water	
Analysis Costs Water	
Sampling Cost Sediment	
Analysis Cost Sediment	
Sum	**836 549,09**
Skarpösundet	
Sampling Cost Water	
Analysis Costs Water	
Sampling Cost Sediment	
Analysis Cost Sediment	
Sum	**847 768,18**

Permits and EIA Estimates	40 000,00
Total Personnel Hours	1 010 000,00
Säbyviken	**2 531 440,09**
Skarpösundet	**2 542 659,18**
Overhead (15%) Säbyviken	379 716,01
Overhead (15%) Skarpösundet	381 398,88
Quote 1T /Day = €1M Est. Installation	1 000 000,00
Total Säbyviken	**3 911 156,10**
Total Skarpösundet	**3 924 058,06**

The potential inclusion of modular sensor platforms has also been considered for fully establishing the oxygen dispersion rate and lateral distribution. These would consist of 3-5 small modular landers monitoring oxygen, temperature, salinity, and having a hydrophone to monitor dispersion of the bubbles. Placing the three sensor platforms around the injection area also allows for better modelling of the impacts around the immediate oxygenation zone. To include 3-5 sensor platforms, this will increase the price for each location by €600,000 – 1,000,000.

Altogether, for each pilot site, the project total cost over six years, including also the scale-up development and including 3-5 sensor platforms is estimated to be in the range of 5-6 million Euros.

4.6.2 Permitting of pilot site

The permitting of BOxIn is currently estimated to take one year based on the ongoing project in Byfjorden. The permitting has not yet been initiated due to uncertainties with project funding. However, the permits required for implementing the pilot project in each of the three potential pilot sites have been investigated and are elaborated below.

4.6.2.1 Byfjorden

A submission of notification of water activities must go through Länsstyrelsen Västra Götaland. This will be sent to the Swedish Agency for Marine and Water Management, the Swedish Maritime Administration, the Swedish Transport Agency, Port operating company “Uddevalla hamnterminal AB”, the Geological Survey of Sweden (SGU), the Coast Guard and the property owner of Gustavsberg 1:25, Gustafsbergsstiftelsen.

Preliminary documents on the project description, including schematics and risk assessments, are to be submitted to the County Administrative Board. Following the submission with the County Administrative Board on the property of Gustavsberg 1:25 in Uddevalla municipality, a decision will be made under certain circumstances to proceed. This may take over a year. Any issues or changes must be provided within five years. Otherwise, a new board will have to make the decision and the process will restart.

Prior to submission, you must have an agreement with the land or property owner. Throughout the project, self-monitoring of the planned activities must be conducted. Depending on building requirements on land, further permits must be established.

4.6.2.2 Säbyviken

A notification of water activities can be sent to the Österåker municipality, but it is recommended that preliminary notification documents are discussed with Länsstyrelsen Stockholm (county board) that can judge if a notification is sufficient or if a full permission is needed. A notification is handled by the municipal Environmental and Health protection board (Miljö- och Hälsoskyddsnämnd) which takes two months. The handling includes so called "strandskyddsdispens" (permit for constructions close to water areas). The county board and the Swedish Maritime Administration will review the notification. Prior to submission, there must be an agreement with the land- or property owner. A permit for handling of dangerous goods may also be needed. If a notification is not sufficient, a permission of water activities is needed which is handled by the Land and Environmental Court (Mark- och miljödomstolen), and the process may take a year.

4.6.2.3 Skarpösundet

A notification of water activities can be sent to the Värmdö municipality, but it is recommended that preliminary notification documents are discussed with Länsstyrelsen Stockholm (county board) that can judge if a notification is sufficient or if a full permission is needed. The remaining permitting process is the same as in Säbyviken.

4.6.3 Financing opportunities for BOxIn

To support covering the estimated budget of the project, various funding calls that were open during the timeframe of the BOxHy project implementation were evaluated. The evaluated funding calls are summarised in Table 7 below.

Table 7. Summary of funding calls that were evaluated for assisting in the implementation of the BOxIn project.

Programme, call and objective	Pre-DL	Final DL	Project duration	Est. max available funding per project	Notable requirements
SBEP / Second joint transnational call / Blue Economy Sectors	10.4.2024	6.11.2024	Max 3 yrs	300 k€ per partner (if different nationalities)	▪ At least two European sea basins ▪ National eligibility requirements NB! Finland is not part of this objective.
Interreg Baltic Sea Region / Special call / Priority 3	17.4.2024	21.6.2024	Max 3 - 3.5 yrs	80 % co-financing, no set limit, earlier projects have been about 4 M€	▪ Only "core projects" (practical, durable) ▪ At least 3 partners from 3 BSR countries ▪ Strict timeline and work packages
Interreg Central Baltic / Regular project call / Objective 4	30.4.2024	31.10.2024	No limit, "typically 2 – 3 yrs"	80 % co-financing, the limit for regular projects is 4 M€	▪ Must be in the Central Baltic area ▪ Partners from min. 2 relevant countries
LIFE Nature and biodiversity		Fall	Usually < 5 years	No limit, usually < 5 M€	▪ Species and/or habitats with unfavourable and declining status need to be the aim and Natura 2000 is prioritized
LIFE Circular Economy and Quality		Fall	Usually < 5 years	No limit, usually < 5 M€	▪ More of "clean-up" than prevention, but if the "clean-up" is necessary for the long term effect, that would be a bonus for us.

The Pre-Application for the Interreg Baltic Sea Region call was started with the Byfjorden pilot site in mind. However, the application was not submitted since the hourly rate limits were not acceptable for all potential partners. The Interreg Central Baltic call was not applied for due to the same reason.

Further implementations into the project have been considered and are being monitored for possibilities. This includes the potential application of munition monitoring in a region of anoxia being reoxygenated. This will potentially open BOxIn to other aspects of funding. The screening of potential funding opportunities continues beyond the completion of the BOxHy project. The screenings are being coordinated by Lhyfe.

5 Investigation of Baltic Sea-wide reoxygenation and the renewable hydrogen economy

While the first step in realising Baltic Sea-wide reoxygenation is to conduct the BOxIn pilot, it is equally important to investigate the future scale-up opportunities from the onshore pilot-scale to offshore pilot-scale to basin-wide scales. To achieve basin-wide scale reoxygenation, multiple offshore platforms will be required with several gigawatts of installed electrolyser capacity. Therefore, a high-level desktop study was conducted to identify potential regions in the Baltic Sea where large-scale POI coupled with the emerging renewable hydrogen economy could be feasible in the future. More specifically, the aim of WP2 was to find a regional overlap between the following three elements:

(1) Anoxic regions in the Baltic Sea with quantified oxygen demands.
(2) Electrolysers (under development or conceptual, onshore or offshore) with capacities to generate sufficient oxygen for meeting the corresponding demands and simultaneously having a viable route to market for hydrogen off-take.
(3) Offshore wind farms under development with sufficient capacities to (in theory) supply electricity to future large-scale electrolysis.

This is visualised below in Figure 16.

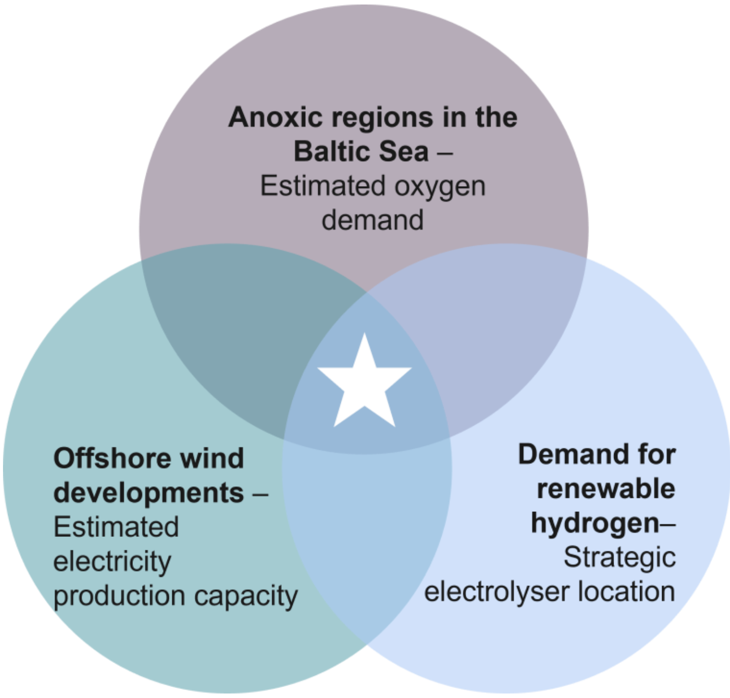

Figure 16. Visualisation of the minimum elements requiring a geographical overlap for an ideal offshore POI/H_2 production site.

The WP was carried out in the following manner: first the anoxic/hypoxic regions in the Baltic Sea were identified and the corresponding oxygen demands were quantified. Next, the hydrogen demands in the Baltic Sea region were quantified to determine potential offtake segments for large-scale renewable hydrogen production. The electrolyser capacities required to meet the estimated oxygen demands were calculated and the potential for sourcing oxygen from existing/developing electrolyser projects in the region was explored. After evaluating land-based electrolysers, the potential for offshore hydrogen production in the Baltic Sea region was evaluated. The pathways for connecting offshore hydrogen production with demand, e.g., via hydrogen pipelines were also evaluated. In parallel, offshore wind farm developments in the Baltic Sea were investigated. Finally, the best opportunity regions considering all three elements are identified and elaborated upon.

5.1 Anoxic regions in the Baltic Sea

Anoxia in the Baltic Sea was mapped and investigated according to the sub-basin definitions depicted in Figure 17. In

Table 8, the oxygen volumes that need to be injected to increase oxygen concentrations to 10 mg/l on the sub-basin and basin scales are presented. The total volumes of anoxic and hypoxic waters change over time and per sub-basin; hence the table also shows the standard deviations for the mean annual data for the years 1960-2022. The oxygen demands are also visualised graphically and pictorially in Figure 18 and Figure 19, respectively.

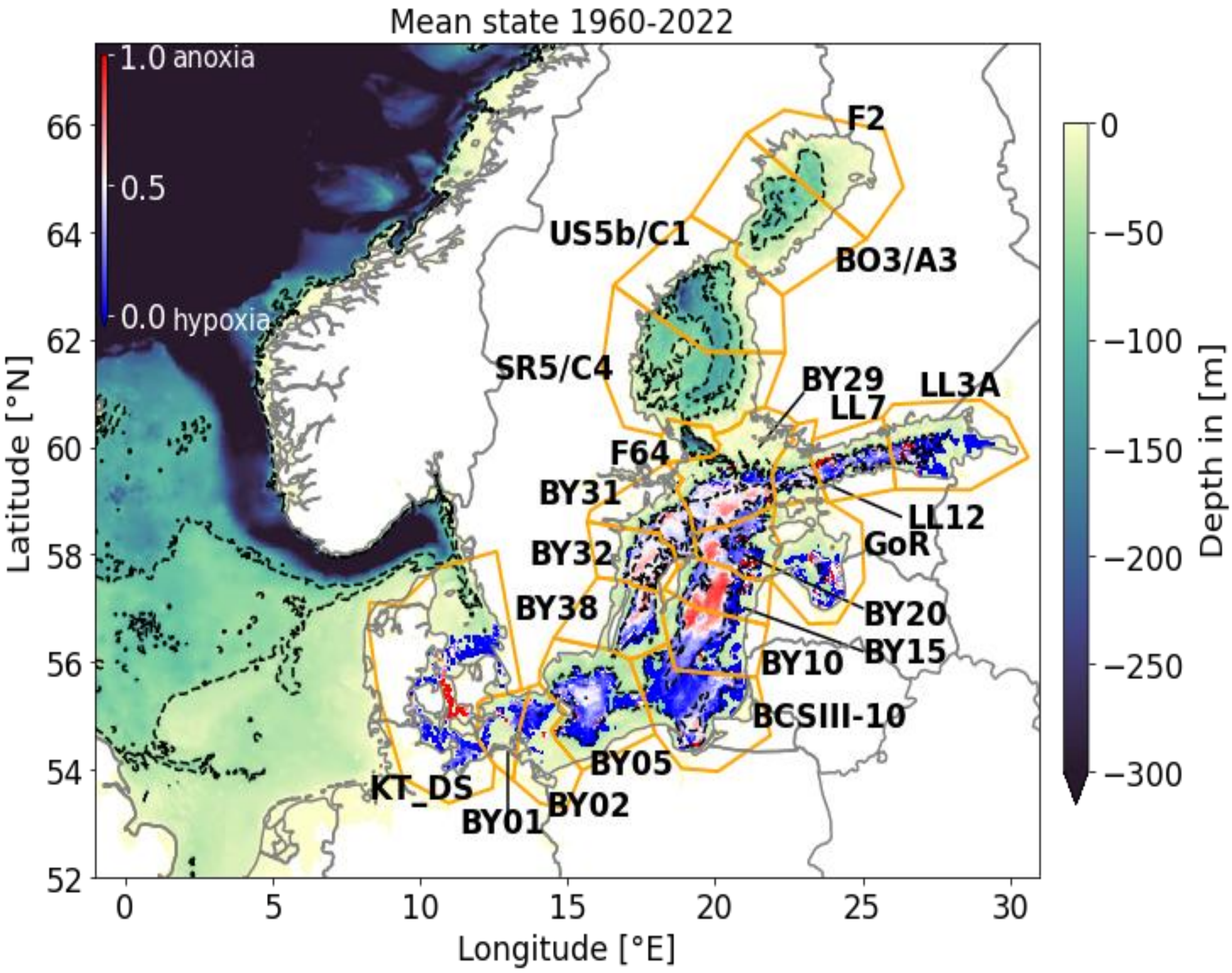

Figure 17. Map of the Baltic Sea region showing bathymetric depth in light green-black colours (see scale on the right), the mean oxygen state between 1960-2022 in blue to red colours (see scale on the left) and the names of the sub-basins based on the work of Rolff et al. 2022. (Rolff, Walve, Larsson, & Elmgren, 2022). Oxygen data is from Hansson and Viktorsson 2023 (Hansson & Viktorsson, Oxygen Survey in the Baltic Sea 2022 - Extent of Anoxia and Hypoxia 1960-2022, 2023).

Table 8. Oxygen demand estimates per sub-basin. This table gives the mean and corresponding standard deviation for the period between 1960 -2022 of the oxygen demand for each of the sub-basins defined in Rolff et al. 2022 (Rolff, Walve, Larsson, & Elmgren, 2022). The sub-basins are listed in order of decreasing oxygen demand. The corresponding area of anoxia/hypoxia per sub-basin and the mean oxygen demand per area are also provided.

Sub-basin	Mean oxygen demand [kilotonnes/day] over the years 1960-2022, and standard deviations	Area [km^2]	Mean oxygen demand per area (tonnes/km^2)
BY05	12.54 +/- 5.449	36 439	0.34
BY15	6.198 +/- 1.95	14 562	0.43
BY31	5.199 +/- 1.857	10 759	0.48
BY10	5.041 +/- 1.827	21 277	0.24
BY32	4.98 +/- 2.194	11 083	0.45
BY38	4.686 +/- 1.574	14 492	0.32
BY29	3.902 +/- 1.919	30 155	0.13
BY20	3.674 +/- 1.36	15 934	0.23
LL12	3.381 +/- 2.155	8 063	0.42
LL7	2.916 +/- 1.56	10 223	0.29
BCSIII-10	2.872 +/- 1.654	30 351	0.09
BO3/A3	1.033 +/- 0.522	20 217	0.05
GoR	0.38 +/- 0.693	18 383	0.02
F2	0.347 +/- 0.516	14 208	0.02
BY02	0.007 +/- 0.021	12 797	0.00
SR5/C4	0.004 +/- 0.008	37 602	0.00
BY01	0.0 +/- 0.0	8 932	0.00
KT_DS	0.0 +/- 0.0	41 992	0.00
F64	0.0 +/- 0.0	4 246	0.00
LL3A	0.0 +/- 0.0	17 305	0.00
US5b/C1	0.0 +/- 0.002	26 460	0.00

Using these values, we calculate that the entire Baltic Sea, including the northern territories would require 57.16 +- 25.261 kilotonnes of oxygen demand/day. For the key areas, which we are focusing on, where potential oxygenation is possible i.e., the Baltic Proper (BY01, BY02, BY05, BCSIII-10, BY10, BY38, BY15, BY32, BY20, and BY31), the Gulf of Riga (GoR) and the Gulf of Finland (LL12, LL7, LL3A), the oxygen demand is estimated as 51.875 +/- 16.536. When including BY29, the estimate increases to 55.776 +- 24.21 kilotonnes of oxygen demand/day.

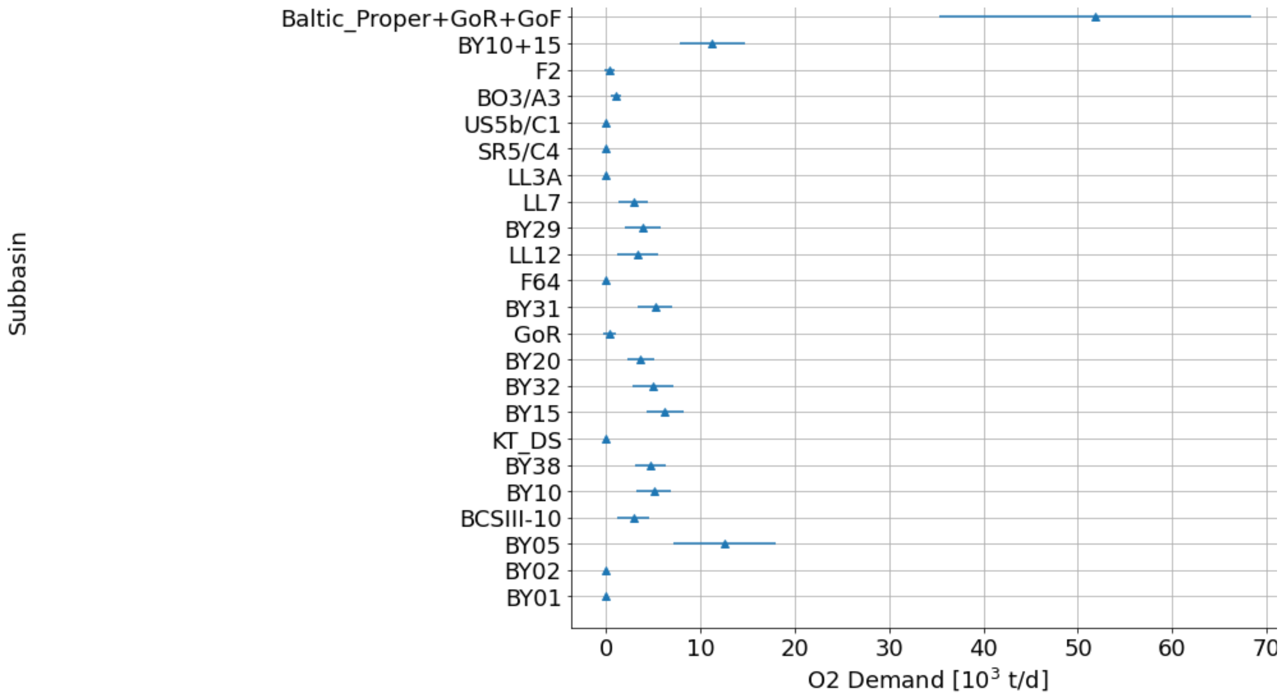

Figure 18. Mean oxygen demand required to raise oxygen concentrations to 10 mg/l in each of the sub-basins and basins from levels of hypoxia (2 ml/l – 2.86 mg/l) and anoxia (0 mg/l).

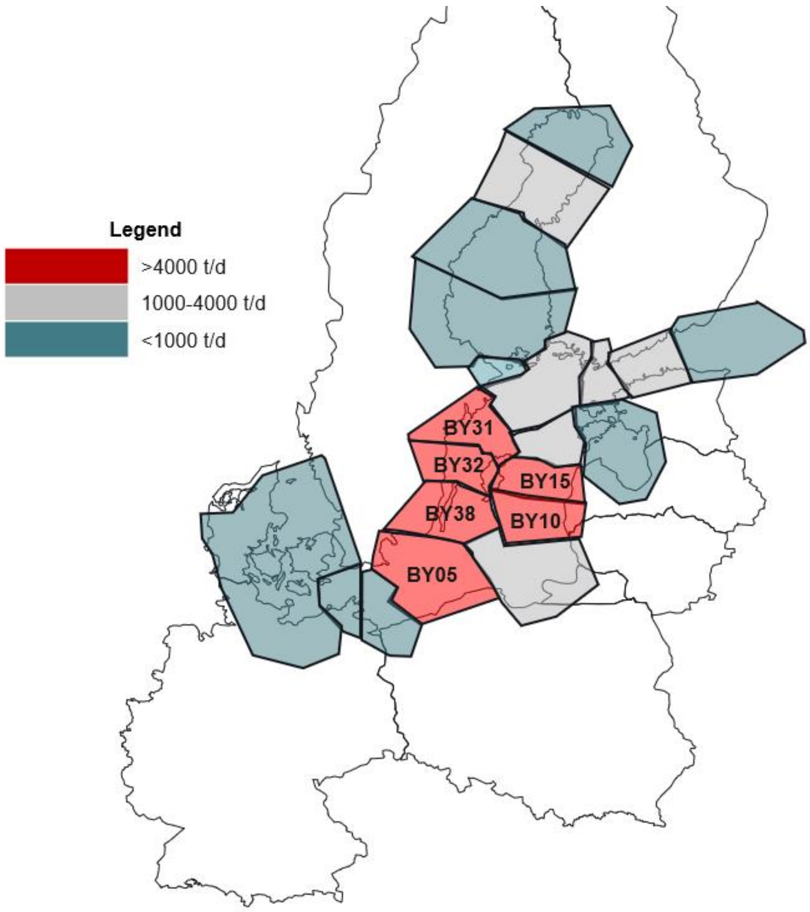

Figure 19. Visualisation of the mean oxygen demands (tonnes per day) per sub-basin. See all sub-basin names and geo-localisations in Figure 17.

It is evident that the individual red coloured sub-basins (Figure 19) with the highest estimated oxygen demands (Figure 17 and Table 8) are those within the Baltic Proper. This is attributed to the internal physical dynamics of the Baltic Sea and hence the counterclockwise spreading of fresh inflow water from the North Sea through the Baltic Sea basins. Sub-basins which are closer to the North Sea influx such as KT_DS, BY01 and BY02 show lower oxygen needs, with some approaching zero, due to higher water exchange rates and influx of oxygen-rich waters from the North Sea. Therefore, the sub-basins within the Baltic Proper are of primary interest when evaluating synergies with hydrogen production and offshore wind project capacities.

5.1.1 Methods for quantifying anoxia

Ventilation estimates by Stigebrandt and Gustafsson (2007) are 9000 tons per day (Stigebrandt & Gustafsson, 2007). Conley et al. (2009) estimate a range of 6 000 – 16 000 tons per day (Conley, et al., 2009). Using empirical oxygen consumption rates in stagnant deep water following oxygenation, Rolff et al. (2022) report a range 4 000 – 14 000 tons per day. To oxygenate the Baltic Sea there is a need to add oxygen corresponding to the existing oxygen deficit but also counteract the continuously occurring oxygen consumption. The literature values here are minimum long-term additions needed to counteract oxygen consumption.

To compute the oxygen demands/oxygen deficit we adapted the methodology from Hansson et al. 2011 where the volume computations are described to be performed on a high-resolution grid (Hansson, Andersson, & Axe, 2011) (Seifert, Tauber, & Kayser, 2001). We used the oxygen data set from 1960-2022 from Hansson and Viktorsson (2023) and interpolated it linearly to the high-resolution bathymetry ETOPO2 (two-minute resolution) (Hansson & Viktorsson, Oxygen Survey in the Baltic Sea 2022 - Extent of Anoxia and Hypoxia 1960-2022, 2023) (National Geophysical Data Center/NESDIS/NOAA/U.S. Department of Commerce, 2024). The oxygen demand to counteract and/or prevent anoxia and to raise oxygen concentrations to 10 ml/l in each of the respective sub-basins of the Baltic Sea are calculated taking a concentration of 2 ml/l ~ 2.86 mg/l for the purely hypoxic volume and 0 mg/l for the purely anoxic volume.

The sub-basins of the Baltic Sea were defined as in Rolff et al. 2022 (Figure 17). The total Baltic Proper includes sub basins BY01, BY02, BY05, BCSIII-10, BY10, BY38, BY15, BY32, BY20, and BY31, the Gulf of Riga is represented by GoR and the Gulf of Finland by LL12, LL7, LL3A.

Since the area of each grid box is known, the grid boxes with anoxic/hypoxic markings are summed up for the Baltic Proper, the Gulf of Finland and the Gulf of Riga and the results then give the total hypoxic and anoxic area. A grid box represents a grid cell of the bathymetry data (ETOPO2), it has a defined area and side lengths dependent on the resolution of the product (numerical model/ bathymetry resolution). The resulting sub-basin areas were compared to the published data from Rolff et al. 2022 (see Table 9). All information on the data sets used to compute the oxygen deficit can be found in the section “Public Data sets used” below.

To assure the correctness of the computation, first the total hypoxic and anoxic area were computed and compared to the published data from Hansson and Viktorsson 2023 (Figure 20 and Figure 21). Comparing these figures, we find a deviation between our data and the area data published in Hansson and Viktorsson 2023. We were not able to exactly reproduce their calculations.

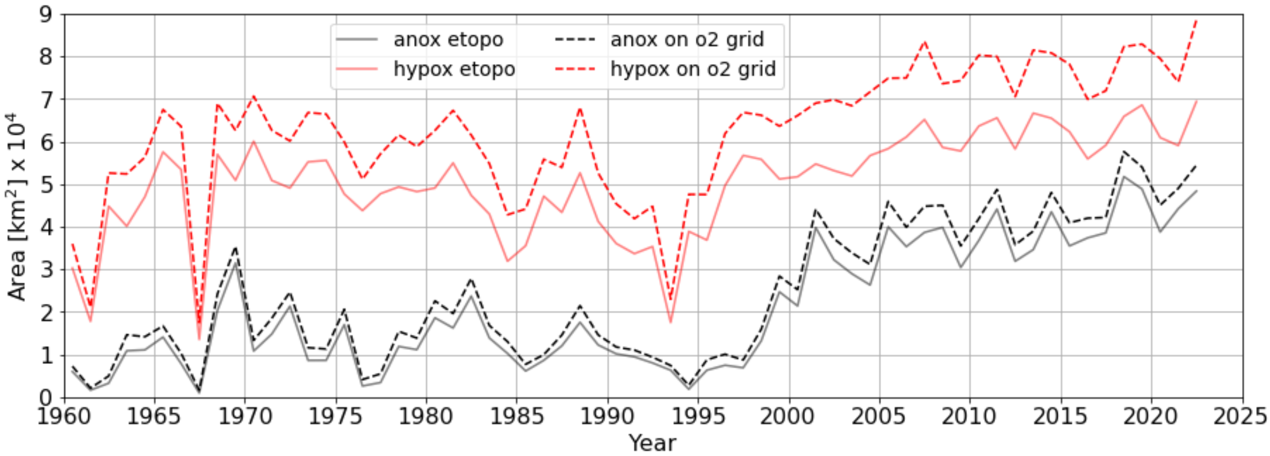

Figure 20. The area extent of hypoxia (red) and anoxia (black) in the Baltic Sea based on data from Hansson and Viktorsson 2023 computed with the original resolution of the oxygen data (--) and computed with the interpolated high resolution data (-).

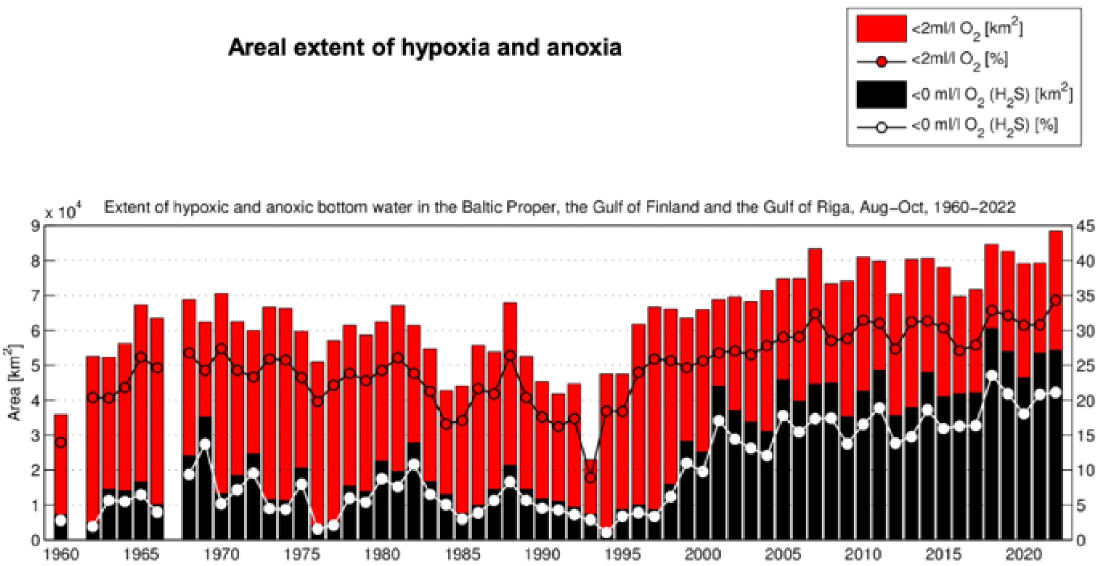

Figure 21. Area extent of hypoxia and anoxia in the Baltic Sea from Hansson and Viktorsson 2023.

Table 9. Subbasin areas based on ETOPO2 and published in Rolff et al. 2022

Sub-basin	Basin Volume ETOPO2 ($km3$)	Basin Volume Rolff et al. 2022 ($km3$)
BY01	0.0	-
BY02	0.0	-
BY05	142.97	147.0
BCSIII-10	361.49	351.0
BY10	600.7	-
BY10+BY15	1192.14	
BY38	72.62	-
KT_DS	4.74	-
BY15	591.44	-
BY32	303.24	299.0
BY20	359.23	351.0
GoR	0.0	-
BY31	386.47	389.0
F64	143.75	-
LL12	53.23	52.0
BY29	605.39	607.0
LL7	38.67	37.0
LL3A	7.28	6.0
SR5/C4	360.67	-
US5b/C1	688.37	-
BO3/A3	132.62	-
F2	28.52	-

For each sub-basin, a concave polygon is fitted to the outer edges of the hypoxic and anoxic area. The polygon outline represents a variety of upper limiting depths that encircle the hypoxic/anoxic area. The depth difference is then computed between the bathymetric depth of each grid box within the polygon and the mean/median/minimum and maximum depth found in the polygon outline for the anoxic area and between the mean/median/minimum and maximum hypoxia depth. This depth difference is then multiplied with the grid box area and then summed up for all grid boxes within the polygon. This results in the respective volume below 2 ml/l and below 0 ml/l O_2 concentration. To compute the pure hypoxic volume, the anoxic volume is subtracted from the total hypoxic volume. The values falling closest (Figure 22) to the published data in Hansson and Viktorsson 2023 (Figure 23) are the mean values resulting from the averaged mean depth and max depth computation (Hansson & Viktorsson, Oxygen Survey in the Baltic Sea 2022 - Extent of Anoxia and Hypoxia 1960-2022, 2023). These mean values were then used for all further computations.

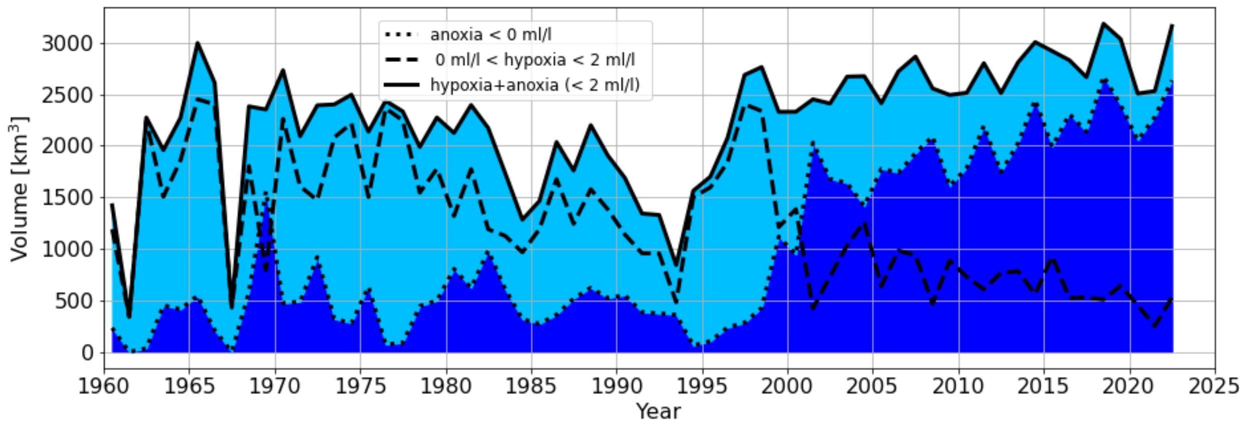

Figure 22. Volume of hypoxia and anoxia in the Baltic Sea based on data from Hansson and Viktorsson 2023 as described in section 5.1.

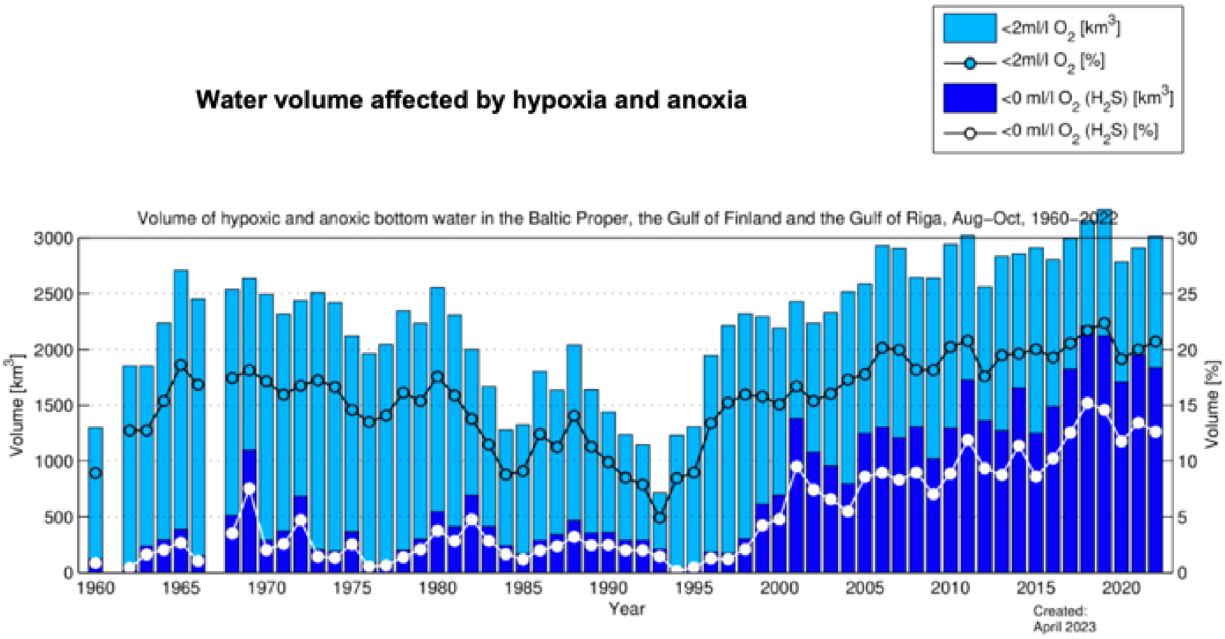

Figure 23. Volume of hypoxia and anoxia in the Baltic Sea from Hansson and Viktorsson 2023.

The oxygen demand values calculated here are reflecting the oxygen deficit. Overall, the demand in our calculations is the oxygen needed to restore the Baltic Sea oxygen deficit per year, ignoring ongoing oxygen consumption in the sediment or water column. It is hence not equivalent to the long-term yearly oxygen consumption. Using various methods, previous studies report a range of 4 000 – 16 000 tons O_2 of oxygen consumption per day for the Baltic Proper (Conley, et al., 2009) (Rolff, Walve, Larsson, & Elmgren, 2022) (Stigebrandt & Gustafsson, 2007).

A spreading analysis of the inserted oxygen should be a matter of future research. Since oxygen consumption and the spreading of the minuscule oxygen bubbles along and cross density layers are not known in the moment (10/2024) and should be estimated in an adequate numerical ocean model setup. However, due to slow current velocities at depths over 120m, we estimate a faster O_2 consumption than the present physical transport ignoring the situation during a major inflow event.

5.1.2 Limitations of the results

When calculating the data for oxygen demand and anoxic and hypoxic conditions in the Baltic Sea, several limitations must be acknowledged:

- **Large standard deviations in oxygen demand**: The given standard deviations represent the O_2 demand variation per sub-basin as a result of the temporal variation of the volume to be reoxygenated. Additionally, it is not clear how exactly the upper depth of the hypoxic and anoxic regions should be treated according to the current HELCOM publications by Hansson and Viktorsson 2023 (Hansson & Viktorsson, Oxygen Survey in the Baltic Sea 2022 - Extent of Anoxia and Hypoxia 1960-2022, 2023).
- **Choice of interpolation scheme and target grid:** The interpolation scheme used here is linear interpolation. It can introduce errors, due to the assumption of a constant rate of change between points, which may not accurately reflect the true variations of in the environment. Interpolation in general can potentially lead to loss of important information.
- **Quality Control**: The original data used from Hansson and Viktorsson 2023, is subject to all measurement errors occurring during seagoing data acquisition. Brought to a regular grid the dataset is as well subject to interpolation errors. Hence all oxygen demand is rather to be seen as an estimate under certain assumptions.
- **Seasonal Bias in data collection**: The dataset from Hansson and Viktorsson was collected during late summer or autumn ship-based data acquisitions. During these seasons oxygen levels are usually at their lowest within shallow coastal water bodies, though at levels below the pycnocline, in the deeper parts of the Baltic Sea, the values should not be subject to strong seasonal bias. This bias can lead to an overestimation of the extent and severity of hypoxic and anoxic conditions.
- **Use of the ETOPO2 bathymetry model**: Although this model provides a resolution of approximately two minutes of latitude and longitude, it may not capture fine/scale variations in topography, potentially leading to inaccuracies in the depth related volume analyses.

5.2 Hydrogen production for meeting renewable H_2 demands coupled with POI

In this section, the emerging renewable hydrogen (H_2) economy is introduced, with a specific focus on the outlook for hydrogen demands in the Baltic Sea region and current pipeline of hydrogen projects in the region. Infrastructure solutions for transporting hydrogen in both gaseous and liquid forms are also briefly introduced. The focus remains high-level, with techno-economic analyses regarding large-scale electrolysis left to section 6. The electrolyser capacities required to meet the theoretical oxygen demands for each sub-basin are calculated. Finally, the synergies between the emerging renewable hydrogen economy and reoxygenation using electrolytic oxygen are explored in two phases: first based on the current onshore electrolyser projects under development and second based on theoretical offshore electrolysers that could be developed in the future.

5.2.1 Background on the emerging renewable hydrogen economy

The European Union under the REPowerEU plan aims at producing 10 million tonnes of renewable hydrogen by 2030 and importing another 10 million tonnes (European Commission, 2022).

Renewable hydrogen is hydrogen produced via electrolysis using renewable electricity input for splitting water into hydrogen and oxygen. According to the EU, renewable hydrogen will play an important role in decarbonising existing transport and industries in which fossil-based non-renewable hydrogen is currently used. (European Commission , 2024). The outlook on hydrogen demands of selected Baltic Sea countries are summarised below.

5.2.1.1 Finland

Finland currently produces and consumes between 140 000 and 150 000 tonnes of hydrogen per year, of which only 1 % can be considered renewable (Ministry of Economic Affairs and Employment of Finland, 2023). The ambition is, however, to produce 10 % (i.e. 1 million tonnes) of the EU's hydrogen production target by 2030 (Business Finland, 2023). Finland has a goal of becoming climate neutral in 2035.

5.2.1.2 Sweden

Sweden produces and consumes about 180 000 tonnes of hydrogen annually, of which around 1 % can be considered renewable (Fossilfritt Sverige, 2021). Sweden aims at producing 0.7 to 1.3 million tonnes of hydrogen in 2030 (Swedish Energy Agency, 2021), and thereafter become climate neutral in 2045.

5.2.1.3 Germany

Germany currently consumes around 1.6 million tonnes per year (DW, 2021), but estimates that the demand will rise to 3.9 million tonnes in 2030 and up to 13.2 million tonnes by 2050. However, the Government plans to import about 70 % of the demand in 2030 (Hydrogen Central, 2023). This makes Germany the Baltic Sea country with the highest future demand. The country aims at becoming climate neutral in 2045.

5.2.1.4 Conclusions

The remaining Baltic Sea countries have published limited information regarding their hydrogen outlook, and hence, only the most relevant countries have been reviewed in this report. A comparison can be seen in Table 10. Note that the estimated consumption volume does not necessarily equal the production volume. When summing the demands of these three countries, by 2030, the total hydrogen demand will be between 4.4 to 6.2 million tonnes per year. Of these three countries, Germany is expected to have the greatest hydrogen demand, with around 10 GW of additional electrolyser capacity required to meet the country's forecasted 2030 demands. The hydrogen production planned in each Baltic Sea country is detailed in the following sub-section.

Table 10. The national hydrogen outlook compared between Finland, Sweden, and Germany.

	Finland	Sweden	Germany
Today [million tonnes]	0.1–0.2	0.8	1.6
2030 [million tonnes]	1	0.7–1.3	2.7–3.9
Climate neutral	2035	2045	2045

5.2.2 Renewable hydrogen projects in the Baltic Sea region

There are numerous electrolyser projects that are already in operation or under development within the Baltic Sea region. A high-level mapping was conducted to identify these projects. Within the scope of this mapping exercise, a minimum electrolyser capacity requirement of 1 MW has been used.

The focus was on commercial-scale projects rather than demonstration sites. All data was gathered from public sources such as the Hydrogen Cluster Finland and project websites. The resulting project locations are shown in Figure 24 below.

To facilitate the addition of more projects as they become publicly available, all projects within a country are numbered from 1 forward (in no particular order of interest). However, when describing a project, they can be referred to as F1 (for number 1 in Finland) or S1 (for number one in Sweden). In Figure 24, the electrolyser projects located at the coastline are marked green, those that are not coastal but have less than 100 km from the coast are marked blue, and the inland projects are marked orange.

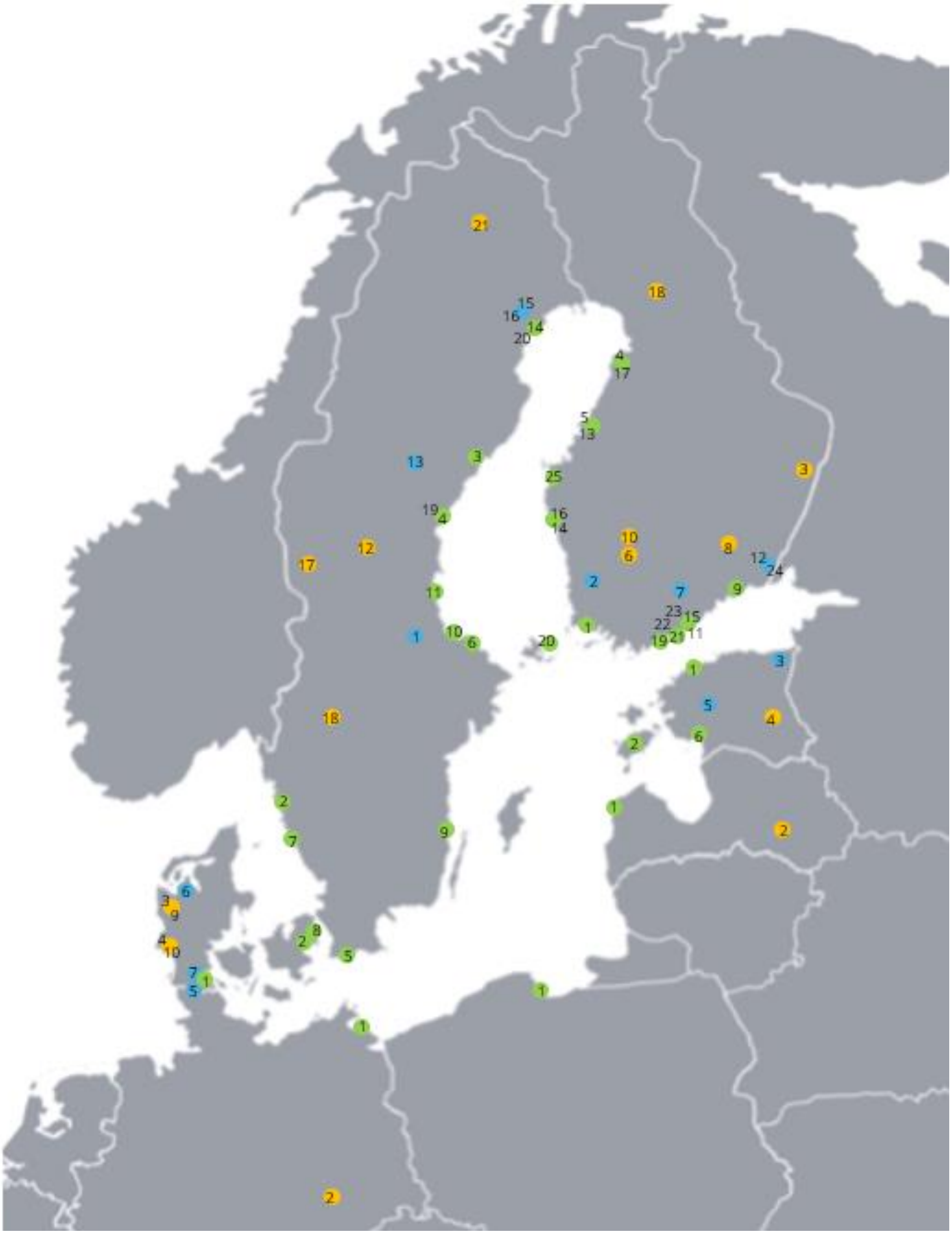

Figure 24. Existing and planned electrolyser projects in the Baltic Sea Area. The coastal projects are marked green, projects with less than 100 km to the coast are marked blue and inland projects are marked orange.

The project capacities range from a few megawatts to a few gigawatts. The largest project, which is being developed by OX2 in the Åland Islands, has a planned capacity of 3 GW. The average electrolyser capacity is around 300 MW. There are a few projects already in operation, with one in Sweden that has been operating since 1990. However, most of the projects have Commercial Operations Dates set for 2025 onwards. In terms of end-products, while many projects plan to produce renewable hydrogen as their primary product, there are also several projects that will produce hydrogen derivatives such as ammonia, methanol and sustainable aviation fuel (SAF). The full list of projects evaluated and a description of the most relevant projects per country in terms of proximity to the Baltic Sea can be found in Appendix 4. The projects are listed in no particular order of interest.

While all the evaluated projects are located on land, the interest in offshore electrolysis is growing, especially when interconnected with offshore wind farms. In 2023, the world´s first offshore hydrogen production pilot called SeaLhyfe, developed by Lhyfe, produced its first renewable hydrogen. The electrolyser demo site was in the Atlantic Ocean, off of the western coast of France, and was powered by a 1 MW floating wind turbine (Lhyfe, 2023). After a successful demonstration, which concluded in November 2023, Lhyfe continues the scale up of offshore electrolysis through the HOPE (Hydrogen Offshore Production for Europe) project. HOPE is a 10 MW electrolyser that is being implemented in the North Sea, 1 km off the coast of Belgium, by Lhyfe and eight other European Partners. The hydrogen product will be transported to shore via a pipeline. In 2023, the project received a EUR 20 million grant by the European Commission, as a part of the European Clean Hydrogen Partnership (Lhyfe, 2023). These projects provide important know-how to further develop and increase the offshore electrolyser capacity.

The challenges with offshore hydrogen production compared to onshore hydrogen production are that the infrastructure is less mature and currently more expensive, yielding higher investment costs. As a result, the hydrogen production costs are also more expensive, yielding uncompetitive prices compared to onshore renewable hydrogen production and especially compared to current non-renewable hydrogen production. However, offshore hydrogen production can also benefit from economies of scale, as there are fewer limitations, e.g., in terms of space, water and competing electricity connections compared to onshore developments. Therefore, as the maturity and scales of the offshore infrastructure increase, production costs are expected to decrease. The levelised cost of offshore wind-to-hydrogen is approximated to be around 5.35 €/t (Franco, Baptista, Neto, & Ganilha, 2021) – 6.5 €/t (BloombergNEF, 2021) with future cost projections being 2.17 €/t and 1 €/t by Franco et al. and BloombergNEF, respectively.

5.2.3 Hydrogen transport infrastructure

The locations with the highest demands for hydrogen do not always match the locations with the best conditions for producing renewable hydrogen, e.g., locations with high availability of low-cost renewable energy such as wind and solar. As a result, safe and efficient methods for transporting large volumes of hydrogen are crucial to building the renewable hydrogen economy. Hydrogen is a complicated molecule when it comes to transportation, as it must be either a gas under high pressure (around 200 bars) or cooled down to cryogenic temperatures below −253°C (−423°F) to be transported as a liquid. Both conversion processes are highly energy intensive and deprive the hydrogen of its original energy content.

Hydrogen can also be transported by hydrogen carriers, such as ammonia or methanol, which chemically bind hydrogen in the form of chemical compounds, which can later be broken to re-obtain the hydrogen. However, this requires multiple conversion steps and is an expensive solution (McCurdy & Podal, 2023). In Table 11, a comparison is made between different methods and modes of hydrogen transport and their parameters, compared with diesel, a commonly used transport fuel (McCurdy & Podal, 2023).

Table 11. Comparison of the transport properties of different fuels reproduced from McCurdy & Podal, 2023 (McCurdy & Podal, 2023).

	Compressed hydrogen	Liquid hydrogen	Methanol	Liquid ammonia	Diesel
Temperature (Celsius)	25	-252.9	25	25	25
Storage pressure (bar)	690	1	1	10	1
Density (kg/m3)	39	70.8	792	600	~833
Volumetric energy density (MJ/L)	4.5	8.49	15.8	12.7	38
Volumetric H2 content (kg H2/m3)	42.2	70.8	99	121	N/A

5.2.3.1 Baltic Sea Hydrogen Collector

The Baltic Sea Hydrogen Collector (BHC) is an offshore hydrogen pipeline infrastructure planned by the Finnish and Swedish transmission system operators (TSOs) Gasgrid Finland Oy and Nordion Energi AB, respectively, together with the companies OX2 and Copenhagen Infrastructure Partners. The BHC is planned to be 1250 km long and will connect Finland and Sweden to Germany. The preliminary route for the BHC is shown in Figure 25. Along the way it will also connect to the so-called “energy islands”, Åland, Gotland, and Bornholm. The BHC will function not only as a hydrogen transport solution, but also as a hydrogen storage. The project will complement other hydrogen infrastructure projects by the TSOs, such as the Nordic Hydrogen Route and the Nordic-Baltic Hydrogen Corridor, see all projects combined in Figure 26.

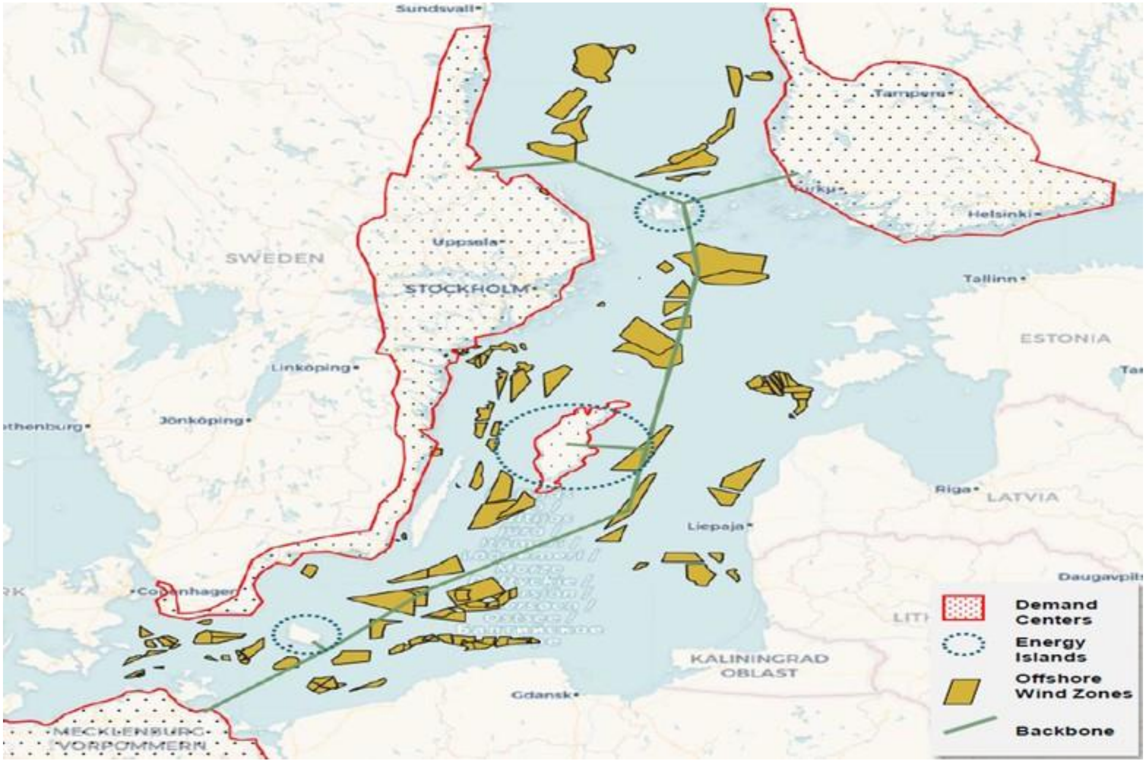

Figure 25. Baltic Sea Hydrogen Collector. Image taken from Renewables now, 2022 (Renewables now, 2022).

Figure 26. Compilation of the BHC, Nordic Hydrogen Route, and Nordic-Baltic Hydrogen Corridor. Image taken from GasGrid (GasGrid, 2024).

These three hydrogen infrastructure projects were included in the Project of Common Interest (PCI) list published by the European Commission in November 2023 and were accepted by the European Parliament and the Council in April 2024. The PCI status is given to projects that are important to developing the internal energy market in Europe, by for example helping the EU reach its climate targets. Receiving this status will facilitate a smoother funding application through the EU as well as receive an accelerated permitting process for the projects (GasGrid, 2024).

5.2.3.2 Ports as hydrogen hubs

A large portion of the future European hydrogen demand (about 50%) is expected to be concentrated near port areas due to ports' proximities to industries. Hydrogen demand from the shipping sector is also expected to grow. As a result, ports are foreseen to become hydrogen hubs in which hydrogen can be produced, consumed and transported, for example via shipping. For more information about the potential of ports as hydrogen hubs, please refer to the "Study on hydrogen in ports and industrial coastal areas" that has been published by the Clean Hydrogen Partnership in March 2023 (Clean Hydrogen Partnership, 2023)

5.2.4 Estimated electrolyser capacities required to meet the calculated oxygen demands

After gaining a background understanding of the emerging renewable hydrogen economy in the Baltic Sea region, the opportunities for integrating this hydrogen economy with combatting anoxia and hypoxia in the Baltic Sea were investigated. Based on the oxygen demands calculated per sub-basin in section 5.1, the corresponding electrolyser capacities required to supply sufficient electrolytic oxygen to meet these demands were calculated. The electrolyser capacities and corresponding hydrogen production volumes were computed using the production capacities of 0.42 tonnes H_2 per day and 3.36 tonnes O_2 per day per 1 MW installed electrolyser capacity corresponding to roughly 150 tonnes per year of hydrogen production per MW capacity, assuming nearly continuous operations. The needed electrolyser capacity is then computed by using the respective oxygen deficit per sub-basin computed in section 5.1. The computed results are shown in Table 12 and Figure 27 below. The sub-basins with the highest oxygen demands require installed electrolyser capacities of over 1.5 GWs, with the largest net capacity of 3.7 GW required to meet the demands in sub-basin BY05. The electrolyser capacity demands per sub-basin are visualised in Figure 28 below.

Table 12. Means and corresponding standard deviations for the period between 1960 -2022 of the electrolyser capacity (GW) and H_2 produced (tonnes per day) for each of the subbasins based on the corresponding calculated oxygen demands.

Sub-basin	O_2 demand [t/d]	Needed Electrolyser capacity [GW]	H_2 produced [t/d]
BY01	0.0 +/- 0.0	0.0 +/- 0.0	0.0 +/- 0.0
BY02	0.007 +/- 0.021	0.002 +/- 0.006	1.0 +/- 3.0
BY05	12.54 +/- 5.449	3.732 +/- 1.622	1568.0 +/- 681.0
BCSIII-10	2.872 +/- 1.654	0.855 +/- 0.492	359.0 +/- 207.0
BY10	5.041 +/- 1.827	1.5 +/- 0.544	630.0 +/- 228.0
BY38	4.686 +/- 1.574	1.395 +/- 0.468	586.0 +/- 197.0
KT_DS	0.0 +/- 0.0	0.0 +/- 0.0	0.0 +/- 0.0
BY15	6.198 +/- 1.95	1.845 +/- 0.58	775.0 +/- 244.0
BY32	4.98 +/- 2.194	1.482 +/- 0.653	623.0 +/- 274.0
BY20	3.674 +/- 1.36	1.093 +/- 0.405	459.0 +/- 170.0
GoR	0.38 +/- 0.693	0.113 +/- 0.206	48.0 +/- 87.0
BY31	5.199 +/- 1.857	1.547 +/- 0.553	650.0 +/- 232.0
F64	0.0 +/- 0.0	0.0 +/- 0.0	0.0 +/- 0.0
LL12	3.381 +/- 2.155	1.006 +/- 0.641	423.0 +/- 269.0
BY29	3.902 +/- 1.919	1.161 +/- 0.571	488.0 +/- 240.0
LL7	2.916 +/- 1.56	0.868 +/- 0.464	364.0 +/- 195.0
LL3A	0.0 +/- 0.0	0.0 +/- 0.0	0.0 +/- 0.0
SR5/C4	0.004 +/- 0.008	0.001 +/- 0.002	0.0 +/- 1.0
US5b/C1	0.0 +/- 0.002	0.0 +/- 0.001	0.0 +/- 0.0
BO3/A3	1.033 +/- 0.522	0.307 +/- 0.155	129.0 +/- 65.0
F2	0.347 +/- 0.516	0.103 +/- 0.153	43.0 +/- 64.0

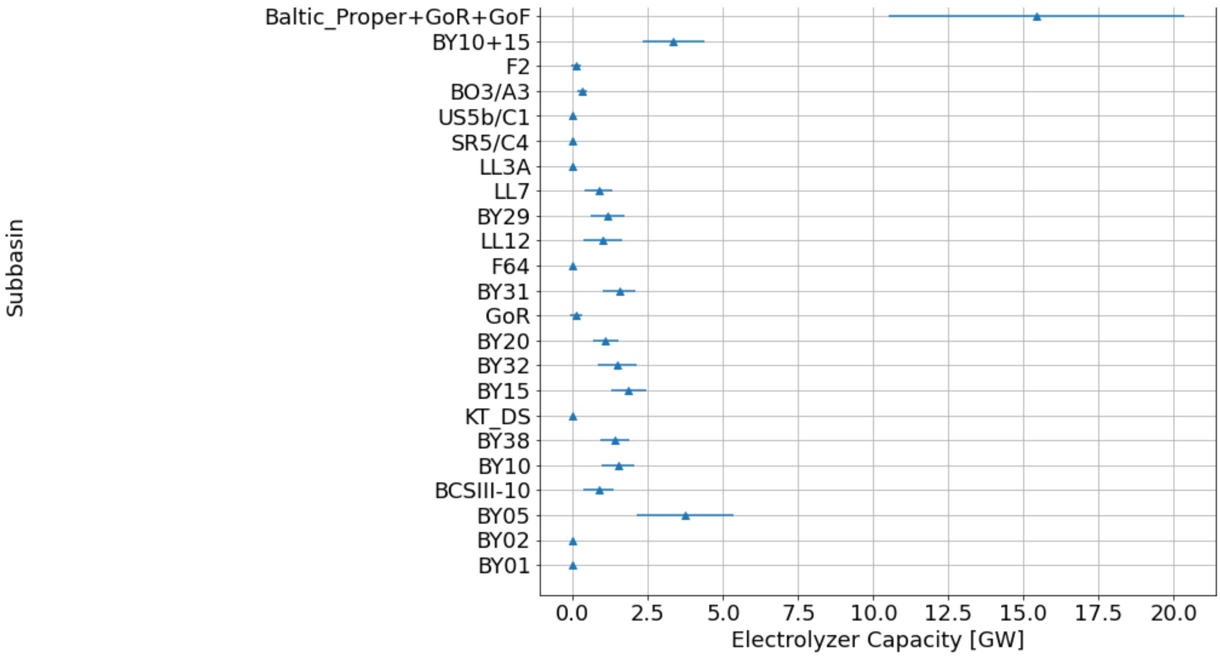

Figure 27. Electrolyser capacity needed to be installed to cover mean oxygen demand of sub-basins and combination of subbasins.

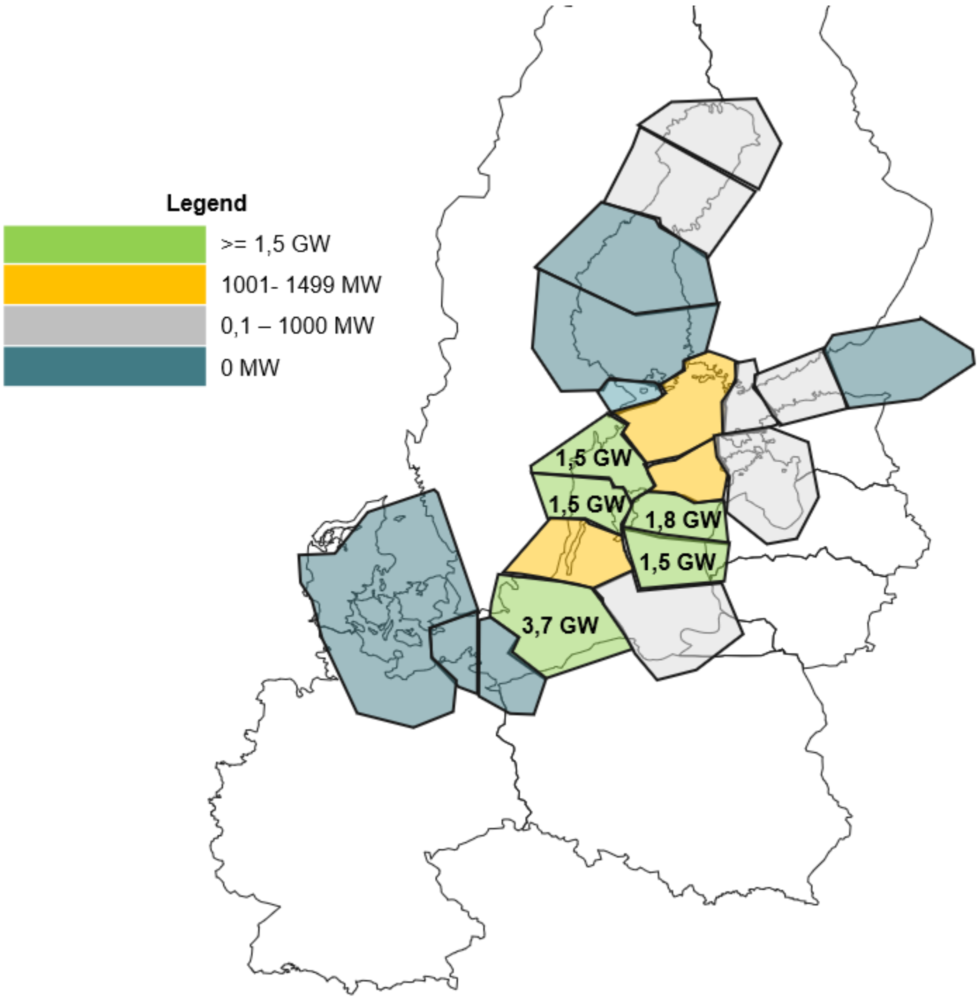

Figure 28. Sub-basins and corresponding electrolyser capacities required to meet oxygen demands.

The total hydrogen that could be produced is 7146 tonnes per day, or approximately 2.6 million tonnes per year. This production volume could be utilised to meet a significant portion of the combined 2030 estimated hydrogen demands of Finland, Sweden and Germany (see section 5.2.1.4).

5.2.5 Best opportunity regions based on synergies between renewable hydrogen demands and oxygen demands for combatting anoxia

When comparing the electrolyser capacities of existing/developing renewable hydrogen projects with the required capacities estimated for reoxygenation, it is concluded that there are only a few sub-basins in which there are/will be theoretically sufficient capacities for supplying the by-product oxygen to POI. The results are summarised in Table 13 and Figure 29 below.

Table 13. Summary of the planned electrolyser capacities adjacent to the respective sub-basin, compared to the electrolyser capacity needed to meet the oxygen demand in each sub-basin, based on Table 12 and Figure 24. Note that not all projects described in Figure 24 are included, only the ones covered by the relevant sub-basins. Hence, the total electrolyser capacity in this Table does not correlate with the total electrolyser capacity of the Baltic Sea region.

Sub-basin	Total planned electrolyser capacity (GW)	Mean Electrolyser capacity needed (GW)
BY05	0	3.7
BY01	0,005	0
KT_DS	2,8	0
BY29	3,28	1.2
SR5/C4	1,277	0.001
BY20	0	1.1
BY38	0,0007	1.4
BY10	0	1.5
BY32	0	1.5
BY02	0,5	0.002
GoR	n/a	0.1
BO3/A3	2,3	0.3
BY31	0	1.5
BY15	n/a	1.8
BCSIII-10	0,1	0.9
US5b/C1	1,28	0.0
F64	0	0
LL12	0	1
LL7	1.2	0.9
LL3A	0.1	0
US5b/C1	1.3	0
F2	1.6	0.1
Total	15.8	17 +/- X

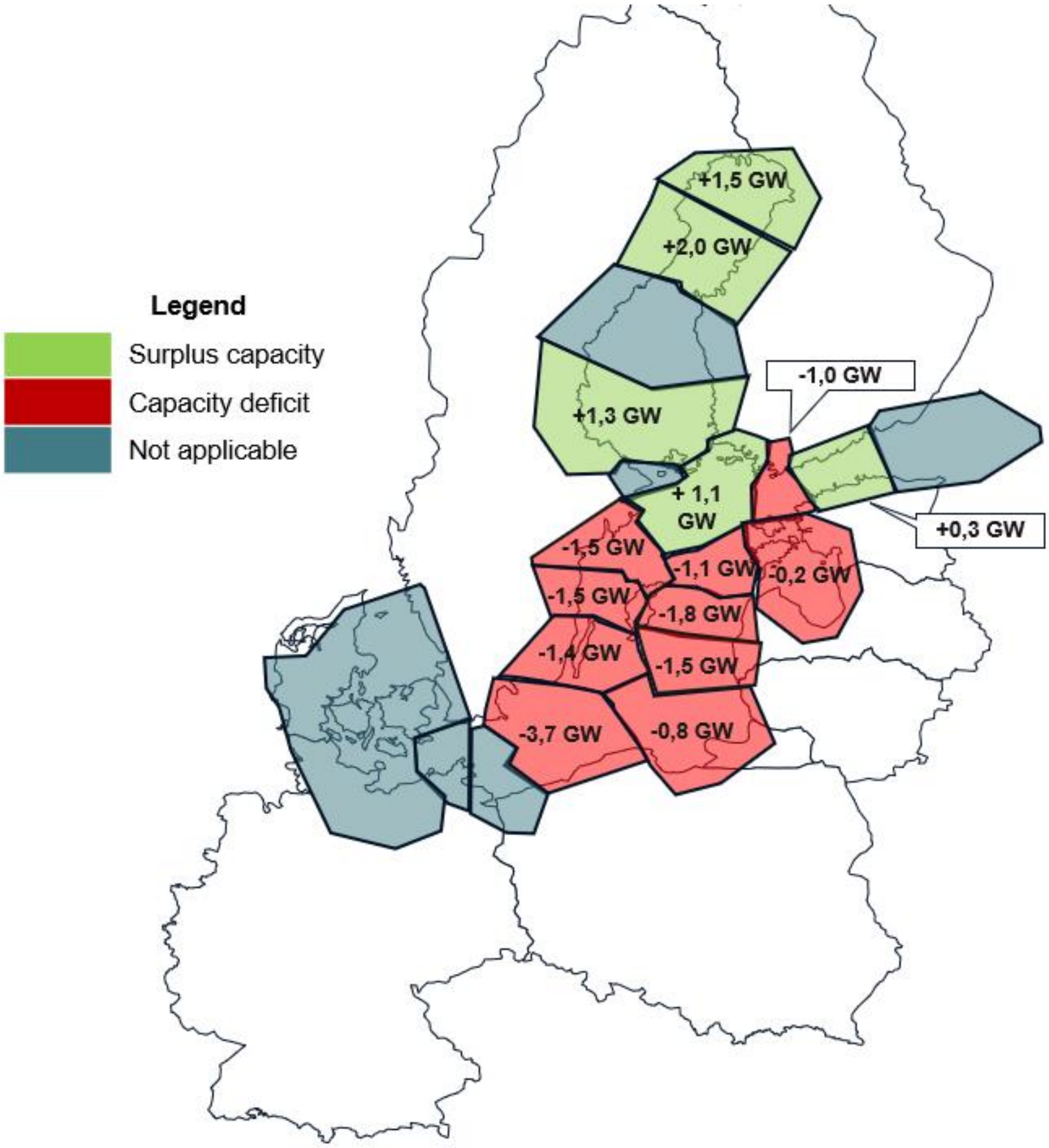

Figure 29. Differences in electrolyser capacity demands for reoxygenation and existing/planned electrolyser capacities.

From these results, it is concluded that over half of the sub-basins' oxygen demands could not be met with the existing and planned electrolysis capacities. In the sub-basins in the Baltic Proper with the highest levels of anoxia and hypoxia (requiring over 4000 tonnes/day oxygen), there is insufficient net capacity. In fact, **BY29, BO3/A3** and **LL7** are the only sub-basins with oxygen demands of at least 1000 tonnes/day that have sufficient electrolyser capacities already under development. Therefore, more electrolyser capacity would be needed to ensure sufficient oxygen supply for combatting anoxia and hypoxia.

However, this evaluation is only based on capacity considerations, not on any other parameters. To source oxygen from such projects, detailed techno-economic analyses and contractual negotiations with the project developers would need to take place. It is important to note that many of the here investigated projects are at an early stage (pre-FID or final investment decision), meaning that there is still a substantial risk that they will not be realised or will be delayed. Therefore, there is a potential need for even more electrolyser capacity to be built. Furthermore, the analysed projects are all located onshore, making the distances between the production site and anoxia far and hence expensive in terms of oxygen transport. We conclude that additional offshore electrolysis capacity will be needed to meet the estimated oxygen demands for mitigating anoxia and hypoxia on the Baltic Sea basin-wide scale. To determine the regions that have the most suitable locations for offshore co-production of hydrogen for meeting regional hydrogen demands and oxygen demands for remediating Baltic Sea anoxia and hypoxia, the following criteria were used:

- Sub-basin with oxygen demand of at least 1000 tonnes/day
- Sub-basin borders one of the Baltic Sea countries with the highest forecasted hydrogen demands (Finland, Sweden and Germany) and/or the sub-basin includes the planned BHC route

The results of the study are shown in Table 14 below.

Table 14. Sub-basins potentially suitable for offshore electrolysis based on oxygen demand and proximity to hydrogen demand and hydrogen transport via BHC.

Sub-basin	Mean oxygen demand 1960-2022 [10^3 t/d]	Borders Sweden, Germany or Finland?	Includes the planned BHC?
BY05	12.54 +/- 5.449	**Yes**	**Yes**
BY15	6.198 +/- 1.95	No	Yes
BY31	5.199 +/- 1.857	Yes	No
BY10	5.041 +/- 1.827	No	Yes
BY32	4.98 +/- 2.194	Yes	No
BY38	4.686 +/- 1.574	Yes	No
BY29	3.902 +/- 1.919	**Yes**	**Yes**
BY20	3.674 +/- 1.36	No	Yes
LL12	3.381 +/- 2.155	Yes	No
LL7	2.916 +/- 1.56	Yes	No
BCSIII-10	2.872 +/- 1.654	No	Yes
BO3/A3	1.033 +/- 0.522	Yes	No

Based solely on these criteria, the following sub-basins could be ideal locations for new offshore electrolysis plants: BY05 and BY29. However, to build new offshore electrolysers coupled with oxygen injection, sufficient renewable power is required to operate the production plants. As a result, the theoretical availability of power from offshore wind parks in operation or under development within the Baltic Sea is evaluated in section 5.3.

5.2.6 Limitations of the results

- The estimated electrolyser capacities required for meeting oxygen demands are based on the oxygen calculations and therefore subject to the same limitations as those calculations.
- The BHC route is still subject to change. It is uncertain at the time of writing (10/2024) whether hydrogen could be injected into the BHC at any point along the pipeline or just at certain designated connection points. This yields additional uncertainties in the optimal placement of offshore hydrogen production and piping and transportation costs.
- The timeline for the BHC is to be determined. There is uncertainty regarding the timeline due development milestones such as permitting and financing.

- When evaluating oxygen supply from existing/planned coastal electrolyser projects, only electrolyser capacities have been considered in the evaluation. Other aspects such as technical requirements for oxygen supply, cost of oxygen, availability of oxygen by-product, transportation costs and infrastructure, etc. have not been considered. Therefore, further techno-economic studies are required.

5.3 Offshore wind developments in the Baltic Sea region

Offshore wind developments in the Baltic Sea region were investigated from the perspective of sourcing electricity to conceptual offshore electrolysers coupled with POI. The data for offshore wind farms was collected from 4C Offshore (2024a) and the capacities and commissioning dates were cross-referenced with data from public sources, such as project-specific websites and news reports. Based on the collected data, as of spring 2024, there is a total of 155.2 GW of offshore capacity in either operational, construction or planning and permitting phases in the Baltic Sea region with a published commercial operations date (COD) year. The full list of evaluated wind parks can be found in Appendix 5. The capacity of projects in the operational phase is 2.8 GW, in the construction phase 3 GW and in the planning and permitting phase 149.4 GW. Thus, the vast majority of the projects have not yet been realised or their future is still partly unsure. The average size of the projects is roughly 1.1 GW.

When investigating the offshore projects and comparing data gathered in the latter half of 2023 and early 2024, a few projects and tenders were cancelled or postponed. For example, a tender with a minimum offshore wind capacity of 9 GW in Denmark had experienced some delays. The delay was due to a lack of consensus between the stakeholders and the government (4C Offshore, 2024b). Another tender that experienced a setback was Lithuania’s second tender for the 700 MW of offshore capacity. This tender was cancelled due to a lack of interest, as there were fewer than two applicants, which was the threshold needed for this tender to be lawful and get passed.

Overall, there have been dramatic changes in the global offshore wind market, such as increased interest rates, supply chain disruptions, rising equipment costs and a lack of willingness to invest in offshore wind by banks and foundations (4C Offshore, 2024c). These changes yield a certain level of uncertainty when investigating future available offshore wind capacities. Nevertheless, the net expected offshore wind capacity per sub-basin and the total capacity needed to meet the electricity demands from corresponding electrolyser capacities required for reoxygenation per sub-basin are shown in Table 15.

Table 15. Offshore wind power capacity by subbasin in the Baltic Sea, including all projects and plants which have released a COD. The capacity needed is derived from Table 13 and all > 0,5 GW capacity needs were considered. This is the total calculated capacity needed to meet the oxygen demands in each sub-basin.

Sub-basin	Total capacity available (GW)	Capacity needed (GW)
BY05	19.5	3.7
BY01	4.0	0
KT_DS	9.6	0
BY29	14.0	1.2
SR5/C4	35.4	0
BY20	1.4	1.1
BY38	9.2	1.4
BY10	4.2	1.5
BY32	2.5	1.5
BY02	6.0	0
GoR	3.3	0.1
BO3/A3	8.5	0.3
BY31	6.4	1.5
BY15	1.1	1.8
BCSIII-10	0.9	0.9
F2	9.1	0.1
US5b/C1	20.1	0
Total	**155.2**	

It is important to note that the data in Table 15 only includes the projects that have published their planned date of commercial commissioning. A wind farm capacity factor of 50% is assumed for all projects. The sub-basins, which have oxygen demands, but lack sufficient data for offshore wind developments include LL7, and LL12. There is a lack of data in these sub-basins regarding the estimated CODs and project developers, which leads to greater uncertainty in the project futures.

The surplus or deficit capacities of theoretical offshore wind required to meet the demands from electrolysis in each sub-basin are provided in Figure 30. The sub-basins in which there is surplus capacity are: BY05, BY10, BY20, BY29, BY38, BY31, BY32, BO3/A3, F2 and BSCIII-10. Only BY15 lacks sufficient capacity out of the applicable sub-basins. Therefore, it is concluded that while there is insufficient onshore electrolyser capacity available to meet the oxygen demands in the sub-basins with the highest levels of anoxia and hypoxia, there is potential to source electricity for new offshore electrolysers from planned offshore wind farms.

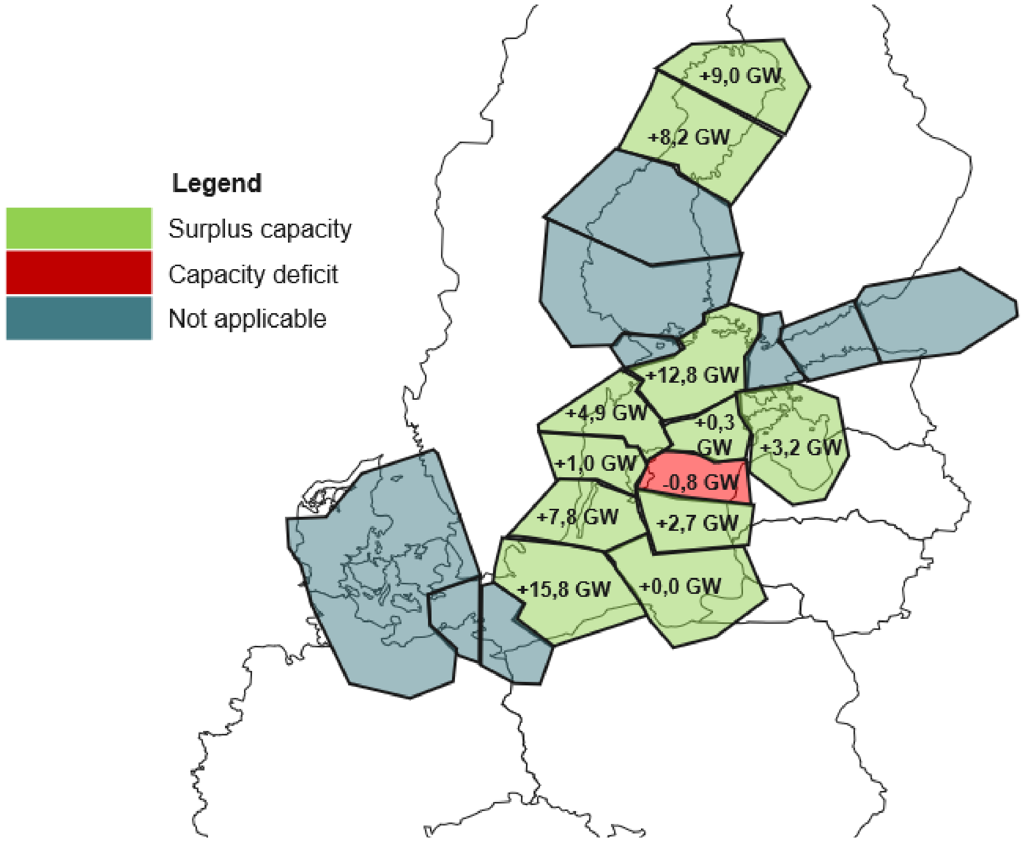

Figure 30. Differences in offshore wind capacity demand reoxygenation and existing/planned offshore wind capacities.

5.3.1 Best opportunity regions based on wind park proximity to anoxia

When analysing and ranking the best opportunity regions, the number of offshore wind projects in each sub-basin and their total capacities are considered. Furthermore, there is an extended history of low oxygen levels in deeper regions of the Baltic Sea (Hansson & Viktorsson, Oxygen Survey in the Baltic Sea 2022 - Extent of Anoxia and Hypoxia 1960-2022, 2023). Therefore, the proximity to of each wind project to deeper isobaths is also an examined feature. An isobath of 120 m was selected as this depth is beneath the rather stable pycnocline in the Baltic Sea. The distances to the nearest 120m isobath were evaluated at <40 km, < 80 km and < 100 km intervals. These intervals were chosen rather arbitrarily, but they give a good grasp of the projects near the 120m isobath. The results are shown for the sub-basins with highest oxygen demands in Table 16. Some sub-basins are excluded from the table as they are much shallower.

Table 16. The number of offshore wind farm projects and their corresponding capacities within the proximity (<40 km, < 80 km and <100 km) of a 120m isobath for sub-basins with the highest oxygen demands. Project capacity is given in GW.

		To 120m depth					
		within 40 km		Within 80 km		Within 100 km	
Sub-basins where the offshore capacity is met	**Total # of projects**	**# of projects**	**Project capacity**	**# of projects**	**Project capacity**	**# of projects**	**Project capacity**
BY05	41	0	0,0	0	0,0	0	0,0
BY29	12	**12**	**25,4**	12	25,4	12	25,4
BY20	19	0	0,0	15	11,0	17	12,8
BY38	7	1	0,8	4	3,0	4	3,0
BY10	10	**3**	**3,5**	8	5,8	8	5,8
BY32	4	**4**	**6,5**	4	6,5	4	6,5
BY31	6	**3**	**4,7**	5	7,0	6	7,6
BCSIII-10	6	0	0,0	1	0,8	3	1,6

As the pilot stage of the oxygenation via BOxIn is set to be completed in 2030 – 2031, any realistic timeline for large-scale Baltic Sea oxygenation is in the late 2030s or early 2040s. This is even later than the currently announced offshore wind projects within the same areas. If the offshore wind projects will not already have their production sold as Power Purchase Agreements to other customers, it means that there is a sufficient supply of offshore wind, at least in the sub-basins BY29 and BY32 within 40 km of 120 m isobath (Table 16). BY29 is the clear favourite here purely based on the number of projects and overall combined capacity of these projects. Other potentially interesting sub-basins are BY31 and BY10. It is possible that new offshore projects will be published within these sub-basins before the planning phase of large-scale offshore hydrogen production and oxygenation, giving more potential sites.

The locations of the wind farms within these four sub-basins (BY29, BY10, BY32 and BY31) are shown in Figure 31. The data for the wind parks included in each region can be found in Appendix 5.

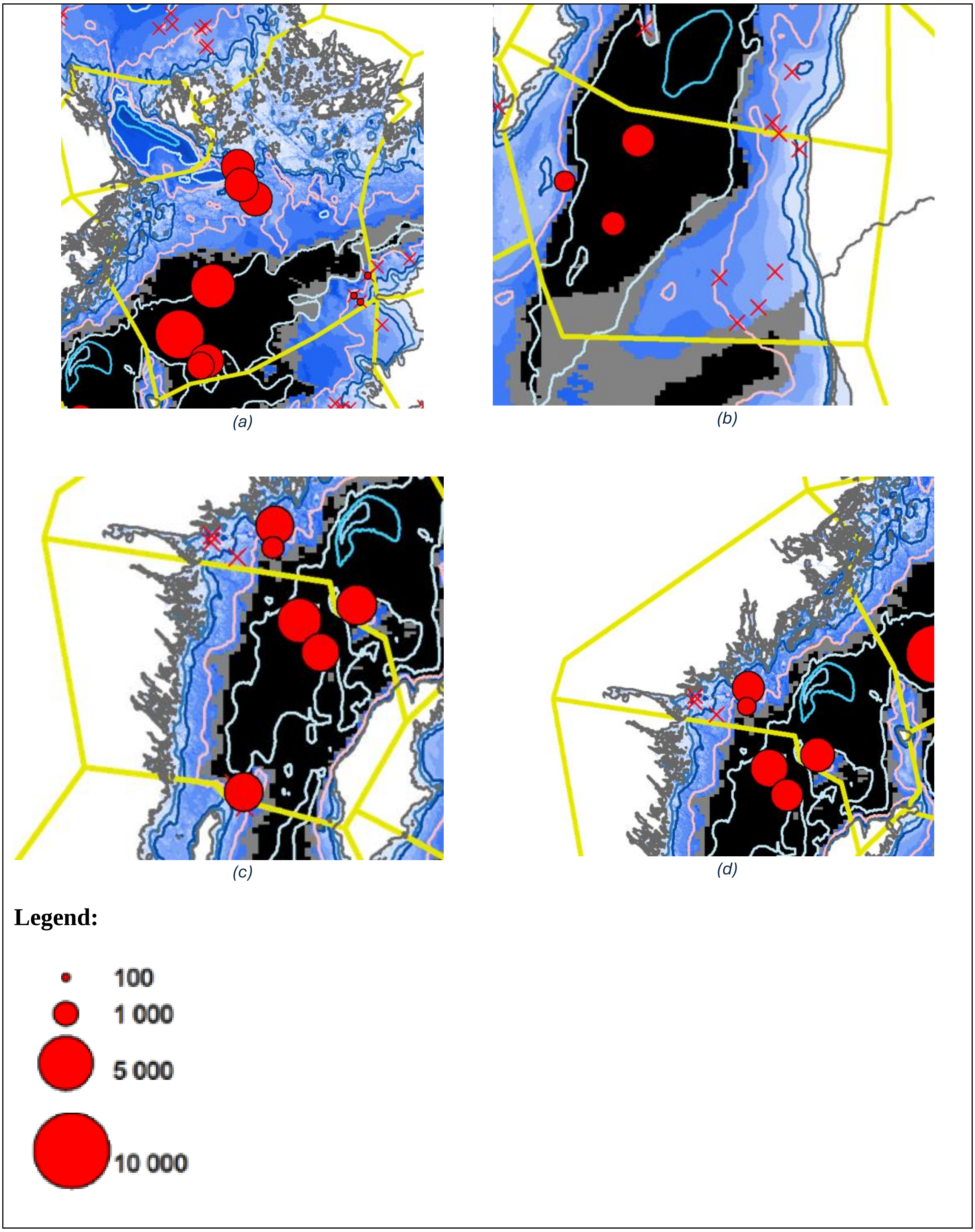

Figure 31. (a) BY29, (b) BY10, (c) BY32, (d) BY31. The red dots indicate the wind parks within 40 km of a 120 m isobath. The size of the dot indicates the capacity (MW) of the wind park. The red "X-s" indicated other wind parks in the sub-basin that are not within 40 km of a 120 m isobath. The black area indicates anoxia, and the grey area indicates hypoxia. The coloured lines indicate different sea depths (dark blue: 20m, pink: 50m, light blue: 100m).

5.3.2 Limitations of the results

However, the results of this study are limited by numerous uncertainties and constraints, such as the following:

- Data was gathered only from public sources. They can contain errors, and some sources even have different commissioning dates and capacities.
- Uncertainty in the developments of the wind farms, including exact locations, timelines, capacities, etc.
- Uncertainties in alignment with project timelines
- Uncertainty in willingness of offshore wind developers to sell electricity to offshore electrolyser projects
- Wind parks were mapped as points rather than areas, could lead to errors in distances to nearest 120 m isobath. The location of the point is the mass centre of the offshore wind farm area.

The uncertainties are decreased by the fact that the amount of surplus capacity available in most sub-basins is on the order of several GWs. Therefore, if some projects were to not be realised, there could still be sufficient capacity to meet electricity demands for oxygen production. Furthermore, insights were gathered from a board of offshore wind developers to better understand their perspectives on offshore electrolysis. The findings from the board meetings are detailed in section 7.2 of this report.

5.4 The best opportunity regions for offshore hydrogen production coupled with POI

In sections 5.1-5.3 the following elements were investigated:

(1) Anoxic regions in the Baltic Sea with quantified oxygen demands/deficits.
(2) Electrolysers (under development or conceptual, onshore or offshore) with capacities to generate sufficient oxygen for meeting the corresponding demands and simultaneously having a viable route to market for hydrogen off-take.
(3) Offshore wind farms under development with sufficient capacities to (in theory) supply electricity to future large-scale electrolysis.

An analysis of overlaps between (1) and (2) yielded the following conclusions:

- Based on the investigated publicly announced coastal electrolyser projects under development, it was determined that for most sub-basins, there is insufficient capacity to meet the calculated oxygen demands. **BY29, BO3/A3** and **LL7** were the sub-basins with oxygen demands of at least 1000 tonnes/day that had sufficient potential electrolyser capacities. However, there is uncertainty in the realisation of all planned electrolyser projects and the techno-economic feasibility of long-distance transport of oxygen from the shore to the injection points. Therefore, potential locations for offshore electrolysers were evaluated based on the forecasted hydrogen demands of Baltic Sea countries and proximities to hydrogen transport infrastructure.
- Based on forecasted hydrogen demands, sub-basins located nearby Finland, Sweden and Germany could be interesting for large-scale offshore hydrogen production. When also considered oxygen demands for reoxygenation, the following sub-basins have demands of at

least 1000 tonnes/day and are proximal to the shores of these three countries and the planned BHC route: **BY05** and **BY29.**

An analysis of overlaps between (1) and (3) yielded the following conclusions:

- The most potential sub-basins based on prevalence of anoxia and offshore wind capacity developments are: **BY05, BY38, BY32, BY31** and **BY10**. In addition, **BY29, BY20** and **BSCIII-10** could also be interesting, although they have lower oxygen demands.
- **BY29** has the highest number of wind projects (12 projects) and resulting highest combined capacity (25,4 GW) within 40 km of a 120 m isobath. **BY10, BY32, BY31** are also potential in this regard, although with fewer projects and lower net capacities within 40 km of a 120 m isobath.

The map in Figure 32 shows an overlay of all the investigated elements. The best opportunity regions are described in more detail below.

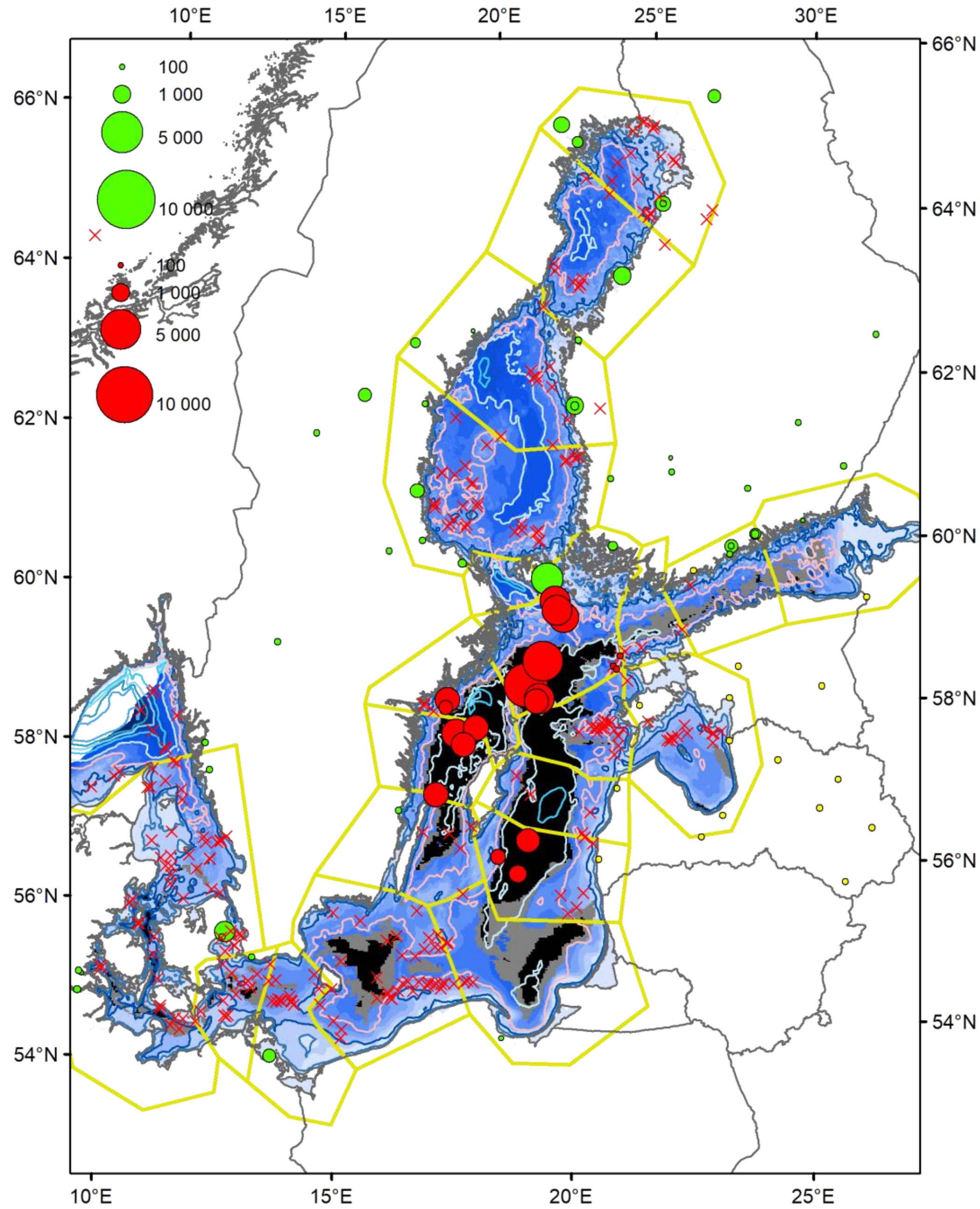

Figure 32. An overlaying map consisting of both the existing and planned coastal electrolysers (green) and major offshore wind farms (red) in and around the Baltic Sea, together with the levels of anoxia (black)/hypoxia (grey). The sizes of the circles correlate to the magnitude (MW) of the electrolyzers (green) and wind parks (red) in the best opportunity regions (see legend in the upper left-hand corner of the figure). The sub-basins are denoted by the yellow outline.

5.4.1 BY29

BY29 is the best opportunity region considering all the evaluated criteria. BY29 already has sufficient coastal electrolyser capacity under development to theoretically meet the 3902 +/- 1919 tonnes per day oxygen demand of the sub-basin. The planned coastal electrolyser projects within BY29 are F1 – Green North Energy´s 280 MW project in Naantali, which is planned to be commissioned in 2026, and F20 – OX2´s and Ålandsbanken´s up to 3 GW "Mega Green Harbor" project in Långnäs, on the Åland Islands. The timeline for the latter project is yet to be determined. The crude estimated distances to potential oxygen injections points from these projects are however long (approximately 200 km and 110 km from F1 and F20, respectively). Therefore, sourcing oxygen from offshore electrolysis powered by offshore wind could still be the more techno-economically feasible solution.

BY29 has the most combined capacity (25.4 GW) of planned offshore wind projects within 40 km of a 120 m isobath. The potential routes to market for renewable hydrogen that would be produced from offshore electrolysis connected with offshore wind in BY29 are further elaborated below. The same routes to market could be explored in more detail for the other sub-basins as well but are excluded from the scope of this report.

5.4.1.1 Fed into the BHC through a dedicated intermediate connection point

The first and most cost-effective transport option would be to feed the produced hydrogen directly into the BHC via a sub-sea hydrogen pipeline from the offshore platform to the nearest point of the BHC. This would, in theory, be the cheapest way to transport the hydrogen to the demand centres in Finland, Sweden, and Germany since transport costs on the project balance sheet would be minimized. The BHC is planned to intersect BY29 as visualised below in Figure 33. This option is, however, dependent on multiple uncertainties, most importantly whether a dedicated intermediate connection point could be created at the BHC for connecting a pipeline feeding hydrogen from the offshore platform(s).

5.4.1.2 Fed into the BHC through Gotland or Åland connection points

If integrating a hydrogen feed-in pipeline into the BHC directly at the offshore production site would prove unfeasible, the hydrogen could instead be transported to the planned energy islands of Gotland or Åland. The BHC developers plan to use these energy islands as primary connection points for feeding renewable hydrogen into the BHC (see Figure 25). Through these main connection points, the hydrogen produced from offshore platform(s) could be fed into the BHC and transported to the final off-takers. This option would however require a separate transport method between the offshore platform and the energy island(s). The transport could be carried out via a smaller subsea pipeline or via ship. The hydrogen could be transported as hydrogen, or in the form of ammonia (further elaborated below). The costs of all potential transport methods would need to be further investigated.

5.4.1.3 Off-take on Gotland or Åland

If the produced hydrogen were to be transported via a dedicated transport method to the energy islands, localised renewable hydrogen off-take on these islands could also be considered. It is important that this possibility remains open in case of force majeure, for example, if the BHC were damaged, not realised, or not realised through BY29. Potential off takers on these islands include the transportation sectors, including road and maritime transport. However, as there is also dedicated hydrogen production planned on these energy islands, there could be increased competition for signing hydrogen off-take agreements. The hydrogen product from the integrated offshore electrolysis platform would need to be cost-competitive on the renewable hydrogen market, considering not only production costs but also transportation costs.

5.4.1.4 Transported to the demand-centres but not through the BHC

Rather than using the BHC to transport hydrogen, and rather than transporting to the nearest energy island, the hydrogen could also be transported directly to the mainland demand centres. This possibility would be relevant only if the BHC was not realised, otherwise it would not be an economically interesting option.

5.4.1.5 Offshore refuelling station

The fifth possibility is to bring the off-takers directly to the offshore production site. For example, the production site could also be equipped with an offshore refuelling station for marine vessels running on alternative renewable fuels, including hydrogen. The number of ships running on alternative renewable fuels is steadily increasing. Please refer to DNV’s Maritime Forecast to 2050 report for further information.

While the marine traffic in the Baltic Sea is moderate, BY29 is in a good position in relation to the current traffic routes. There is a clear fairway reaching from the Danish straits to the Gulf of Finland. Figure 33 is a simplified visualisation of the marine traffic in the Baltic Sea (as of May 2024) in relation to the BHC (green), the BY29 sub-basin (outlined in yellow), and the offshore wind farms in the area (outlined in orange). If an offshore refuelling station would become relevant, this map is a good indication of frequent movement in the region. It is predicted that freight vessels would be the most suitable candidates for offshore refuelling, as it is unreasonable to assume that roll-on/roll-off passenger (Ro-pax) vessels would stop and refuel in the middle of the Baltic Sea.

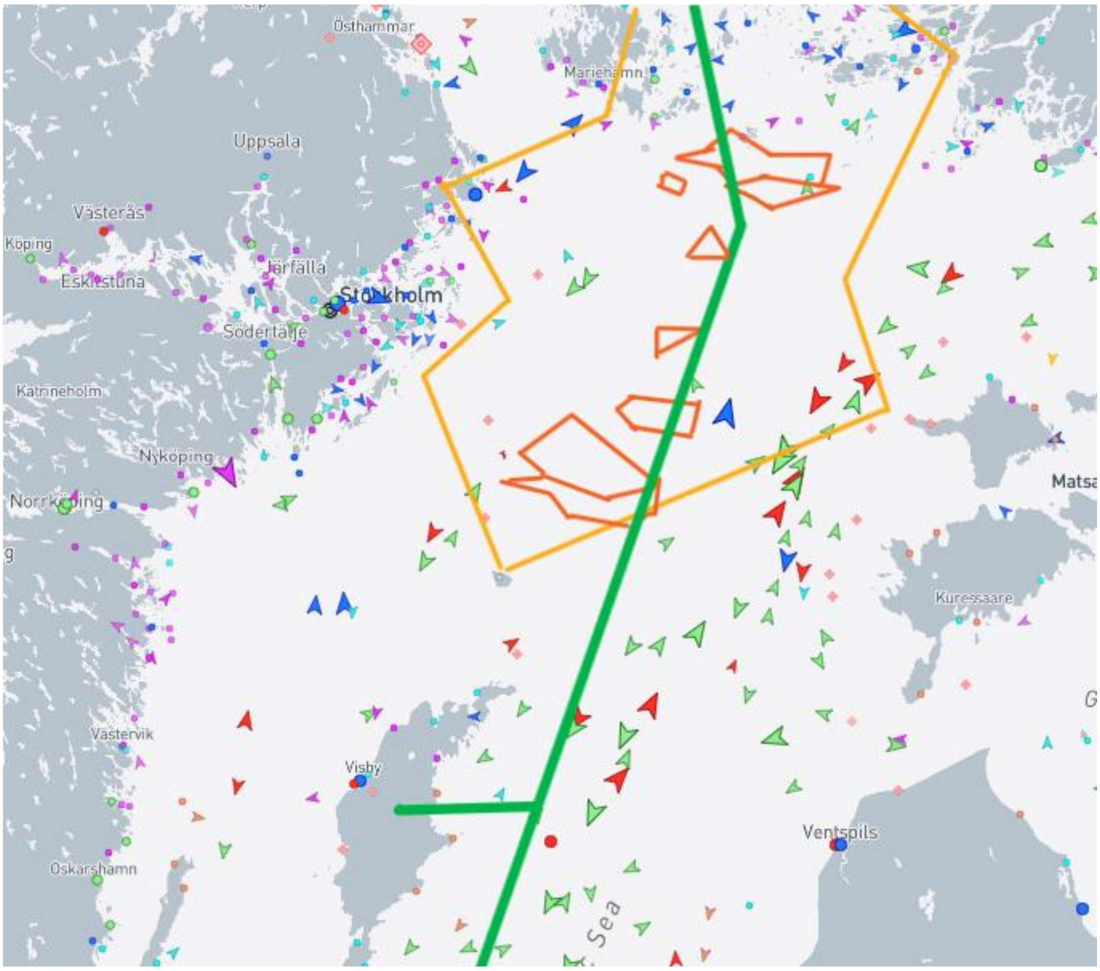

Figure 33. Vessels on the Baltic Sea (Marine Traffic, 2024) in relation to the BHC (green), the BY29 sub-basin (yellow), and the offshore wind farms (orange). The red arrows symbolize tankers, while green indicates cargo vessels, blue indicates passenger vessels and purple indicates pleasure crafts (Marine Traffic, 2024).

5.4.1.6 Ammonia production integrated with the offshore platform

As discussed in section 5.2.3, hydrogen can be transported in numerous physical forms. While gaseous pipeline transport is considered the most feasible option in the Batlic Sea, the hydrogen product could theoretically be processed into ammonia onsite and transported via sub-sea ammonia pipeline or ship to shore. Ammonia has a higher energy density and higher liquefaction temperature (-33 °C) than hydrogen, making it slightly easier to transport. Once onshore, the hydrogen could be re-obtained via ammonia cracking. Alternatively, ammonia off-takers could be brought to the offshore production site.

An example of offshore ammonia production is the concept developed by the Norwegian company, *H2Carrier*, that is planning to build a floating PEM electrolyser in combination with a Haber-Bosch ammonia production unit. The facility will produce 100 000-230 000 tonnes of green ammonia annually and has the possibility to be scaled up to 820 000 tonnes annually. The H2Carrier will be moored close to shore, but the knowhow of on-loading fuel from a floater will nevertheless be valuable (H2Carrier, 2021).

5.4.2 Potential placement of offshore electrolysers in the Baltic Sea

Besides, BY29, the other potential sub-basins of interest are BY10, BY32 and BY31. Considering the locations of planned offshore wind parks in these sub-basins and proximities to hydrogen transport infrastructure and anoxic/hypoxic regions, potential locations within these sub-basins for building POI-integrated offshore electrolysis platforms were investigated. The resulting locations are shown in Figure 34, with the proposed platforms numbered in no particular order.

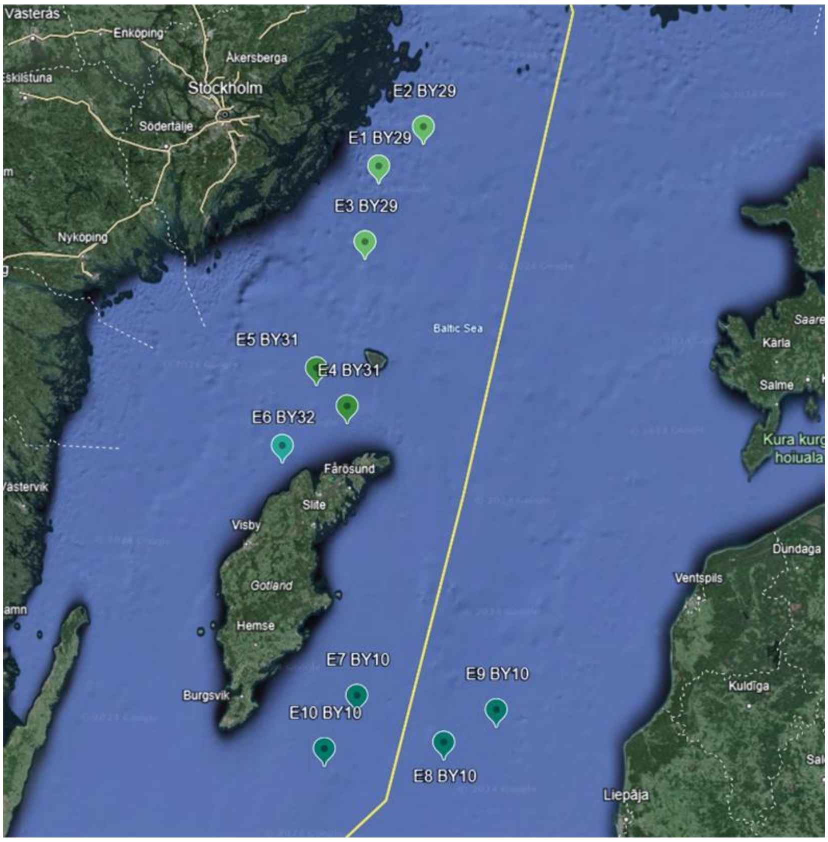

Figure 34. Proposed offshore electrolyser locations in BY29, BY31, BY32 and BY10, based off selected criteria. The locations have been mapped in Google Earth. Please refer to Appendix 6 for the exact coordinates of the proposed platforms.

The criteria used to determine the optimal offshore electrolyser platform locations are detailed below. The data for each proposed electrolyser platform can be found in Appendix 6. The techno-economic design of a conceptual offshore hydrogen production platform integrated with oxygen injection is detailed in section 6.

5.4.2.1 Electrical connection criteria to renewable power source

The maximum distance from the localised wind farms has been limited to 40 km. As the offshore electricity transmission costs increases with the cable length, cables that are too long are economically unfeasible. Furthermore, all the proposed electrolysers and oxygen injection points are located outside of the boundaries of the wind farms, with a minimum distance of 10 km. The actual minimum distance required would need to be evaluated on a case-by-case basis together with the wind park developer.

5.4.2.2 Technical and environmental criteria

The electrolyser sizing had to be carefully evaluated. The electrolyser modules considered for offshore production have capacities of 25 MW each with the opportunity to be stacked up to hundreds of megawatts of capacity. To meet the oxygen demand in each of the sub-basins up to 15 x 100 MW (1.5 GW) electrolysers would be required in each sub-basin. Hence, among other reasons, the offshore electrolyser platform capacities were increased to 400 MW each. However, with the limitations of distances being relatively short, it posed a challenge to locate enough points within each sub-basin that were far enough away from each other, regardless of the increased capacities. Hence, only two (BY10 and BY29) of the four best opportunity regions' oxygen demands were able to be met. In the two remaining sub-basins (BY31 and BY32) only two and one oxygen injection point could be identified within the limitations, respectively.

The Ro-pax ferry traffic between Stockholm and Helsinki will not be a threat to the identified locations, as the routes are situated north of all the potential electrolyser positions. However, some of the electrolysers in the BY10 sub-basin may or may not interfere with a bigger fairway between Gotland and Latvia. Thus, similar identification systems as wind farms must be considered to avoid collision. Thorough integration of offshore infrastructure into national and international marine spatial planning must be ensured.

5.4.2.3 Hydrogen pipeline connection

For long pipeline routes (>100 km), frequent compressors are needed to maintain the pressure, as transporting a gas in pipelines results in a significant pressure drop (Khan, Young, & Layzell, 2021). The capacity of short hydrogen pipelines without compressors have been calculated to be 1-1.2 tonnes of hydrogen/day/km (tH_2/d/km) (Khan, Young, & Layzell, 2021). For avoidance of additional infrastructure costs associated with long pipeline routes, the hydrogen pipeline distance in the study was set to a maximum of 100 km. Hence, the minimum distances from the oxygen injection points to the nearest port as well as the distance to the BHC were evaluated. Concerning the ports, the nearest known industrial port was identified for each electrolyser platform, with the vision that the hydrogen delivered at the port could be utilised in nearby industries or transported further inland by road or rail transport.

6 Early-stage concept design of an offshore electrolyser platform integrated with POI

In WP3, the basic requirements and boundary conditions for the conceptual design of an offshore hydrogen production platform integrated with POI were defined. A "Basis of Design" (Appendix 7) was used for the concept design to integrate both technical and economic aspects foreseen for the successful implementation of oxygen injection integrated with a hydrogen production platform in the Baltic Sea.

6.1 Adaptation of Lhyfe's existing offshore hydrogen production platform concept

The standalone offshore electrolyser platform concept (without POI) has already been developed and tested at MW-scale by Lhyfe. Based on the already known design of offshore hydrogen production platform (LHYFE®), both technical and economic aspects of integrating POI onto the platform were evaluated. The main added elements are listed below:

- Pressurised oxygen production and oxygen purification system.
- Oxygen transportation pipeline.
- Oxygen injection system.

Renewable energy (e.g., from offshore wind farms) and purified seawater are input to the electrolyser to produce hydrogen and oxygen. The hydrogen produced will be exported onshore e.g., via an H_2 export pipeline. The final user can be either an industrial client located close-by or H_2 can be injected to a national/European backbone H_2 network. Examples of hydrogen transport methods to end-users from the best opportunity region of sub-basin BY29 are listed in section 5.4.1. The water-saturated oxygen product will be dried to reduce its water content and then injected to the oxygen injection network located around the production platform. Oxygen will be transported via subsea risers to the oxygen diffuser located at the bottom of the sea where it is emitted via the bubble plumes to compensate anoxia and hypoxia.
For the preliminary techno-economic analysis of offshore platform concept, the full list of assumptions and data inputs used in the Basis of Design can be found in Appendix 7. In this document are described design conditions such as:

- Site and environment.
- Operations and Maintenance.
- Performance criteria.
- Heath, Safety and Environment management.
- Interfaces.

For example, the global plant load is summarized in the table below.

Table 17 Extract: Global Plant Load from Basis of Design.

	Nominal conditions	Maximal conditions
Plant load factor	88%	100%
H_2 Flowrate (Nm^3/h)	70 000	80 000
H_2 Flowrate (t/d)	151	173
O_2 Flowrate (t/d)	1 199	1 370
Operating capacity (MW)	350	400
Installed capacity (MW)	400	400
LCOE (€/MWh)	65	65
Plant Design Availability	94%	92%

6.1.1 Process description ISBL (H_2 Plant)

A brief explanation of the offshore hydrogen platform (H_2 Plant) and its key components is given in the following sub-sections for a better understanding of the whole concept. The figure below provides a simplified block diagram of the offshore hydrogen plant concept (without integrated POI).

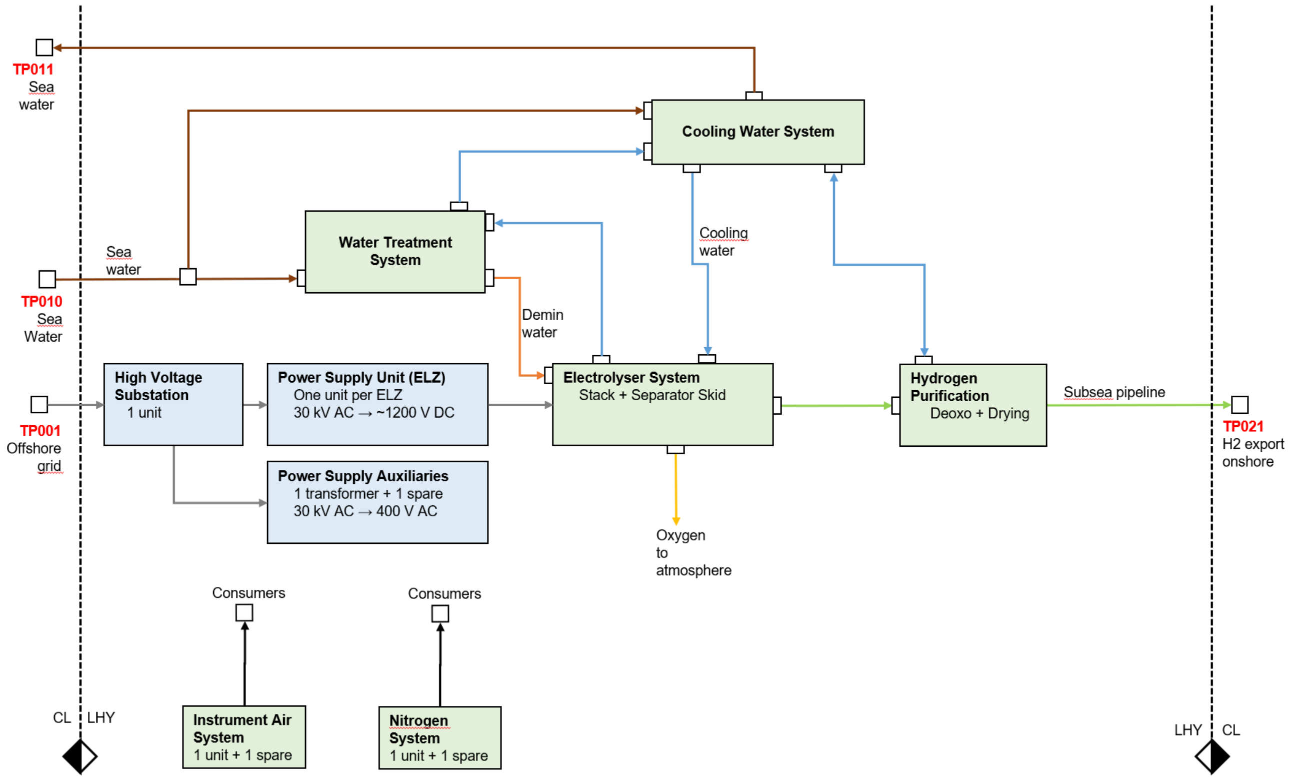

Figure 35. Typical Block Flow Diagram for an offshore H_2 plant concept.

6.1.1.1 Overview of the PEM electrolysis process

The electrolysis solution considered is PEM (Proton Exchange Membrane) electrolysis technology. It is a pressurized solution, with a hydrogen pressure at the outlet of the package of 30 to 40 barg. The oxygen pressure at the outlet is up to 20 barg. To perform the electrolysis, an electrical power input needs to be provided. The expected performance of electrolysis can be found below.

Table 18. Electrolysis performance.

Description	Range (kWh/Nm3 of H_2)
Expected (AC) Specific consumption	4.32 to 4.91

From seawater and waste heat from electrolysis, the water purification system (demineralised water generation unit) is producing deionised (DI) water that will feed the electrolysers. Electricity together with DI water are the two elements needed for electrolysis (Figure 36).

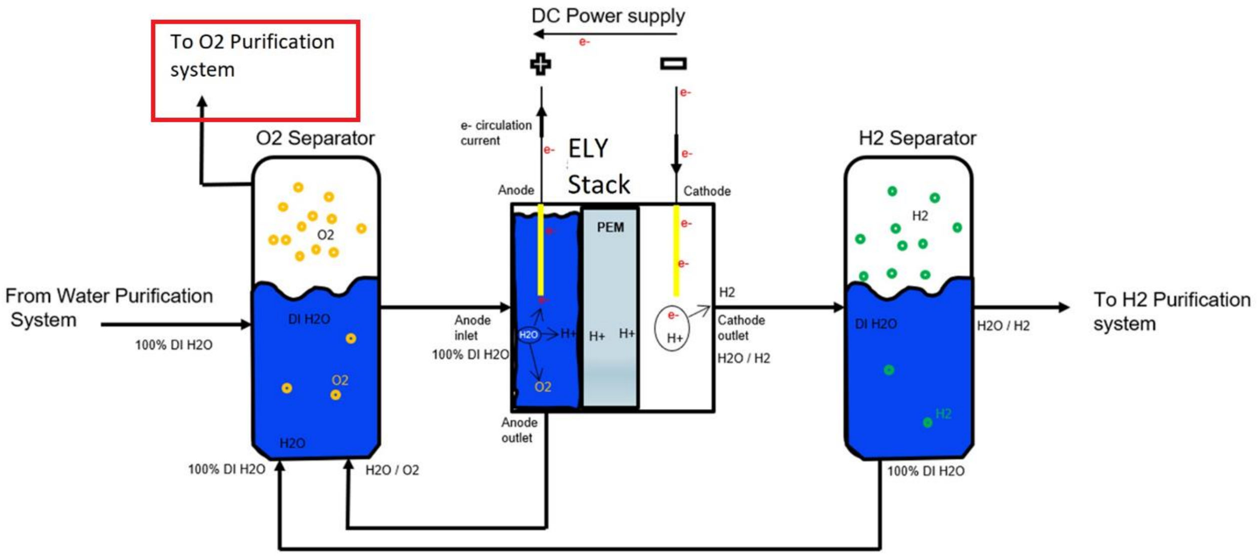

Figure 36. PEM Electrolysis scheme.

PEM technology has the advantage of a smaller footprint and not releasing any potassium hydroxide (compared to alkaline electrolysis) in the condensate after the splitting of the water molecules into hydrogen and oxygen. PEM technology uses a polymer electrolyte membrane to split the water molecules. The suggested PEM technology has a technology readiness level (TRL) of 8 and is commercially available on the market from several original equipment manufacturers (OEMs).

For POI, pressurized oxygen is needed to transport and compensate the water column at the subsea injection point. Two options were foreseen:

- Electrolyser with pressurised O_2 outlet (20 barg range).
- Electrolyser with atmospheric O_2 outlet (< 1 barg) combined with O_2 compressor

The first option considered is more capital expenditure (CAPEX) intensive. The second option brings more complicated operations and maintenance by using large scale rotating equipment offshore. This second option also requires more safety requirements (compression of oxygen).

6.1.1.2 Hydrogen Purification

Hydrogen is purified in a deoxidation (deoxo)/dryer package at about 30 barg, resulting in the removal of oxygen and water from H_2 stream (Figure 37). The deoxo/dryer section include the following main sections:

- Deoxidation: oxygen is removed on a catalytic bed from the H_2 stream by converting oxygen and H_2 into water.
- Dryers: the resultant water is removed from the H_2 stream by passing through desiccant beds. Two beds are provided and are working in parallel in cycles: One bed allows water absorption while the other bed is regenerating the desiccant by water desorption.

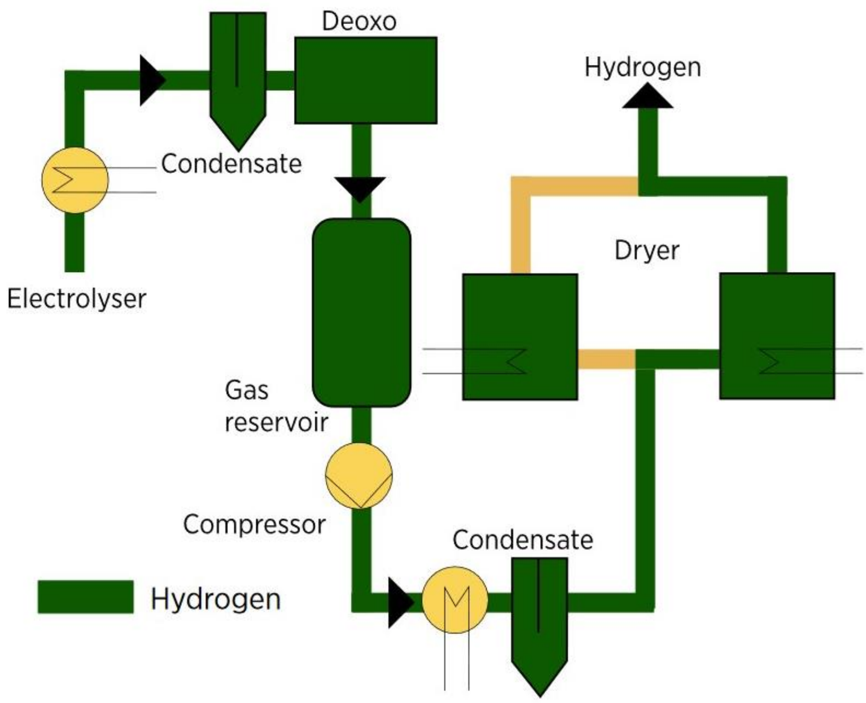

Figure 37. Typical system design for Deoxo/drying for hydrogen (International Renewable Energy Agency, 2020)

At the outlet of the deoxo/dryer, the H_2 is sent via the H_2 export pipeline. Note that this stream requires water removal in the drying section for:

- Bulk H_2: water content imposed by mobility specifications.
- H_2 export: gas transportation requirement.

Additionally, is it easier for H_2 compressors to handle dry gases instead of saturated (wet) gas. Hence, H_2 streams need to be dried upstream the potential recompression unit located onshore.

6.1.1.3 Cooling system

The Plant cooling system is based on closed glycol water loops, cooled down by an open seawater circuit. The percentage of glycol is adjusted depending on the minimum ambient conditions to prevent the cooling solution from freezing. The cooling loops are supplying the following:

- Electrolysers, as cooling media for the electrolysis process.
- Demineralized Water Generation Unit, as heating media to vaporize water.
- H_2 purification.
- Others cooling duties.

6.1.2 Process description OSBL (Pure Oxygen Injection)

Below is explained the required adaptation needed on the H_2 platform concept to be suitable for supplying oxygen for POI in the Baltic Sea.

6.1.2.1 Oxygen Purification

Oxygen is purified in a dryer package at about 20 barg, removing water from the O_2 stream. This drying process of oxygen is analogous to the hydrogen drying. The water removal step is necessary for:

- O_2 Transportation: avoidance of oxidation on metallic materials.
- O_2 injection: Bubble plume diffuser design based on dry oxygen injection.

The drying section includes:

- Dryers: water is removed from O_2 stream by passing through desiccant beds. Two beds are provided and are working in parallel in cycles: One bed allows water absorption while the other bed is regenerating the desiccant by water desorption.

At the outlet of the dryer, O_2 is sent via the O_2 riser to subsea bubble plume diffuser.

6.1.2.2 O_2 Transportation

Once purified, the oxygen flowrate will transit via riser pipelines installed in parallel. Oxygen transportation is based on two parts. The first part (Starting from O_2 purification) is a carbon steel pipeline based on a low gas velocity design to prevent from oxygen impingement effect (EIGA, 2020). The transition to the second part of the pipeline is made of a concentric reduction (carbon steel) with internal coating (nickel). The second part is made of HDPE (High Density Polyethylene) for easier connection with the existing HDPE based technology of O_2 injection. A certain caution is taken on this HDPE pipeline (DR 7.0) regarding the maximum design pressure reduced by the environment effect of O_2 on this material.

By considering the oxygen effect on pipeline transport and considering the large flowrate of O_2 generated by the overall electrolysis plant, several riser pipelines are to be planned to transport properly the oxygen in a safe and reliable way. The O_2 transport from the platform to the diffuser is visualised in the figures below.

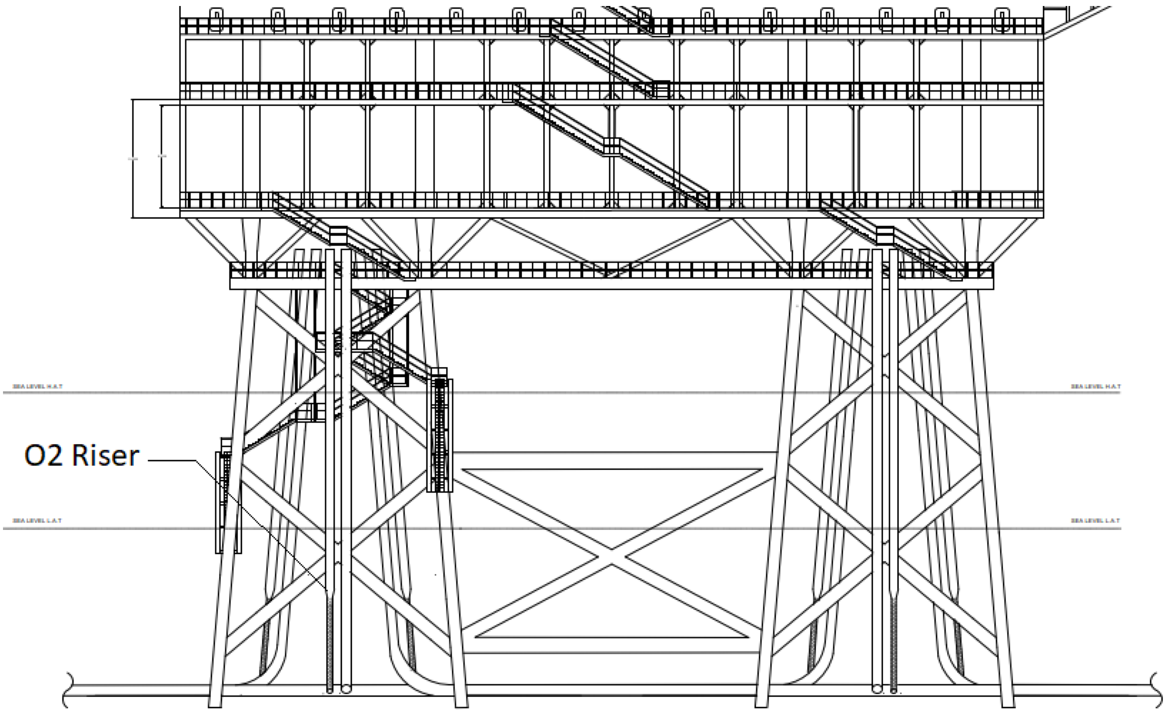

Figure 38. Extract of the General elevation view for H_2 Plant combined with POI. See Appendix 9 for the full drawing.

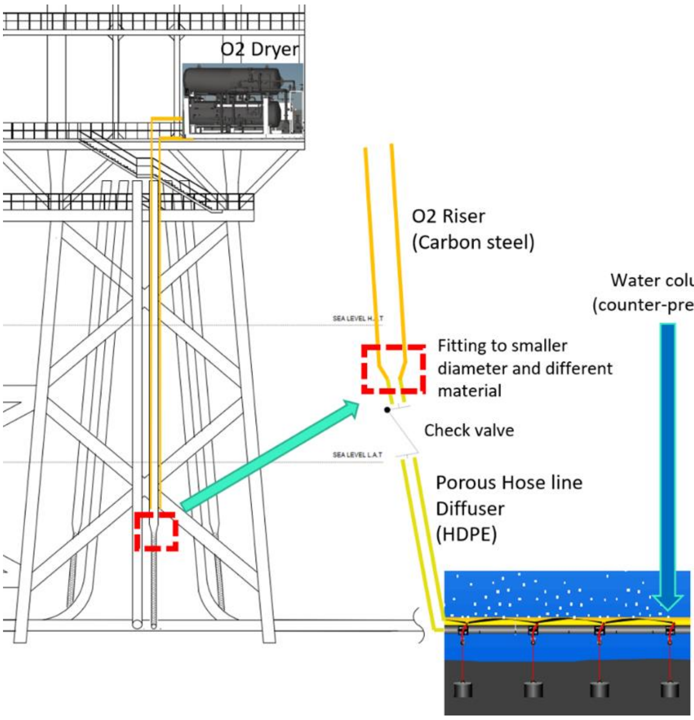

Figure 39. Basic view of oxygen riser to oxygen diffuser.

6.1.2.3 O_2 Injection

Based on the existing technology developed by Jacobs and Mobley Engineering (Vahanen; Jacobs, 2022), one kilometre-length units of bubble plume diffusers are installed subsea around the offshore platform. The length is limited to one km due to technical constraints such as pressure drop in the diffuser. The linear diffuser is a simple and economical design that spreads bubbles over a large area and is installed and retrieved for required maintenance (Mobley, et al., 2019). The system uses long lines of flexible porous hose (Figure 40).

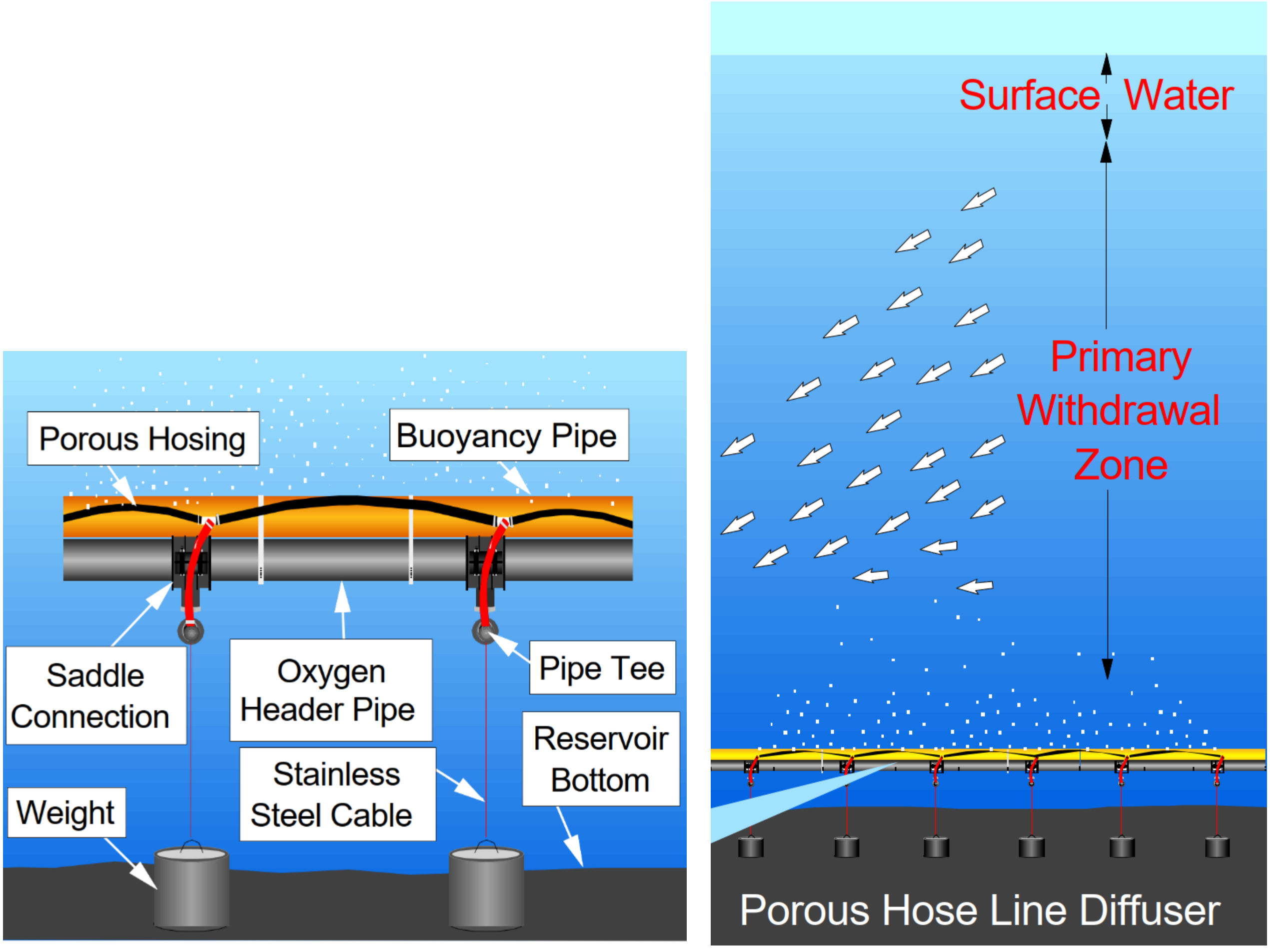

Figure 40. Linear diffuser design foreseen for POI in Baltic Sea based on existing technology developed by Jacobs and Mobley Engineering (Vahanen; Jacobs, 2022).

Linear diffusers have three basic elements: a buoyancy pipe, an oxygen supply pipe, and diffuser lines discharging from a network of orifices. For saline applications, the 316 stainless-steel fittings would need to be replaced by corrosion-resistant materials such as titanium, but the high-density polyethylene and rubber elements of linear diffusers are suitable for marine applications.

6.1.2.4 Synthesis - Technical implications of oxygen injection integration into the platform design

The figure below is a synthetic view Block Flow Diagram (BFD) showing the main elements of an offshore H_2 Plant and the additional items required for oxygen injection. The details of this documents can be found in Appendix 8.

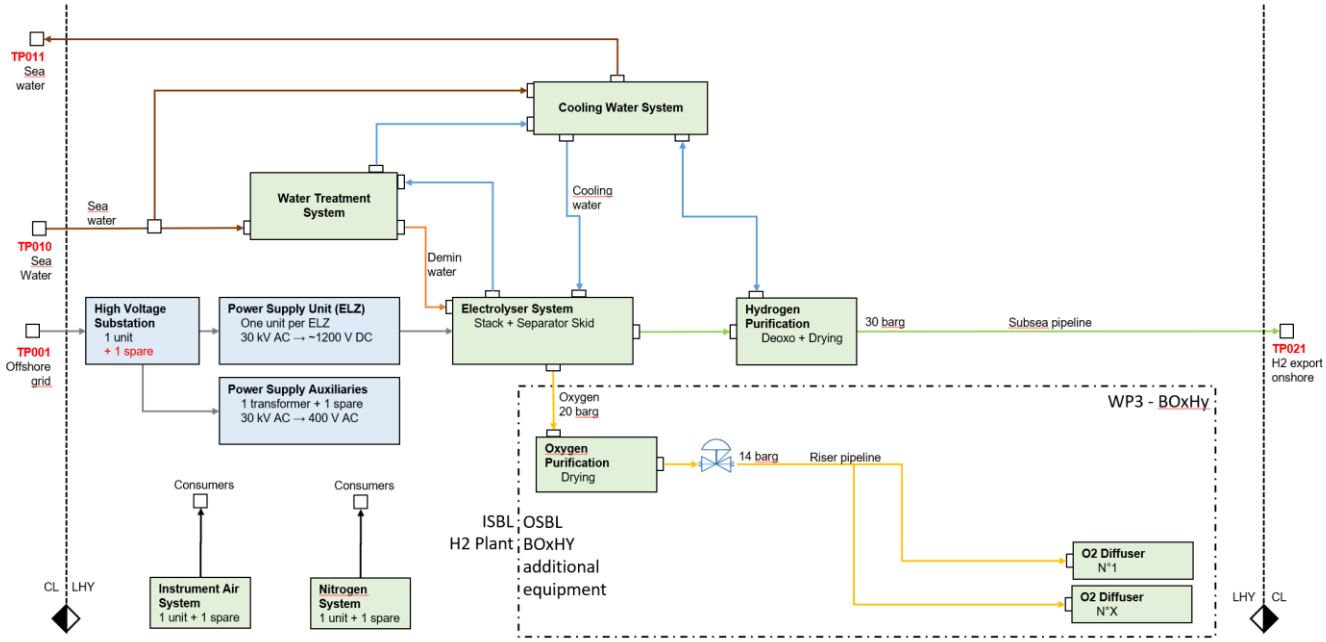

Figure 41. Extract of Block Flow Diagram for an offshore hydrogen production plant integrated with POI.

The inside battery limits (ISBL) is composed of a topside steel structure housing the H_2 production unit and will support the following equipment:

- Ultra-pure water treatment system
- Cooling water system
- HV transformers and rectifiers
- Electrolysers (ELZ) system
- H_2 purification system
- Offshore control rooms
- Auxiliary systems (i.e., instrument air system, nitrogen production unit,)

To perform the injection of pressurized oxygen into the ocean, the BOxHy project considers that the following elements are outside battery limits (OSBL) and will need to be added to the design:

- PEM electrolyser modules with pressurized oxygen outlet.
- Oxygen purification (based on gas drying technology).
- Additional steel structure: to compensate the additional footprint and weight needed for the OSBL equipment added on the offshore structure.
- Oxygen riser pipeline: to make the connection between oxygen purification and oxygen subsea diffusers.
- Oxygen bubble plume diffusers: existing technology used to reoxygenate water.

The table below summarise the main elements that form the integration offshore production Plant:

Table 19. Main equipment list extract.

AREA	TAG	DESIGNATION	QUANTITY INSTALLED	QUANTITY IN OPERATION	SPARE PHILOSOPHY
Offshore	20_PKG01	H_2 Plant	1	1	1 x 114%
Offshore	27A1/A16_ELZ01	O_2 Pressurized outlet option on ELZ	16	14	16 x 6,25%
Offshore	27_SST01	O_2 Additional Steel Structure	1	1	1 x 100%
Offshore	27_PKG01A/B	O_2 Dryer	2	1	2 x 100 %
Subsea	27A1/A8_O2T01	O_2 Transport riser	8	8	8 x 12,5%
Subsea	27A1/A8_BDV01	O_2 Diffuser	8	8	8 x 12,5%

The below figure gives a Situation View of the integrated offshore Plant. From this drawing can be seen the O_2 diffusers (each one km in length) installed around the H_2 Plant. For full details, please refer to Appendix 10. This preliminary layout for the diffusers can be optimised based on the hydrographic conditions and the bathymetry of the chosen location.

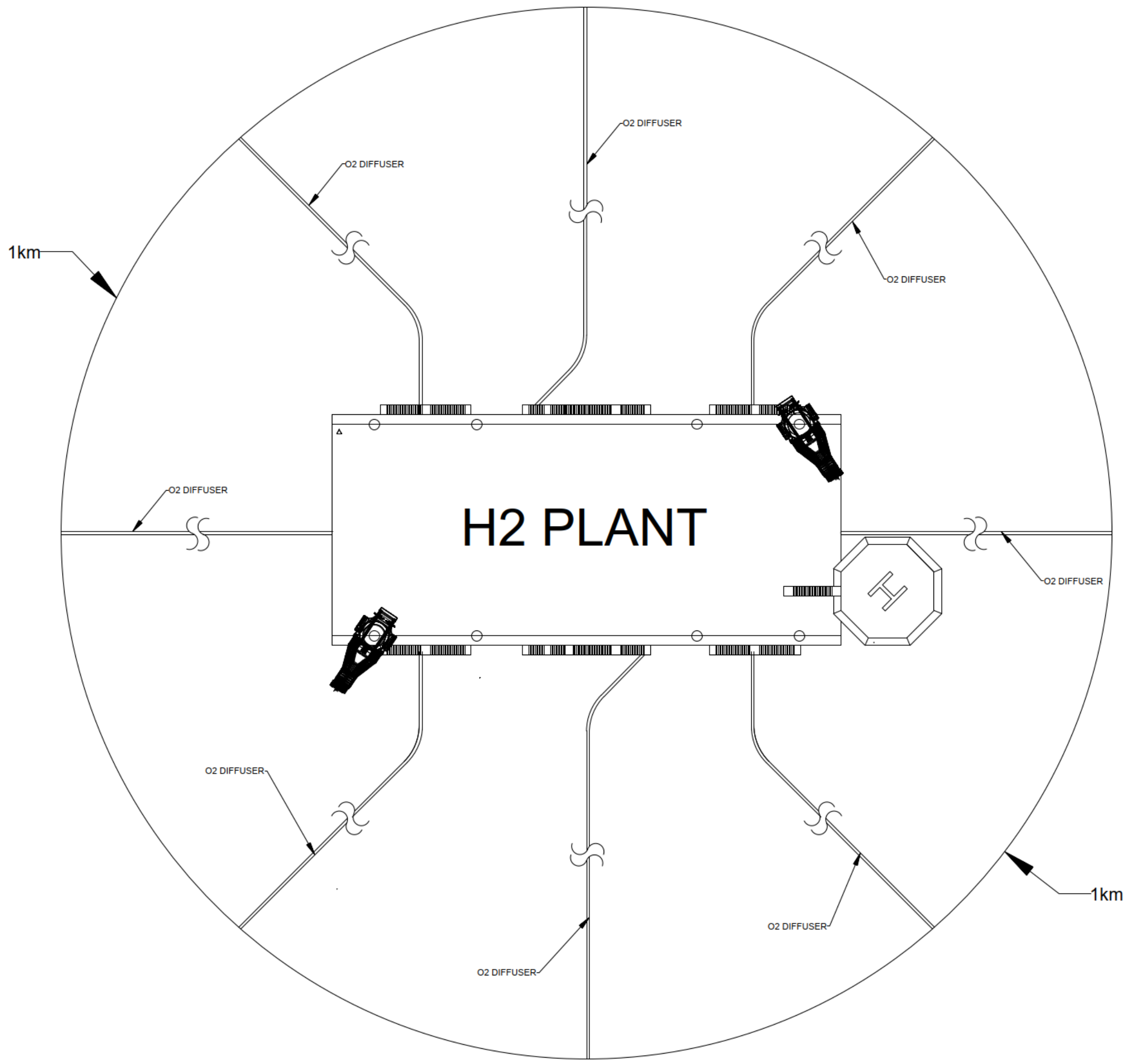

Figure 42. Extract of Situation View. 400 MW H_2 plant integrated with DOI.

6.1.3 Economic implications of POI integration in the platform design

After defining the technical modifications that need to be implemented on the H_2 platform for integrating POI, the objective was to evaluate the economic implications of such modifications and additions, i.e., changes to CAPEX and operational expenditures (OPEX). For such an early-stage concept, the accuracy of the cost estimate has an order of magnitude of class 5 (-30% to +50% accuracy). Below is a reference to class 5 cost estimate methodology (AACE, 2020).

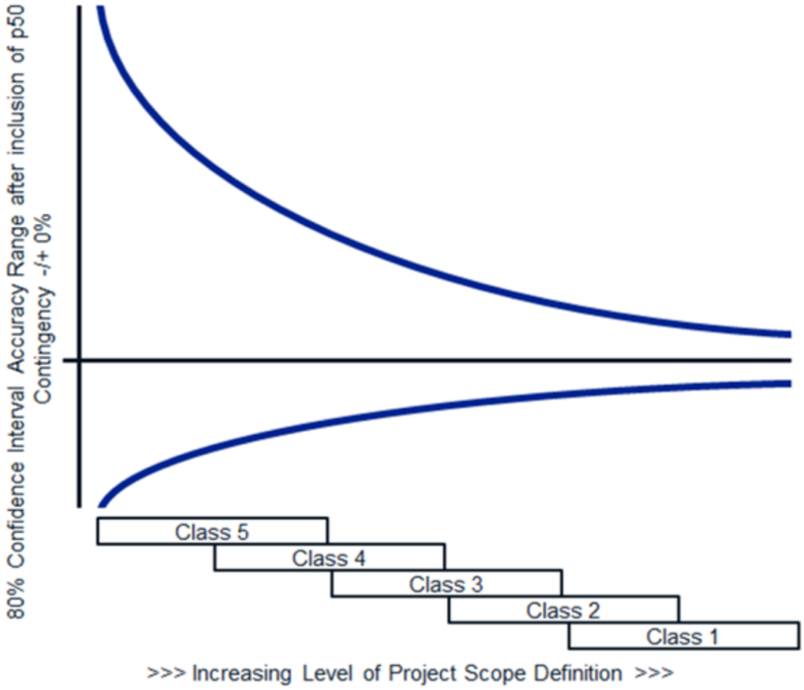

Figure 43: Cost estimate classification. Image obtained from AACE International (AACE, 2020).

Table 20. Cost Estimate Classification Matrix for Process Industries. Table obtained from AACE International (AACE, 2020).

	Primary Characteristic	***Secondary Characteristic***		
ESTIMATE CLASS	**MATURITY LEVEL OF PROJECT DEFINITION DELIVERABLES** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges at an 80% confidence interval
Class 5	0% to 2%	Concept screening	Capacity factored, parametric models, judgment, or analogy	L: -20% to -50% H: +30% to +100%
Class 4	1% to 15%	Study or feasibility	Equipment factored or parametric models	L: -15% to -30% H: +20% to +50%
Class 3	10% to 40%	Budget authorization or control	Semi-detailed unit costs with assembly level line items	L: -10% to -20% H: +10% to +30%
Class 2	30% to 75%	Control or bid/tender	Detailed unit cost with forced detailed take-off	L: -5% to -15% H: +5% to +20%
Class 1	65% to 100%	Check estimate or bid/tender	Detailed unit cost with detailed take-off	L: -3% to -10% H: +3% to +15%

The assumptions made in the economic considerations include the following:

- Expected cost accuracy range: - 30% /+50%
- Economic conditions: Q3 – 2024
- Currency: EURO
- Location factor: Location factor in Sweden considered in the quotation (from (Compass International Inc., 2023) LF = 1,07)
- Climate conditions: Extreme winter temperature: - 20°C

Based on LHYFE internal data from analogic conceptual studies for a North Sea project, the extra costs of POI integration (OSBL) have been evaluated for BOxHy and the resultant additional CAPEX and OPEX costs of POI are presented in the figures below.

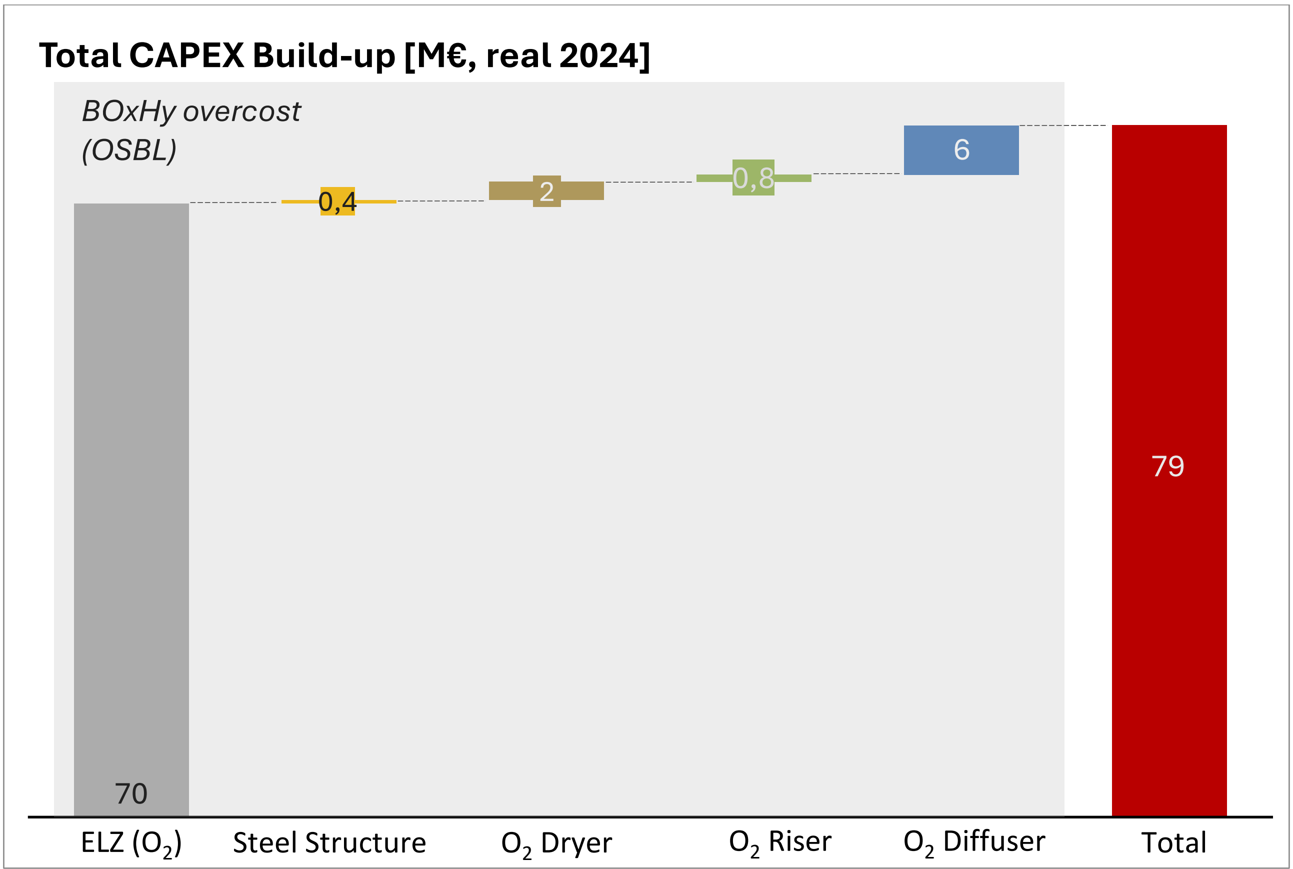

Figure 44. BOxHy additional CAPEX cost estimation for POI.

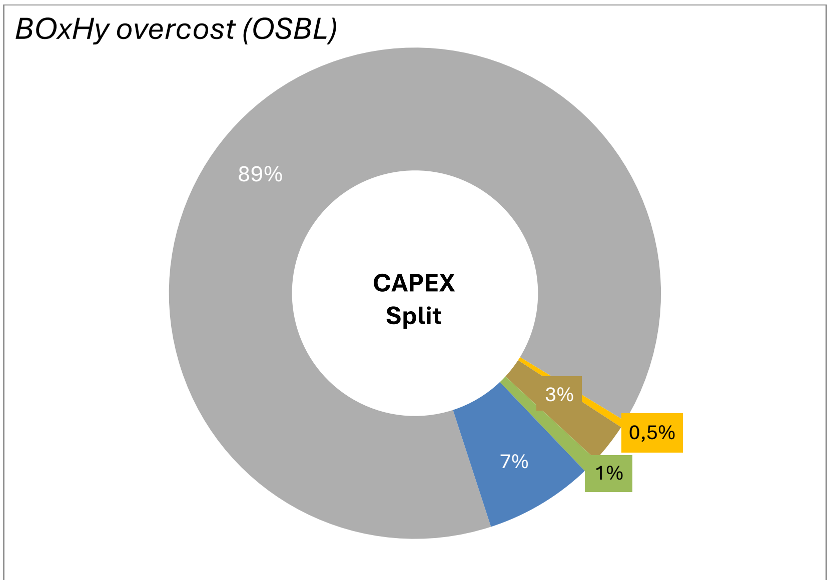

Figure 45. CAPEX breakdown. The colors are the same as in Figure 44.

Regarding CAPEX, it is foreseen that the largest part of additional expenditures related to POI will be incurred by the additional equipment needed to produce pressurized oxygen at the outlet of the electrolysers. Few OEM suppliers of PEM electrolysers have the maturity to propose this pressurized oxygen. This technological advantage increases the unitary price on electrolysers.

Regarding OPEX, it is foreseen that the largest part of additional expenditures related to POI will be incurred by the O_2 drying section (desiccant replacement and power consumption) combined with O_2 diffuser lines (subsea inspection and curative maintenance).

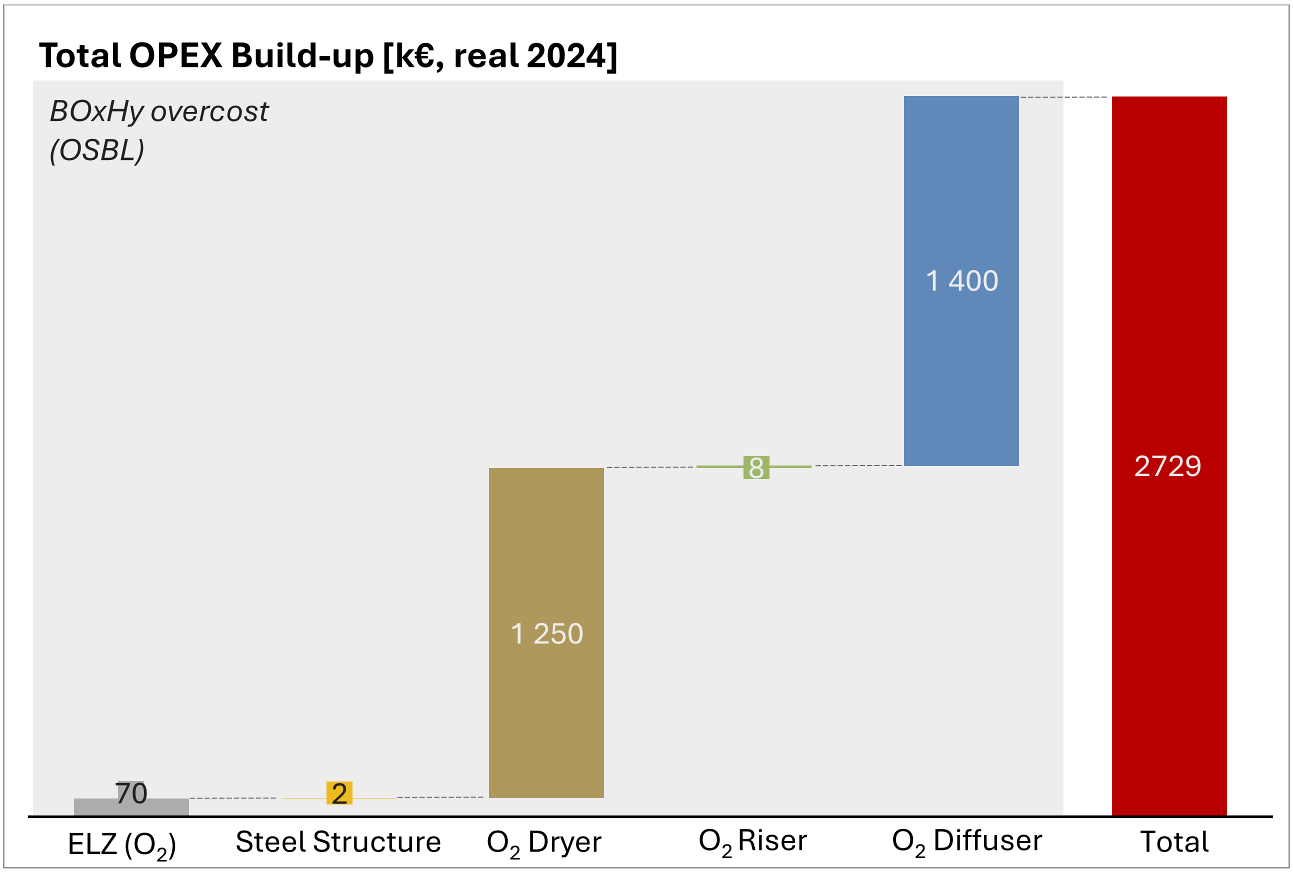

Figure 46. BOxHy additional OPEX for POI cost estimation.

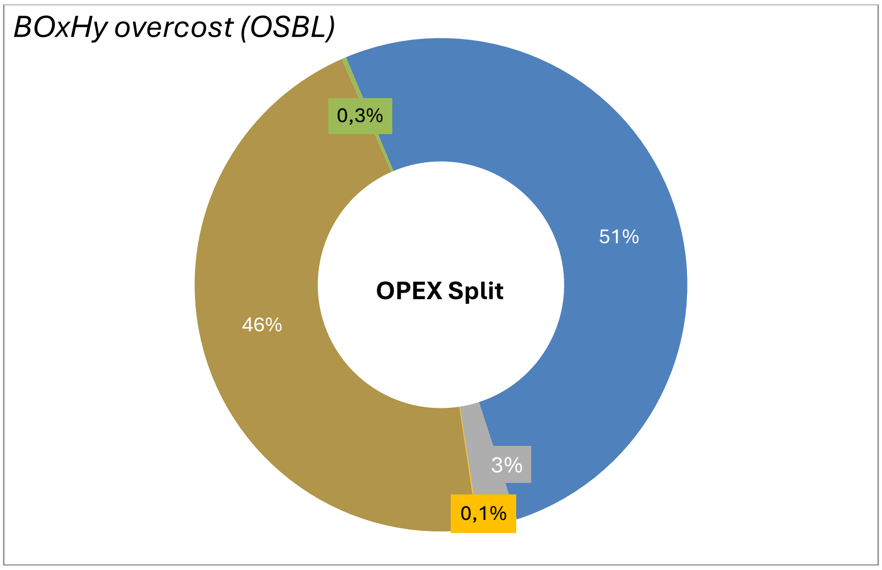

Figure 47. BOxHy additional OPEX for POI split. The colors are according to Figure 46.

The current poor state of the Baltic Sea results in an estimated annual economic loss of 5.6 billion Euros from direct and indirect losses of e.g., marine resources, marine biodiversity and public health implications (HELCOM, 2023). The above economic analysis shows that the initiative of integrating POI with an offshore renewable hydrogen plant has a certain "over cost". However, as well as reducing our carbon footprint (via renewable H_2 production), POI could be provided as an additional service to the environment to restore and stabilize the natural ecosystem of the Baltic Sea. The theoretical cost of such a reoxygenation service is exemplified in the table below, which includes two different case studies for electricity supply to the 400 MW electrolyser plant.

*Table 21. Reoxygenation service - *Cost overview (no inflation, no net present value evaluation, only rough analysis as preliminary assessment, 25% contingencies assumed); **Including a 10% service fee*

Parameter	Case 1 - Direct connection to 400MW windfarm with grid connection limited to safety load	Case 2 - Windfarm consumption & full power backup from the electric grid
For 400 MW electrolyser plant:		
Production rate	50%	92%
O_2 Production capacity (tonnes/year)	250 000	460 000
Capex (M€)	79	79
Opex (M€/year)	2.17	2.73
Total cost of POI over 25 years* (M€)	167	184
O_2 injection selling price (€/tonne)**	29.3	17.6
O_2 services for 400MW (M€/year)	7.3	8.1
For entire Baltic Sea:		
Required O_2 for Baltic Sea (tonnes/year)[1]	20 863 400	20 863 400
Yearly cost for whole Baltic Sea reoxygenation (M€/year)	612	367
Yearly impact on Baltic economy (M€/year)[2]	5600	5600

[1] Calculated from Table 8 for the entire Baltic Sea (tonnes/year)

[2] Estimated from the 'poor state' of the Baltic to surrounding countries, including direct and indirect impacts which include hypoxia and anoxia (HELCOM, 2023)

In Case 1, the annual oxygen production capacity of a 400 MW offshore electrolysis plant is nearly half of that in Case 2 due to the lower production rate resulting from the limitations of not having the full power backup from an electrical grid connection. However, the POI investment cost is the same and operational cost is only marginally lower for Case 1 compared to Case 2. As a result, the unit cost of oxygen is nearly twice as high in Case 1 as in Case 2 (29.3 €/tonne compared to 17.6 €/tonne, respectively). Since the oxygen demand for comabatting anoxia and hypoxia is the same in both cases, the yearly cost for oxygen injection on the Baltic-sea wide scale is significantly higher for Case 1 than in Case 2. At the lower production rate, more 400 MW platforms are needed to be able to meet the same oxygen demands. Therefore, it is concluded that it is economically favourable to have higher production rates (e.g., through full power backup from the electric grid) at each offshore electrolysis plant. On the other hand, when the yearly costs of reoxygenation as a service are compared with the current yearly direct and indirect costs resulting from the poor state of the Baltic Sea, the costs for both cases are significantly lower than the 5.6 billion Euros estimated by HELCOM. Therefore, reoxygenation as a service is seen to yield a long-term potential cost benefit to Baltic Sea states. There are however a few limitations to consider in this analysis:

- The positive impacts of reoxygenation as a service do not necessarily combat all of the direct and indirect losses in the Baltic Sea or may take several years in order to do so. The results of the BOxIn pilot study and further discussions with Baltic sea stakeholders are needed to draw a more accurate cost comparison.
- The costs considered in the build up of the oxygen injection sales price are limited to those illustrated in Figure 44 through Figure 47. Other costs are excluded from this analysis as they are assumed to be allocated to e.g., the hydrogen sales price and covered by other investments (e.g., for infrastructure such as grid connection and hydrogen pipelines). If these other costs were also required to be allocated in part or in whole to the reoxygenation service, there would be an increase in the yearly price for the whole Baltic Sea reoxygenation.

6.2 Infrastructural opportunities and technical challenges with the platform location

The main infrastructures considered in connection with the offshore platform were the following:

- Subsea architecture definition.
- Electrical connection to renewable power source.
- Hydrogen pipeline connection.

These aspects are further elaborated in the following sections.

6.2.1 Subsea architecture design and challenges

6.2.1.1 Mounting procedure

According to Jacobs and Mobley Engineering, the mounting procedure is based on a basic sinking of the line via a ballast filled with water. Once the oxygen diffuser is landed at the seabed, the bubble plume orifice can be accessed either with a subsea rover or with a complete refloating procedure.

The recovery/refloating of the diffuser is commonly done from 75 m depth in freshwater (lakes). One of the technical challenges will be to confirm the feasibility of refloating in marine conditions. The main concerns are damage due to marine growth blocking the anchors to the seabed or damage due to uneven rising of the structure.

Figure 48. Linear diffusers towed into place with weights installed. Photo: Jacobs Engineering.

6.2.1.2 Bubble plume diffuser and flooding

Due to H_2 plant shutdown, we estimate several flooding events of the O_2 diffuser lines per year. Due to the resulting absence of pressure on the gaseous side, water can intrude and temporarily flood the diffusers. With limited duration and frequency, those events are deemed to remain acceptable due to adapted materials. Thus, orifice fouling risk will be under control. However, to mitigate the flooding, a check valve can be installed inside the O_2 riser to maintain an overpressure against water intrusion in the shutdown scenario. One of the challenges using this valve installation is to verify if potential O_2 loss at the orifices to the marine environment will not empty the oxygen header pipe and decrease the pressure maintained by the check valve. This would lead to the flooding of the full diffuser line. Once the H_2 plant is restarted, pressurized oxygen is injected to the O_2 risers with a higher pressure than the pressure at the bubble plume orifices at the diffuser installation on the seafloor. All the remaining seawater is flushed back to the marine environment and the POI can start-up again.

6.2.1.3 Design pressure and oxygen effect on pipelines

The design pressure and oxygen effect on various linear diffuser materials is elaborated below.

6.2.1.3.1 Carbon steel

As mentioned earlier, the oxygen in gaseous phase has an impingement effect on the material used to transport it (EIGA, 2020). The use of carbon steel in the first part of the O_2 riser is economically interesting because it is a commonly used material in the industry. However, a certain attention must be paid to the respect of the below impingement curve:

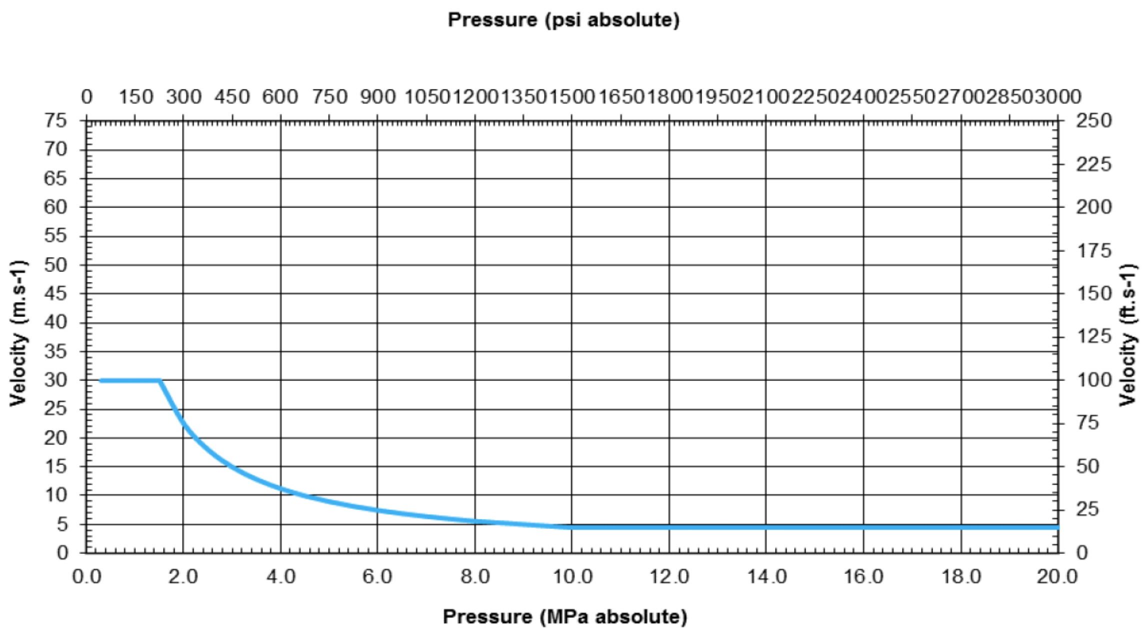

Figure 49. Impingement velocity curve (valid for design temperature curve (200°C). Image from EIGA (EIGA, 2020).

The equation of the impingement velocity curve in the figure above is defined as follows:

- If 0.3 MPa, abs (45 psia) < P < 1.5 MPa, abs (225 psia) then V (m/s) = 30 m/s (100 ft/s).
- If 1.5 MPa, abs (225 psia) < P <10 MPa, abs (1500 psia) then P • V = 45 MPa, abs • m/s (22 500 psia • ft/s).
- If 10 MPa, abs (1500 psia) < P < 20 MPa, abs (3000 psia) then V (m/s) = 4.5 m/s (15 ft/s)

In terms of design, it will be required to always have a diameter large enough to provide a gas velocity lower than the impingement velocity curve for safety reasons (accelerated corrosion, erosion, and thermal effects).

6.2.1.3.2 HDPE

For the final part of O_2 riser and the O_2 diffuser, HDPE is the material used to transport oxygen. The internal pressure rating of a HDPE pipe is based on the following equation:

$$P = \frac{2(HDB) f_E f_T}{(DR - 1)}$$

Where P = internal pressure rating, lb/in^2
HDB = hydrostatic design basis at 73°F, lb/in^2 (1600 lb/in^2 for PE 4710)
f_E = environmental design factor
f_T = service temperature design factor
DR = pipe dimension ratio

$$DR = \frac{OD}{t}$$

OD = pipe outside diameter, in
t = pipe minimum wall thickness, in

Oxygen can have a strong decreasing effect on the maximum allowable pressure rating through the f_E, the environmental design factor. This means that at equivalent HPDE pipe thickness, the maximum operating pressure will be lower if the fluid transported is gaseous oxygen. Example, if we consider the highest thickness of HDPE available (DR 7):

Table 22. Influence of oxygen on HDPE pressure rating

DR	Material	Fluid	Environmental Design Factor	Internal pressure rating (barg)
DR 7	HDPE	Freshwater	1	36.8
DR 7	HDPE	Gaseous oxygen	0.32	11.8

Thus, for the composition of the O_2 riser and O_2 diffuser an optimum needs to be found between the following three properties:

- HDPE max operating pressure (Internal pressure rating + Seawater column pressure).
  - This bottleneck effect can be modulated with the use of a carbon steel pipe adjusted to the required depth, where the water column starts to be large enough to compensate the limit of HDPE internal pressure rating.
- Electrolyser maximum pressure at the oxygen outlet.
  - Up to 20 barg max. according to OEM of electrolysers. O_2 compressors can be added if needed but it requires more complicated operations & maintenance procedures and hence will influence both CAPEX and OPEX.
- Pressure loss along the bubble plume diffuser line (ΔP = 3.6 bar / km of a 4-inch diffuser line)
  - Pressure loss can be reduced by dividing the flowrate by additional diffusers installed in parallel.

6.2.2 Electrical connection to renewable power source

Depending on the offshore site location, different electrical connection methodologies can be used. The key factors for the electrical architecture design are the distance between the H_2 site and renewable/green energy source, but also between the H_2 site and the shore infrastructure. For the green energy source location, the CAPEX is directly impacted, for the energy transportation (mainly cables and switchgears) but also the energy distribution with higher transformers. The energy cost is also higher with more distance due to the greater losses during transport. For the shore distance, mainly the operation cost is impacted due to the wind farm maintenance.

As of today, three main connections are identified:

- *Permanent* – Direct connection to a green energy source with grid connection sized to the H_2 production capacity (i.e. wind farm with high power grid connection). It allows us to have a permanent energy source whatever the wind conditions (Figure 50).

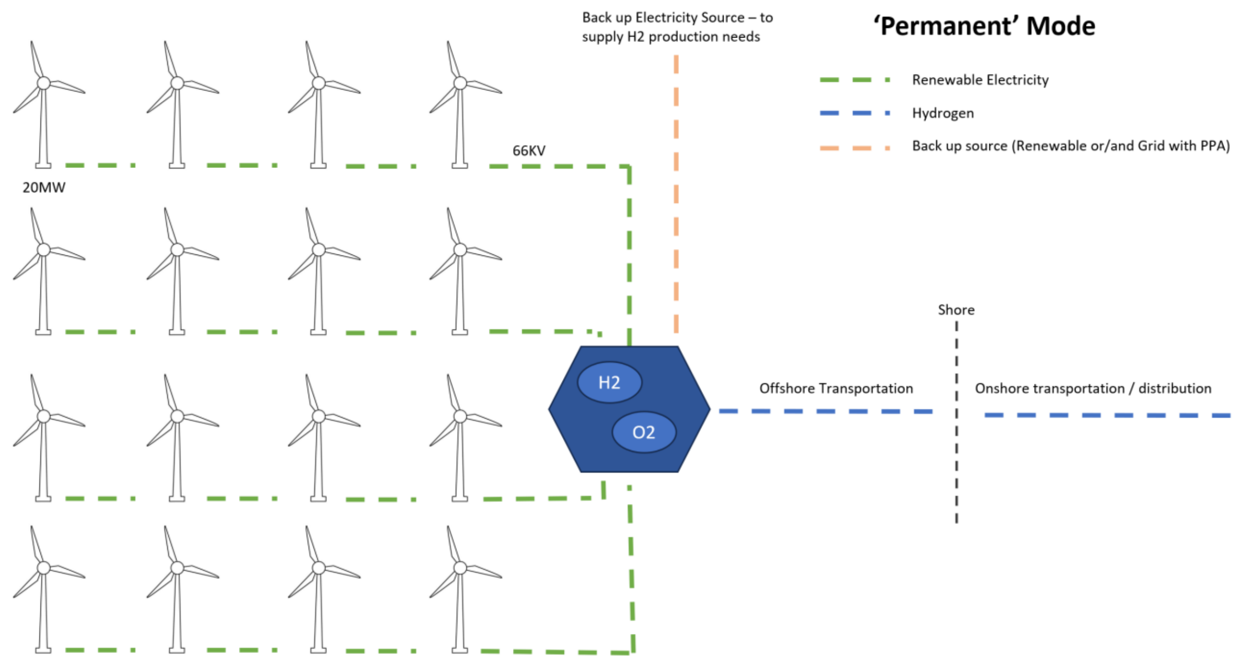

Figure 50. Permanent alternative for electrical connection.

- *Hybrid* - Direct connection to a green energy source with grid connection, only sized for the windfarm start up and preservation / maintenance phase (i.e., H_2 production energy source is only coming from the wind farm) (Figure 51).

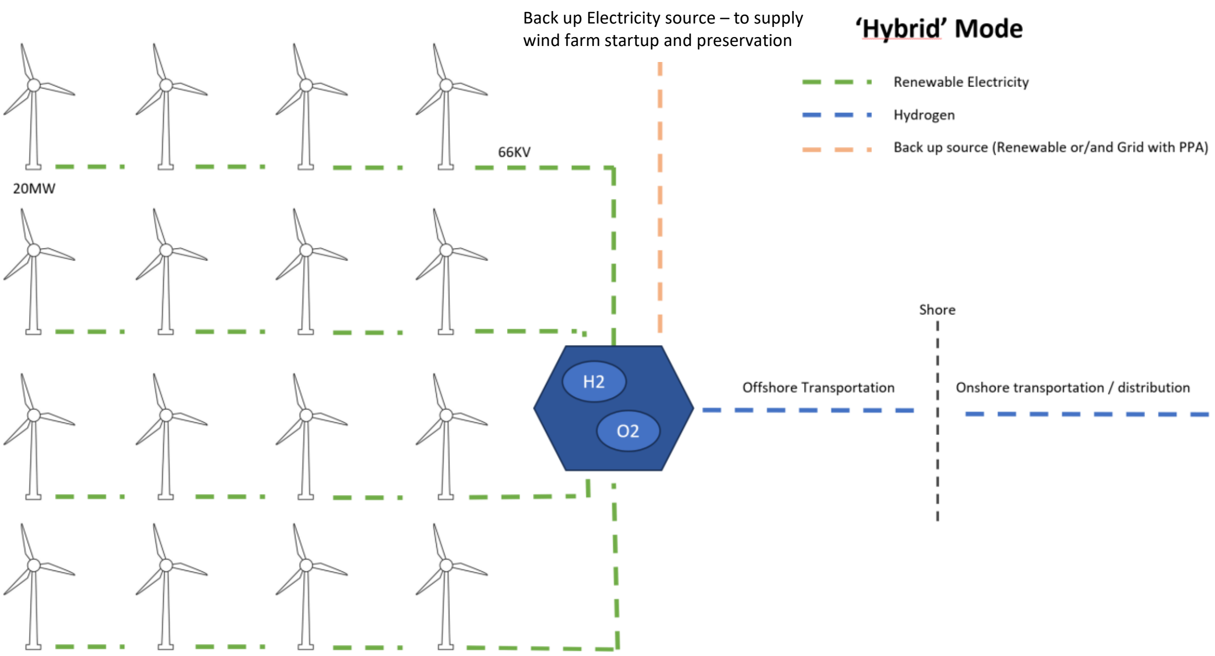

Figure 51. Hybrid alternative for electrical connection.

- *Island* - Direct connection to a Green Energy source without any grid. The wind farm start up is done by grid forming, based on a battery pack. The system is recharged as soon as there is energy production (Figure 52).

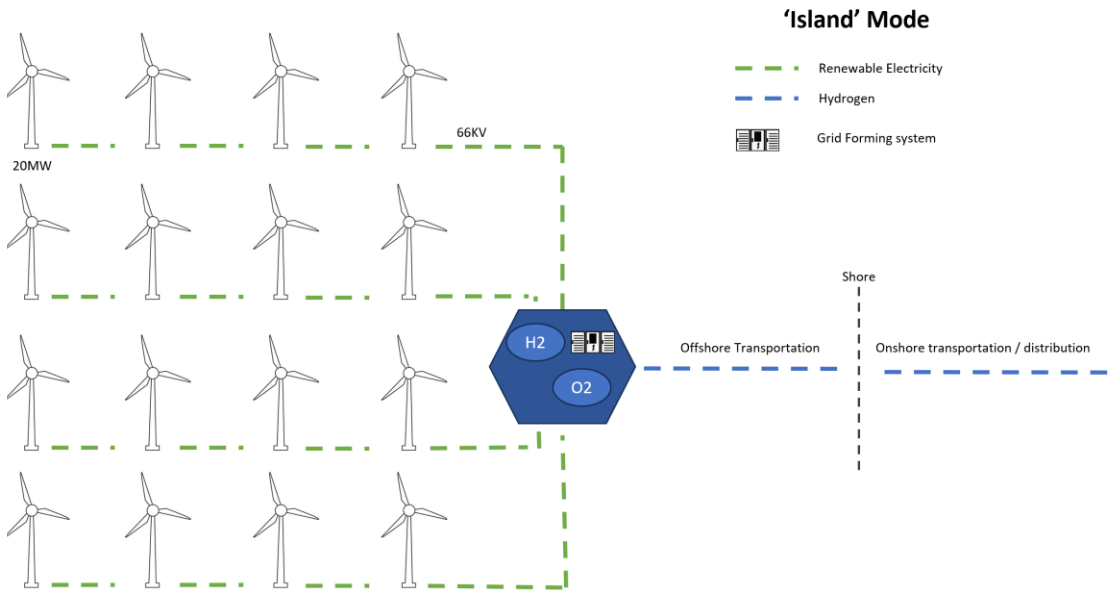

Figure 52. Island alternative for electrical connection.

The challenges and risks for each of these possible connection methods are presented in Table 23. The selection of the connection method will be done on a case-by-case basis, in discussion with the respective wind developer(s) supplying the electrical energy to the electrolyser platform.

Table 23. Electrical connection modes – comparison of pros and cons.

	Pros	Cons
Permanent	- Continuous H_2 and O_2 productions	- Capex: Cost of energy transportation (cables) & transformation - High energy loss in transportation cables
Hybrid	- Capex saving compared to two other connections	- No permanent production (but with high load factor > 65%)
Island	- Autonomous & independent from other parties - No energy transportation loss	- Capex: Cost of Energy storage and Power electronics - Design: More complex and needs to be considered in early stage – even on wind turbine - No permanent production

6.2.3 Hydrogen pipeline connection

The hydrogen export interface yields several challenges which could lead to changes in the final integrated offshore production platform location. Firstly, the environmental conditions must be carefully considered. For example, water depth is directly related to the external pressure that the pipeline will withstand, and therefore has an important impact on material selection (e.g., to avoid collapse risk). In the Baltic Sea, the seabed can be deep and hence composite material, which is very convenient for installation and elimination of the corrosion risk, may be of limited interest. Moreover, the seabed composition and profile, (sand, clay, rocks, etc.) has an impact on layout (necessity to avoid pipeline damage by peeling, important free span) and could lead to additional specific protection and subsea structure requirements.

Secondly, the existing industrial setup and/or global plan impact the export line layout and operation strategy. Several “architectures” are possible. An integrated network where several offshore H_2 plants are connected would oblige to have a global and coordinated plan for H_2 production & POI. Knowing in advance the strategically best locations would permit to design a pipeline network with subsea tie-back. This approach could significantly reduce the investment cost and minimize environmental impact. It could permit to have a single gas transport operator dedicated to this offshore network, thereby insuring operability excellence. It would also lead to reduced landfall area. The BHC is one example of this concept, as discussed in section 5.4.1.

Landfall areas are very often located within densely packed industrial ports, where it can be difficult to identify a proper location for the H_2 pipeline arrival. On the other hand, having an integrated H_2 pipeline network does add constraints for the Offshore H_2 platform operators. Here, the required export pressure to flow in the export network could be higher than a direct export pipeline pressure, leading to additional compressor requirements on the platform. In addition, the interface management could lead to unexpected shutdowns and the specifications of injected H_2 would have to be compliant with the H_2 transport operators’ requirements, which could be equal or higher than in the case of direct delivery to a final client.

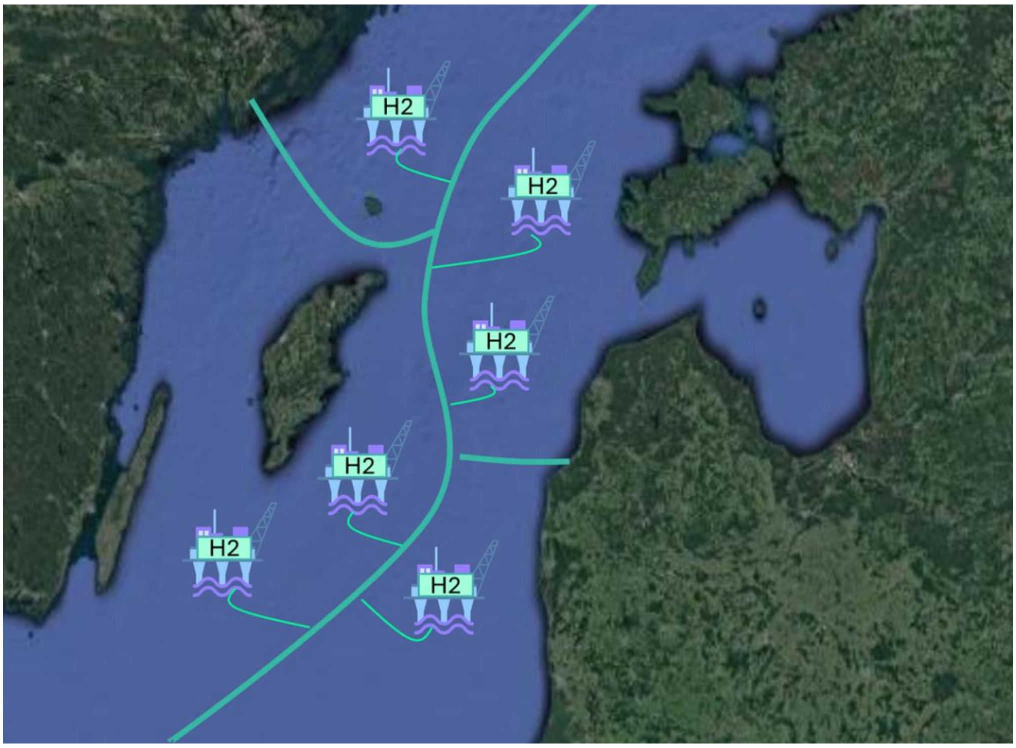

Figure 53. Typical backbone architecture for H_2 export. The BHC is one example of this, although offshore H_2 platforms integration has not yet been considered in the BHC planning.

On the other hand, the second option of having direct export from the platform to the client(s) could permit the H_2 producer to remain fully independent. This design is robust and built "fit for purpose", although it does not benefit from the flexibility offered by an integrated export network. The main challenge of building an integrated network is the ability to engage different Baltic stakeholders, based on mutual interest, of building a long-term plan, identifying H_2 production & O_2 injection site locations, then designing an optimized export network and respective landfall areas.

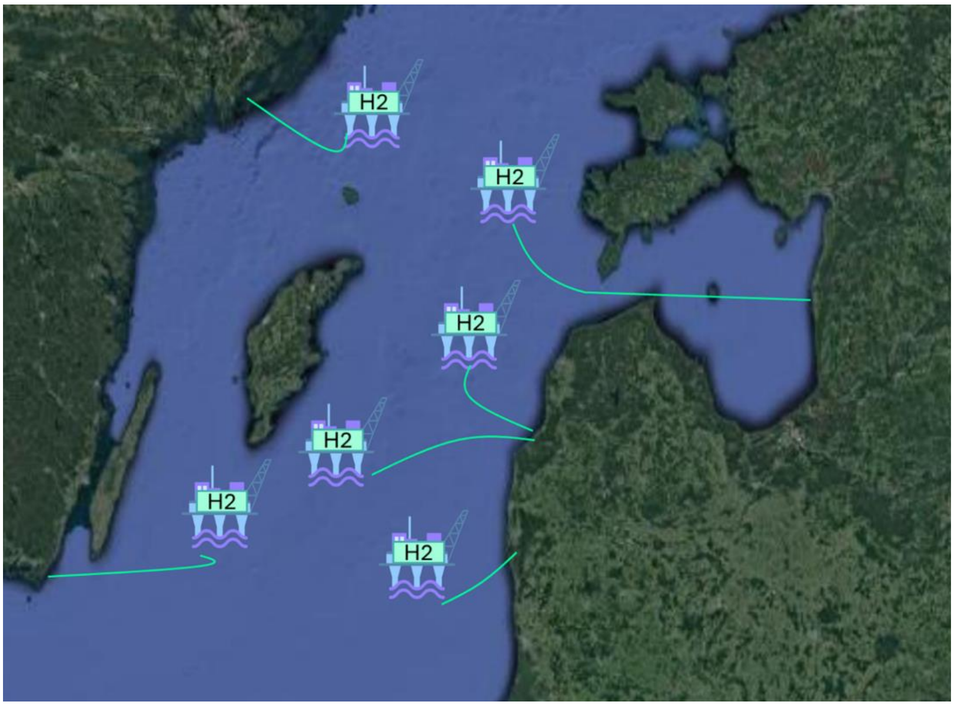

Figure 54. Typical direct & independent architecture for H_2 export.

The different material options for H_2 pipeline infrastructure are quite limited. Composite material and carbon steel material are the two main options. The advantages of the first is the ease of installation with a reeling vessel, the very low maintenance requirements and the internal roughness is very low, leading to a very low pressure drop. Unfortunately, this type of pipeline has limited resistance to collapse and burst and cannot be used in deep waters, and/or in case of high-pressure export. Also, composite pipelines have a limited range of diameters which can limit the flowrate of the export gas. The other option is a carbon steel pipeline, which can deal with high collapse and burst pressure. It is also possible to achieve large diameters in carbon steel pipelines (above 1m) but the installation of a carbon steel pipeline is more difficult, slower and more expensive than for the composite case. Carbon steel pipelines also require a high level of maintenance to ensure continuous protection against corrosion. Depending on the use case, the preferred option can vary. A foreseen option, in the case of Baltic offshore H_2 pipelines, is having the main line (the collector line) in carbon steel and then each tie-back line from the H_2 platforms through a composite pipeline.

6.2.4 Safety and Environmental Challenges

All hazards impacting people, environment and assets related to the production of renewable hydrogen and oxygen offshore during the plant's operation phase have been identified through a preliminary HAZID review. The HAZID review identifies all hazards, analyses their initial risk, lists the existing measures and procedures to decrease or prevent them, analyses the residual risk, and produces all related recommendations. This HAZID review has been performed according to the Lhyfe risk ranking matrix.

The outcome of the HAZID is that the main risks related to the hydrogen and oxygen production offshore are related to:

1) The offshore structure (i.e. collision with vessels, structural failure).
2) The lifting operations (i.e. dropped objects).
3) The intrinsic nature of the gases produced (fire and explosion).

All these three risks are well known and managed by both a design following industry standards and a regular inspection and maintenance schedule. The risks related to the harsh offshore environment (e.g., winds, waves, rain/snow), are managed through making the basis of design according to the weather conditions present onsite. Potential additional measures such as heat tracing, enclosures, and HVAC are integrated. Northern climate conditions are well-known in the oil and gas industry and its related requirements are transferable to a renewable H_2 platform operated offshore. The HSE management plan from LHYFE for the BOxHy project can be found in Appendix 11.

6.3 Next steps for realising an offshore platform pilot in the Baltic Sea

To proceed with the follow-up pilot project involving a more detailed design of the offshore platform, a systematic approach must be taken. To ensure that we develop the most environmentally and economically sustainable solution, we must thoroughly understand the underlying science, assess the environmental impacts, evaluate the actual risks, consider the potential limitations, and analyse the overall economic and environmental costs and benefits of this project before advancing with a platform into open waters. Once in open water, it is crucial that we fully understand the processes and impacts of our methods to prevent the creation of another unforeseen and complex human-made situation.

Firstly, we need to implement and evaluate the results of BOxIn, the onshore pilot project described here in our BOxHy report (section 4.6.1). From this pilot, we can critically assess the processes and the results. The pilot project will enable us to ensure that we can effectively monitor the situation, assess the impacts on the surrounding areas, and identify the optimal injection rate of oxygen and time to provide a more oxygenated habitat, determine the appropriate materials to use and estimate the long-term operational costs. This will potentially lead to the establishment of best practices for reoxygenation using the linear diffusion injection technique. As the Baltic Sea region incorporates multiple countries and stakeholders who could benefit from reoxygenation, the BOxIn pilot will provide an opportunity to promote further stakeholder engagement. By sharing the results, we can foster greater transparency and trust, ensuring that all parties are informed and involved in the process as the project progresses. Additionally, we could also model the effects of the oxygen injection more accurately, enhancing our oxygen calculations and injection costs. Altogether, this comprehensive understanding would provide a solid foundation for running an offshore platform pilot in a more sustainable and effective manner.

7 Coalition building and knowledge sharing

To enable cross-collaborations across multiple disciplines and receive external perspectives on the project work, the project team engaged with third parties throughout the project. The engagement took place via collaboration with pro-bono advisory boards and hosting of stakeholder dissemination events. The BOxHy project was also opportune to receive the United Nations Ocean Decade endorsement in the spring of 2024. The project was also represented by Jakob Walve at the EGU24 General Assembly event held in Vienna in April 2024. The coalition building, stakeholder engagements and workshops are briefly summarised in this section.

7.1 Science and Technology Advisory Committee for Oxygenation (STACO)

To ensure that the BOxHy project had the latest knowledge as well as scientific and industrial insights, the Science and Technology Advisory Committee for Oxygenation, or *STACO* in short, was set up. The STACO provided feedback, open discussions and advice to the project. After the completion of each work package, roughly every three months, a STACO meeting was set up to ensure we continued to complete relevant work that would be applicable for developing a reoxygenation pilot project. An overview meeting was given on the main findings of the work package, including the methods, issues or errors arising from the methods or outcomes, and any questions that may have come up during the work period. The committee consisted of the members listed in Table 24.

Table 24. STACO members.

Name	Area	Description
David Austin	Industry	M.Sc. Water Resources Management, M.Sc. Civil & Environmental Engineering, Prof. Eng., Senior Ecologist – Ecological Society of America, leads the Natural Treatment Systems technology group at Jacobs. He is deeply experienced with POI reservoir systems and has advanced the concept of Baltic-wide POI coupled to green hydrogen electrolysis production.
Dr Paul Gantzer	Industry	Senior expert in sediment oxygen demand and POI technology. His company Gantzer Water Resources has worked on many projects with Jacobs. His Ph.D. thesis under Prof. John Little focused on the performance of oxygenation and aeration systems.
Marc Mobley	Industry	Marc Mobley invented and developed POI technology while working for the Tennessee Vally Authority. His company, Mobley Engineering, Inc. has constructed all the linear diffuser systems operation. Jacobs has developed POI technology working with Mr. Mobley.
Prof. Dr Anders Stigebrandt	Academia	From the University of Gothenburg, oceanography expert of the Baltic Sea and fjords, elected member of the Royal Swedish Academy of Sciences. He has conducted oxygenation experiments in the Baltic Sea environment and is an author on multiple studies using in-situ and numerical model data to understand the physical and biogeochemical dynamics relevant for oxygenation of the Baltic Sea.
Prof. Dr John Little	Academia	Prof. Little is on the faculty of Virginia Tech University in the Department of Environmental and Water Resources Engineering. His pioneering research established bubble plume dynamics for pure oxygen system that are foundational to POI technology.
Prof. Dr Mark Beutel	Academia	Prof. Buetel is on the faculty of the University of California – Merced in the School of Engineering where he is the Graduate Program Chair. He worked on the first POI systems in the USA that used downflow oxygen contactor technology as part of his Ph.D. at UC-Berkeley. He has been engaged in oxygenation of lakes and reservoirs since then and has advised on the potential for oxygenation in the Puget Sound.
Dr Lee Bryant	Academia	Dr. Bryant is a lecturer at Bath University in the Department of Architecture & Civil Engineering, Research Unite for Water, Environment and Infrastructure Resilience, water Innovation and Research Centre. Dr. Byant's Ph.D. at Virginia Tech under Prof. Little investigated oxygenation and aeration impact on sediment-water fluxes. She continues her research focusing on biogeochemical cycling in aquatic systems (freshwater and marine) as well as her emphasis on drinking water quality.
Dr Sunke Schmidtko	Academia	Is a senior research scientist at the GEOMAR Helmholtz Center for Ocean Research Kiel. Dr. Schmidtko worked extensively on the global oceanic dissolved oxygen budget and deoxygenation trends in oxygen deficit zones and attended many measurement campaigns in various regions. His works are widely cited and used a basis for many regional and trans regional studies. He is an expert for data analysis dealing with heterogeneous datasets spanning seasons to decades.

The main purpose of the STACO was to bring together the experts from different domains, get important steppingstone advice to advance oxygenation as a sea-based measure, bridge the knowledge gap between the scientific and the engineering world concerning oxygenation, widen the horizon of possibilities for both communities, get insights into stakeholder acceptance, and to secure a realistic theoretical framework and feasibility of our project.

7.2 Offshore Wind Advisory (OWA) board

The offshore wind advisory (OWA) board was formed to support the project work, in particular WP2 and WP3, with perspectives on the offshore generation and integrated platform concept development from the offshore wind industry point of view. To form the OWA board, Flexens invited around 20 developers within the company's network of contacts to join as board members. Of the invitees, the following four developers were confirmed as board members: Eolus Offshore Finland Oy, RWE Renewables Sweden Ab, Ilmatar Offshore Ab and Ørsted Wind Power A/S. The board participation consisted of attending board meetings, which were held approximately every three months beginning in January 2024 and ending in October 2024.

During the meetings, the board members made active and constructive contributions to the following discussion topics:

- Planned offshore wind farm developments in the Baltic Sea region (locations, capacities, estimated timelines)
- Perspectives on energy supply to offshore electrolysers (challenges and opportunities from technical, economic, social, political, regulatory perspectives)
- Perspectives on offshore wind development potential in the Baltic Sea regions that are identified as the most potential for pure oxygen injection during the project

The main conclusions and perspectives from the board members are summarised in Table 25.

Table 25. Key conclusions of OWA board meetings.

Discussion Topic	Discussion Question	Industry perspectives	Industry Questions raised	Key Conclusions
Offshore wind farm (OWF) developments in the Baltic Sea region	Are the identified anoxic/hypoxic sub-basins compatible with offshore wind developments and why?	• The sub-basins with anoxia/hypoxia that are bordering Sweden (e.g., BY29, BY31, BY32, BY38, BY05), are interesting from an OWF development perspective since the regions contain mostly shallow waters suited for turbines • There are several ongoing projects being developed by the companies represented by the board members in the identified sub-basins • Some floating OWFs are planned in the BY05 region. Are potentially suitable for POI locations in deeper waters.	• Is the oxygen demand continuous or not? Are there seasonal variations in demand that would impact production profiles?	• There is a mismatch in synergies when considering that shallower water depths have (so far) been more favourable for OWFs while anoxia/hypoxia is generally concentrated at great depths (e.g., near 120 m isobaths). However, floating OWF concepts yield opportunities for deeper regions. • From the perspective of electrolyser operation profiles and project financials, it is best to operate the electrolyser as continuously as possible and with a stable load. There is a lot of uncertainty remaining in oxygen demand periods and seasonal variations, which will need to be further investigated. Therefore, the operation profile would need to be optimized to both H_2 and O_2 production demands. In times of low O_2 demand, produced O_2 could also be vented to atmosphere.
	What are the capacities and timelines for development of publicly announced parks in the identified sub-basins?	• Capacities of projects are generally over 1 GW and timelines are planned for after 2030. However, the projects are still in very early phases • General consensus was that the timelines are 2030s-40s. However, it is very difficult to determine at this time since there can be many delays in OWF development due to e.g., permitting, lack of exclusivity, etc.	• What timelines do we estimate for the development of POI via offshore electrolysis?	• Both the timelines of OWF commercial operations dates and offshore POI development are still highly uncertain. The results of the BOxIn pilot study will yield more insight into the next steps for POI on the Baltic sea-wide scales. It is important to maintain frequent communication with OWF developers in the sub-basins of interest and to begin electricity supply discussions at an optimal time (e.g., early enough for the wind farms to account for supply to offshore platforms in their logistics plans, but late enough that there is some maturity on the offshore platform design and increased certainty in project realisation)
	If there is insufficient planned capacity,	• In terms of building new OWF capacities, the main criteria that is considered by wind developers is		• Only BY15 has identified theoretical OWF capacity deficit. However, timelines and other sources of electricity demand are also important factors to consider

	can the remaining electricity demand in these sub-basin(s) be met?	wind conditions and water depth. Areas with environment, military and social interests are key barriers to implementation.		
	Would there be other sub-basins that are of higher interest from the OWF development perspective?	• Some OWFs being developed are not in the identified sub-basins with the highest oxygen demands (e.g., in the Northern Baltic Sea).	• Is it possible to transport oxygen from one sub-basin to another?	• The BOxHy project team briefly investigated transport of oxygen from one sub-basin to another via dispersion currents in the Baltic Sea. However, the currents were determined to be too weak (and with many other uncertainties) to transport O_2 over the distances that would be required to reach anoxic/hypoxic sub-basins
	How do you see building grid connections in the identified regions and what are the associated techno-economic impacts?	• Currently, OWFs under development are planning to build grid connections to land. Connection cables are dimensioned to be able to meet the maximum electricity demands. • In the Southern part of Sweden there is still need for increased onshore electricity supply.		
Perspectives on Energy supply to offshore electrolysers	What criteria need to be considered in coupling offshore wind with electrolysers?	• Distances to wind parks need to be considered. There should be enough space for boat mobilization for servicing both the wind parks and the offshore platforms. However, the platforms (footprint of ca- 20m x 40m) could potentially be located closer to the wind park than the current assumption of 10 km minimum distance. • Some of the developers have already been considering supply of electricity for H_2 production, while others have not and have limited experiences in this topic	• Will there be several wind parks supplying energy to one electroylser? Or Multiple electrolysers and multiple parks?	• 400 MW electrolyser capacity is considered per offshore platform. In most cases, one wind park could supply sufficient electricity capacity to one or even several offshore electrolyser platforms of this size. • Distancing between the offshore wind park and offshore electrolyser platform would need to be further investigated on a case by case basis.
	What risks do you see with	• It is vital to the business case to have some sort of grid connection		• Investments for offshore electrolyser and wind production projects should go hand-in-hand

	electricity provision to large-scale electrolysers?	as a flexibility/safety resource. Islanded mode of operation is not seen as feasible with intermittent power supply to the platforms. • Electricity provision to offshore platform needs to be decided early enough to avoid unnecessary infrastructure investments to the wind park.		
	What challenges and opportunities do you see for offshore electrolysers (e.g., technical, economic, social, political, regulatory?	• Placement of offshore electrolysers needs to consider environmental and regulatory constraints such as Natura 2000 and military areas that are protected also from an OWF development perspective.	• What is the value of locating the H_2 production offshore (besides POI potential)?	• Offshore H_2 production can yield long-term benefits such as economies of scale and avoidance of competition for land utilization • Best route to market for offshore hydrogen produced in the Baltic Sea is via the Baltic Sea Hydrogen Collector, but there are still a lot of uncertainties related to routing and timeline.

7.3 Stakeholder Information session

During internal discussions regarding stakeholder engagement within the project, a need was identified to engage local stakeholders in the potential pilot regions, creating a bridge between the pilot site mapping task and discussions with stakeholders from the most potential locations. On the 19th of February 2024, a one-hour information session was held for relevant stakeholders in the regions surrounding the identified potential locations for a pilot. The information session was a closed event on Microsoft Teams, with 27 invited stakeholders in total, of which 15 participated. The invitees were from both the Stockholm- and the Åland region and included both local decision-makers and permitting authorities.

The objective of the information session was to present the overall objectives of BOxHy project, objectives of the BOxIn pilot, the pilot site and the related criteria, and to gauge the interest of the stakeholders. After that, the discussions continued via one-on-one meetings with the stakeholders who showed interest after the information session on hosting a potential pilot site.

7.4 Dissemination event

A webinar was held on the 1st of October 2024 through Microsoft Teams to disseminate the results of the BOxHy project to interested stakeholders. The event lasted 1.5 hours and presented an overview of the project, the results of all four work packages, and finished with a Q&A session.

The invite was sent to 97 people including, among others, researchers, policymakers and relevant organisations, infrastructure and renewable energy source developers, and the invitees from the stakeholder information session. The invite was also published in the UN Decade online newsletter. The registration page was viewed by 300 people, of which 48 registered and 39 participated in the webinar. The event was also recorded and shared to the participants by e-mail afterwards.

The audience was active in the Q&A, asking highly relevant questions that were addressed by the project members. The question topics included the timeline of the BOxIn pilot, energy consumption for hydrogen production, monitoring, reduction of anoxia and oxygen calculations.

7.5 Other events and collaborations

7.5.1 EGU conference presentation (European Geosciences Union, general assembly meeting, 14-19 April 2024, Vienna)

The BoxHy project was orally presented on the 15th of April 2024 by Jakob Walve at the European Geosciences Union (EGU) General Assembly conference in Vienna, Austria, held 14-19 April 2024. The EGU General Assembly attracts many of the world's geoscientists each year, this year with 18,388 attendants from 116 countries and 18,896 presentations given in 1,044 sessions. The presentation about the BoxHy project was part of the Ocean Sciences session OS2.2 "Oceanography at coastal scales: Modelling, coupling, observations and applications". The presentation was titled "The BOxHy Project: Preparing a Pilot Site Study to Remediate Low Oxygen Conditions in Coastal Seas" and authored by Patricia Handmann, Jakob Walve, Szilvia Haide, David Austin, and Lee Bryant (abstract EGU24-18024). The presentation had an audience of around 150 persons. The conference attendance included a meeting with Douglas Wallace, Canada, who attended the same session.

7.5.2 The United Nations Decade endorsement and participation

The United Nations Decade of Ocean Science for Sustainable Development aims to support efforts to reverse the cycle of decline in ocean health and gather ocean stakeholders worldwide behind a common framework that ensures ocean science can fully support countries to achieve the 2030 Agenda for Sustainable Development. Individual projects are typically attached to endorsed Decade programmes within the Ocean Decade Implementation Plan.

The BOxHy project applied to the *Call for Decade Actions No. 05/2023 – Request for Endorsement for a Decade Project linked to an endorsed Decade Programme* in August 2023. The project applied under the Global Ocean Oxygen Decade (GOOD) Programme with the aim of contributing to the following Decade Outcomes:

Outcome 2: A healthy and resilient ocean where marine ecosystems are understood, protected, restored and managed.

Outcome 4: A predicted ocean where society understands and can respond to changing ocean conditions.

The GOOD Programme is led by the Global Ocean Oxygen Network of IOC-UNESCO (the Intergovernmental Oceanographic Commission of UNESCO). GOOD raises global awareness on ocean deoxygenation, provides knowledge for action and facilitates the development of climate change mitigation and adaptation strategies and solutions. These aim to ensure the continued provision of ecosystem services while also minimising impacts on the ocean economy through local, regional, and global efforts, including transdisciplinary research, innovative outreach, and ocean education and literacy. The programme is undertaking eight activities until 2030 and hosts further regional Decade actions. (UNESCO, 2024)

As an endorsed Decade Project, BOxHy ensured close and regular coordination and communication with the nominated Decade coordination structures. For example, BOxHy project members have participated in meetings with other Decade Actions endorsed by GOOD. Furthermore, the IOC-UNESCO representatives were kept informed regarding the dissemination of project results. The project members have also become involved in the following groups via the Ocean Decade Network: Integrated Ocean Carbon Research, Ocean Practices Network and Ocean-Climate Solutions and Innovations Network. The aim of these groups is to exchange knowledge, news and ideas around the group topics.

8 Conclusions

The BOxHy project proposes an innovative approach to tackling the environmental challenges related to internal nutrient loading and resultant anoxia and hypoxia in the Baltic Sea. While methods for remediaing anoxia and hypoxia in the Baltic Sea other than POI have been tested, POI has thus far only been implemented in smaller scale freshwater environments. Furthermore, while other studies have been conducted on utilising by-product oxygen from electrolysis for combatting anoxia and hypoxia, the conceptual design of the 400 MW integrated POI and offshore electrolysis plant is considered the first-of-its-kind, at least in the Baltic Sea region. Further conclusions are summarised by WP below:

In WP1, based on the evaluated technical, operational, socio-economic, and regulatory criteria and geographic scope of the study, the following three sites are concluded to be the most potential sites for a small-scale POI pilot in the Baltic Sea region:

1. Byfjorden, Uddevalla, Sweden:
   - Benefits from knowledge and experiences of the previous/ongoing reoxygenation projects and established monitoring programs.
   - Challenges include timeline conflict for BOxIn with the current project that is already running. Therefore, we would need to wait for the current project to conclude, and even so may have confounding variables. For this reason, the other two sites are seen as more suitable for the pilotting.
2. Säbyviken, Stockholm, Sweden:
   - Consistent summer anoxia and suitable land area in the marina.
   - Requires further evaluation of infrastructure and stakeholder engagement.
3. Skarpösundet, Stockholm, Sweden:
   - Deep central area with consistent summer anoxia.
   - Small oxygen demand and suitable site identified for oxygen storage.

While sourcing oxygen from electrolysers under development nearby these sites and from new-build electrolysers was studied, it is concluded that importing oxygen from a local supplier such as Linde is the most techno-economically feasible option for the pilot. The pilot project is estimated to take six years, including permitting, engineering, procurement, construction, installation, monitoring and decommissioning and further studies on pilot scale-up and integration of reoxygenation with electrolysis. When considering the full scope of the pilot, the cost is estimated in the range of 5-6 million Euros. Various funding calls and opportunities for covering the project budget were evaluated as part of BOxHy, and continue to be evaluated by Lhyfe.

In WP2, it is concluded that on sub-basin and basin-wide scales, the integration of electrolysis with POI is not only technically feasible but also non-negotiable considering the scales of oxygen demand in the Baltic Sea. The total POI demand to increase oxygen concentrations to 10 mg/l on the sub-basin and basin scales is calculated to be 57.16 +- 25.261 kilotonnes O_2/day, requiring nearly 20 GW of offshore electrolysis capacity. The current total electrolyser capacity under development in coastal sites around the Baltic Sea is insufficient to meet these demands and poses additional logistical challenges with long-distance oxygen transport offshore. On the other hand, there is a surplus of offshore wind capacity under development in the Baltic Sea region that could be used for electricity supply to offshore production. Overall, sub-basin BY29 stands out as the best opportunity region based on all evaluated criteria. This sub-basin already has sufficient coastal electrolyser capacity under development to theoretically meet its oxygen demand of 3902 ± 1919 tonnes per day. BY29 also boasts the highest combined capacity (25.4 GW) of planned offshore wind projects within 40 km of a 120 m isobath and has potential routes to market for hydrogen, with the most cost-effective transport option being feeding the produced hydrogen directly into the BHC via a sub-sea hydrogen pipeline. Besides, BY29, the other potential sub-basins of interest are BY10, BY32 and BY31.

In WP3, the economic implications and infrastuctural opportunities and challenges for POI integration with a 400 MW offshore electrolysis platform were evaluated. The additional costs for producing oxygen for POI and integrating POI with such a platform are 79 million Euros in capital expenditure and 2.17-2.73 million Euros per year in operational expenditure (depening on production rate). The largest additional CAPEX for POI integration is related to the additional equipment needed to produce pressurized oxygen. Additional OPEX is mainly due to the oxygen drying section and subsea inspection and maintenance of oxygen diffuser lines. The comparison of two case studies for electrolyser operation shows that higher production rates (with full electricity supply backup from the grid) are more economically favorable, reducing the unit cost of oxygen significantly. The resultant annual cost for providing reoxygenation as a service to the entire Baltic Sea is 367-612 million Euros, which compared to the current estimated annual economic loss of 5.6 billion Euros from direct and indirect losses due to the poor state of the Baltic Sea is a small price to pay. Regarding subsea architecture, the main challenges include the mounting procedure, flooding of oxygen diffuser lines, and the design pressure and material effects on pipelines. Environmental conditions, seabed composition, and existing industrial setups impact the hydrogen pipeline layout and operation strategy. Overall, hydrogen export via an integrated hydrogen network, such as the BHC, is seen as the favoured approach compared to direct hydrogen pipeline export to clients.

The stakeholder engagements conducted via WP4 indicate that the topic of reoxygenation as a service to the Baltic Sea coupled with the emerging renewable hydrogen economy has gained significant momentum across many different disciplines and forums. The BOxHy project helped to foster further thinking and collaboration on this topic among scientists, industrial actors, municipalities, private individuals and more via various communication channels, including dissemination events, presentations, the U.N. Ocean Decade Network, etc.. The next steps to continue the work presented in this report will be to implement and evaluate the results of the BOxIn onshore pilot project to provide a foundation for running an offshore platform pilot sustainably and effectively.

Public Data sets used

Data availability

Etopo2 data can be downloaded under https://sos.noaa.gov/catalog/datasets/etopo2-bathymetry/

Datasets to share:
Area: o2_maps_HELCOM_high_res_bathy_etopo2_volumes.nc

Volumes: Oxygen_data_volume.nc

Etopo2: etopo2.nc, National Geophysical Data Center, 2006. 2-minute Gridded Global Relief Data (ETOPO2) v2. National Geophysical Data Center, NOAA. doi:10.7289/V5J1012Q [03.04.2024]
Subbasin data as defined in Rolff et al 2022: BasinPolygons_V4/ BasinPolygons_V4.shp
The code for these computations will be shared as well to stay transparent – we have to upload the final versions on a server accessible to all (e.g. zenodo)

Data from the monitoring program of Svealands kustvattenvårdsförbund (SKVVF, www.skvvf.se), available through SMHI Shark database (https://www.smhi.se/data/oceanografi/datavardskap-oceanografi-och-marinbiologi), or SKVVF.

(The Swedish Maritime Administration) website:
https://geokatalog.sjofartsverket.se/kartvisarefyren/

Area maps on eniro.se: https://kartor.eniro.se/m/ebKIy

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Appendices

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Appendix 1. Literature review of anoxia-induced greenhouse gas effects

Patricia Handmann and Jakob Walve

Marine greenhouse gas emissions, biogeochemistry and low oxic conditions in relation to the Baltic Sea

In regions with poor ventilation and sluggish currents, oxygen concentrations can reach very low values which alter the ecosystem and biogeochemical cycles, subsequently leading to internal feedback on biogeochemical processes [Conley et al., 2002]. Oxic environments feature oxygen concentrations of larger than 2 ml/l O_2, hypoxic environments feature oxygen concentrations between 2 ml/l O_2 and 0 ml/l O_2, and anoxic environments do not feature oxygen at all or even contain hydrogen sulfides [Hofmann et al., 2011]. Low oxygen conditions (Oxygen Minimum Zones; OMZ) can be found in some regions in the tropical ocean, in the eastern tropical South and North Pacific, the eastern tropical South Atlantic, the Arabian Sea, and the Bay of Bengal [Wyrtki, 1962, Stramma et al., 2008, 2012], or in coastal regions [Tyson and Pearson, 1991], semi enclosed seas or fjords [Rabalais et al., 2010, De Brabandere et al., 2015, Breitburg et al., 2018, Malone and Newton, 2020, Dai et al., 2023]. Within OMZs, oxygen levels are too low for higher life and macrofauna. Moreover, the biogeochemical cycles in the water column and the sediment undergo profound change [Kamykowski and Zentara, 1991, Moore et al., 2013, Noffke, 2014, Watson et al., 2017, Kemena et al., 2019].
In the upper ocean, where sunlight penetrates (i.e., euphotic zone), organisms that can do photosynthesis use light energy and available nutrients to produce organic matter and oxygen. This organic matter (made up of carbohydrates, proteins, nucleic acids and lipids) is 95% constituted by the elements carbon (C), hydrogen (H), nitrogen (N), oxygen (O), phosphorous (P) and sulfur (S) [Moore et al., 2013]. The downward transport of this organic material as ”marine snow” in combination with oxygen-consuming remineralization leads to enhanced nutrient concentrations and decreased oxygen concentrations below the euphotic zone. Hence, the cycling and availability of nutrients in this region is largely influenced by biological activity. In order to assess how these biogeochemical cycles may be influenced by ocean deoxygenation, the structure of the dominant ecosystem and oxygen dynamics shaping these cycles must be well understood.

The biogeochemical processes influenced by low oxic conditions can differ strongly between different regions in the ocean, e.g. open ocean OMZ of different geographic regions, coastal ecosystems, or semi-enclosed seas. Of particular importance is if the low-oxygen zone is in contact with the sediment or not. Under hypoxic to anoxic conditions, sediment release of reduced, soluble chemical species is increased, including nutrients (internal loading), particularly phosphate (PO_4) (see section 1.1.5), ferrous iron (Fe(II)) as well as ammonium (NH_4) [Conley et al., 2002, Rapp et al., 2019, Resplandy et al., 2024]. This can fuel primary production in the euphotic zone, which in turn drives further organic matter settling and internal nutrient loading [Vahtera et al., 2007, Noffke, 2014, Hutchins and Capone, 2022]. The exact chemical environment associated with low-oxygen concentrations is dependent on the degree of severity of oxygen depletion and the length of exposure to the low-oxygen conditions [Rabalais et al., 2014].

Respiration

The process of **respiration** is fundamental for life and is based on the availability of high-redox-potential electron acceptors such as oxygen. Respiration usually degrades organic matter and releases carbon dioxide and inorganic nutrients (remineralization). When phytoplankton is formed or bacteria grow, organic carbon and nutrients are lost from the upper ocean layer through the settling (sedimentation) of organic matter to the ocean depth, the so-called biological pump. In the deep water or sediments, settled debris is then consumed by other microbes and, via the respiration process, partly remineralized back to inorganic forms.
Microorganisms such as certain bacteria or archaea can be found in hypoxic or anoxic environments, because they have the ability to use other electron acceptors than oxygen, such as nitrogen oxides (NO_x, nitrite (NO_2), nitrate (NO_3, denitrification, at $O_2 \leq\sim 5\ \mu$mol [Battye et al., 2017]), manganese oxides (Mn(IV), Mn^{+4}), ferric (III) nitrates and oxides

(Fe(III), Fe^{+3}), (organic) sulfur oxides (S, SO_x, sulfate reduction) and others [Richardson, 2000, Middelburg and Levin, 2009, Robinson, 2019]. In comparison to the upper euphotic surface layer where light penetrates, benthic environments are usually aphotic (no sunlight) and the abundance of organic matter is high, leading to a net consumption of oxygen; this can lead to anoxic conditions when oxygen consumption exceeds oxygen supply by currents or mixing. The microorganisms that decompose the organic matter also produce CO_2, which leads to an increase in carbonic acid concentration in the water, especially when excess organic matter is present due to, e.g., eutrophication. This increases the water acidity (pH decreases), which presents a major threat to calcifying organisms [Wallace et al., 2014]. In the following sections, we shortly summarize the key marine cycles of carbon, nitrogen, phosphorus, iron, and sulfur in order to highlight how they are affected by lox oxygen levels. For further reading, review articles are cited in the beginning of each element cycle subsection.

Carbon cycle

Carbon dioxide CO_2 is the dominant anthropogenic greenhouse gas (GHG) driving anthropogenic climate change, representing $\sim$ 77% of the total anthropogenic GHG emissions overall [Masson-Delmotte and , eds.]. The ocean reservoir holds $\sim$50 times the amount of CO_2 as the atmosphere reservoir [Solomon et al., 2007], implying that the tiniest change in the ocean CO_2 inventory can have drastic repercussions for the atmosphere. The imposition of anthropogenic CO_2 emissions to the atmosphere disturbs a delicate ocean-air equilibrium developed since the last glaciation period that facilitates net oceanic CO_2 absorption [Sabine et al., 2004]. As CO_2 is continuously cycled between the atmosphere, oceans and land biosphere and its net removal from the atmosphere involves a range of processes with different time scales it does not have defined specific lifetime [Solomon et al., 2007]. An extensive review of the marine carbon cycle can be found in Bolin and Fung [1992], Millero [2007], DeVries [2022] or Siegel et al. [2023].
Through the air-sea interface, the ocean continually exchanges carbon with the atmosphere. Additionally, biological activity pumps carbon into the ocean. The carbon is stored as inorganic and organic forms in various chemical states depending on air-sea temperature differences, solubility, chemistry (temperature, salinity, alkalinity of the water, etc.), and biological activity [Lauderdale et al., 2016]. Respiration and

remineralization, depending on where in the water column it takes place, sequesters CO_2 stemming from the atmosphere on timescales of months to millennia [Siegel et al., 2023]. In general terms, the ocean takes up CO_2 in the mid-latitudes, emits it in the tropics and features small fluxes in the high latitudes [Gruber et al., 2009]. Hence, as part of the global climate system, the ocean plays a critical role in the control of the atmospheric CO_2 concentration, and thereby Earth's climate, on timescales of tens to thousands of years. It absorbs about one third of the anthropogenic CO_2 emissions [Masson-Delmotte and , eds.] and stores it in both the upper and deep ocean. This additional carbon uptake results in ocean acidification, reducing the chemical buffering capacity [Sabine et al., 2004]. This reduced storage capacity paired with the consequences of a warming climate, ocean warming and changes in ocean circulation and biology will ultimately decrease the ability of the ocean to take up CO_2 in the future [Joos et al., 1999, Gruber et al., 2023].

Even if shelf regions and marginal and coastal seas only account for a small part of the ocean surface, they play a crucial role for global marine primary production. Their biological activity sequesters large amounts of CO_2 and hence plays a major role in the marine carbon system. The exact relationship between the net production and mineralization of organic carbon determines whether a region acts as a sink or source of CO_2 to the atmosphere. When mineralization dominates over biological production, CO_2 is emitted; if the contrary holds, CO_2 is taken up [Wesslander et al., 2010].

In marine areas with OMZ, featuring **low oxic to anoxic** conditions, CO_2 is stored due to the high productivity of the surface waters and sinking of organic matter to deeper water. Once this water upwells and reaches the surface, it will represent a major source of CO_2 ocean-air emission [Borges, 2011, Reusch et al., 2018]. Overall, the exact influence of anoxia and hypoxia on the ocean-air CO_2 fluxes is hard to estimate. In a case of high organic matter input, the enhancement of denitrification at low oxygen levels will increase the production of CO_2 and could lead to increased ocean-air fluxes [Borges, 2011]. On the other hand, in the Baltic Sea, anoxic sediments are relatively rich in organic carbon [Struck et al., 2000, Winogradow and Pempkowiak, 2014, Nilsson et al., 2019]. This indicates that OMZ in this region are better carbon sinks. However, the overall influence on the GHG budget may be offset by enhanced production of methane (section 1.2.1) and nitrogen oxide (section 1.3) in anoxic regions [Resplandy et al., 2024].

Before industrialization, the **Baltic Sea** was thought to be a net source of CO_2 to the atmosphere, due to large input of (mainly dissolved) organic matter from forests and bogs in the drainage basin. With anthropogenic CO_2 emissions and nutrient-driven eutrophication, it has been driven towards a net CO_2 sink featuring strong seasonal variability. Current studies disagree on the overall role of the Baltic Sea as a source or sink of CO_2. Observations show that the Bothnian Bay, the East Gotland Sea as well as the Bornholm Sea represent net CO_2 sources for the atmosphere, whereas the Bothnian Sea and the Kattegat were found to act as net CO_2 sinks [Wesslander et al., 2010, Löffler et al., 2012]. Some studies have found the central basin of the Baltic to be a net CO_2 sink [Schneider et al., 2014, Gustafsson et al., 2014] whilst others have described the entire Baltic as a net source [Kulinski and Pempkowiak, 2011].Eutrophication may have a dampening effect on the Baltic Sea surface water acidification and, at the same time, may have increased seasonal pH variability (low in winter, high in summer) [Omstedt et al., 2009].

Methane

Methane (CH_4) is one of the most abundant carbon compounds on earth and a potent GHG with a global warming potential of ∼22 times that of CO_2 over 100 years [Shine et al., 2005, Masson-Delmotte and , eds.]. Overall aquatic ecosystems contribute ∼ 53%, with the ocean only providing 2% - 10% [Cicerone and Oremland, 1988, Judd et al., 2002] of the of the total global anthropogenic CH_4 emissions from anthropogenic and natural sources. Even though estuaries and shelf areas only represent a small portion of the world ocean, they contribute about 75% of the total oceanic CH_4 emissions [Bange et al., 1994]. Due to coastal urbanization, increasing nutrient pollution and the warming climate, total aquatic CH_4 emissions are expected to increase [Rosentreter et al., 2021]. CH_4 is produced through either thermochemical breakdown of organic matter in sediments or through biological processes, such as methanogenesis in anoxic water (anoxic fermentation of organic matter). In-depth information about the CH_4 cycle can be found in Canfield et al. [2005], Reeburgh [2007] or Whiticar [2020].

Oceanic CH_4 usually remains at close to equilibrium with the atmosphere. The majority of CH_4 is likely to form in anoxic microzones (e.g., fecal pellets, detritus, zooplankton guts) in highly productive areas, especially within estuaries and coastal areas. However, CH_4 supersaturation in oxygenated surface waters (the ”marine methane paradox”) may also be caused by aerobic methylphosphonate decomposition. Shallow near-shore environments, where CH_4 is released from the seafloor and can escape to the atmosphere before oxidation, dominate the global flux to the atmosphere [Weber et al., 2019]. There are three main pathways by which CH_4 can be released via ocean-air interactions: ebullition (of gas bubbles), diffusion, and plant-mediated transport. The rate of CH_4 production in sediments or algal mats in relation to the rate of oxidation, as well as its solubility in the water

(as a function of temperature and salinity), determine the amount of ocean-air fluxes [Lundevall-Zara et al., 2021].

In **anoxic environments**, CH_4 is formed by archaea through the splitting of acetate with hydrogen (CH_3COO) and the reduction of CO_2 by hydrogen. The produced CH_4 accumulates in the deep surface sediments; as it diffuses upward, this can facilitate the release of sulfides to the overlying water column through CH_4 bubbles [Maltby et al., 2016]. In coastal upwelling regions, linked to high primary production and open ocean OMZ, CH_4-enriched subsurface waters emerge to the surface and release CH_4 to the atmosphere [Kock et al., 2008].

In the **Baltic Sea** context it was found that, apart from the water and air temperature, floating algal organic matter and sediment organic content are important controlling factors for CH_4 emissions from coastal regions [Lundevall-Zara et al., 2021]. There is a steep dissolved CH_4 gradient from the deep, saline central Baltic Sea to the surface, with the amount of dissolved CH_4 decreasing. The strongest CH_4 oxidation was found at the oxic-anoxic transition zone [Schmale et al., 2012]. The same holds if a major Baltic inflow event introduces oxygen-rich saline water to the former anoxic bottom water, forming a second transition zone [Schmale et al., 2016]. Under stable conditions, the shallow, less-saline coastal regions are expected to feature higher CH_4 emissions [Scranton et al., 1993, Bange et al., 1994] than the deeper saline regions of the Baltic Sea [Schmale et al., 2012]. However, if stratification breaks due to, e.g., upwelling, substantial amounts of CH_4 could mix from the anoxic bottom water into the upper water column and then released to the atmosphere

[Scranton et al., 1993, Gülzow et al., 2013]. Overall, the Baltic Sea has been found to be a source for CH_4 to the atmosphere throughout the year, with predictions estimating this situation lasting even under a high atmospheric CH_4 scenario [Bange et al., 1994]. Observations have shown that seasonal pycnocline stratification facilitates the formation of CH_4 reservoirs in the Gulf of Finland and the Bornholm Basin. Once this deeper water is mixed to the surface in autumn or winter, CH_4 emissions from these regions to the atmosphere subsequently increase. In shallower regions like the Mecklenburg Bight, the equilibrium between sedimentary production and consumption in combination with the solubility and winds mixing the water column could further impact the amount of CH_4 emissions. Regions with a permanent stratification on the other hand, like the Baltic proper, do not feature such strong CH_4 emissions to the atmosphere [Gülzow et al., 2013].

Nitrogen cycle

Nitrogen gas (N_2) is the most abundant gas in our atmosphere (78%) but it is not available to most life in its gaseous N_2 form. The ocean contributes about 16-33 % of the global atmospheric N_2O pool [Nevison et al., 2003, Naqvi et al., 2010, Myllykangas et al., 2017]. Its oxidized form, nitrous oxide (N_2O), is a potent greenhouse gas featuring ~290 times the global warming potential of a CO_2 molecule within 100 years [Shine et al., 2005]. For extensive review of the marine nitrogen cycle, please see Capone et al. [2008], Hansell and Carlson [2014], Battye et al. [2017], Pajares and Ramos [2019], Zehr and Capone [2021] or Hutchins and Capone [2022].
In the ocean, nitrogen is present in different oxidation states varying from ammonium (NH^+_4 ; electron donor) to nitrate (NO^-_3 ; electron acceptor), where microorganisms mediate and change the concentrations of the different nitrogen compounds. Most plants and microbes need biologically available (”fixed”) forms of nitrogen, including in the marine environment nitrate ($NO3^-$), nitrite (NO^-_2) and ammonium (NH^+_4), where “reduced” nitrogen compounds (e.g., NH^+_4) are easier for most microbes to use than “oxidized” nitrogen ($NO3^-$). Fixed nitrogen often limits marine primary production as the ”proximate limiting nutrient”, thereby regulating the strength of the biological carbon pump linked to the oceanic uptake of atmospheric CO_2 [Gruber and Galloway, 2008, Pajares and Ramos, 2019]. In the upper 100 m within the euphotic layer, dissolved N_2 gas is fixed by cyanobacteria or heterotrophic bacteria through ”nitrogen fixation” to NH^+_4 which is assimilated into organic matter nearly as quickly as produced. $NO3^-$ and NO^-_2 can also be assimilated by some bacteria. When organic matter is decomposed, NH^+_4 , particulate organic nitrogen (PON), as well as dissolved organic nitrogen (DON), are released [Lønborg and Markager, 2021]. In the presence of oxygen in the aphotic zone, NH^+_4 (ammonium) in turn is converted to NO^-_2 (nitrite) and then oxidized to biologically available $NO3^-$ during the “nitrification” process, highlighting the critical role of oxygen as well as its absence in OMZ. The PON and DON is in turn ”remineralized” by bacteria to NH^+_4
.
The two processes ”denitrification” and ”anammox” can remove fixed nitrogen, recycling fixed nitrogen back to N_2 and thereby constituting major nitrogen sinks[Codispoti et al., 2001]. During denitrification within **low oxic to anoxic zones** ($O2 \leq 5\mu$mol), reactive nitrate ($NO3^-$) is reduced in a series of chemical reactions to nitrite (NO^-_2), nitric oxide (NO) and finally to GHG N_2 and water (H_2O). Similarly under low oxic conditions, via the

"dissimilatory nitrate reduction to ammonium" (DNRA) process, $NO3^-$ can be respired during organic matter remineralization instead of oxygen and be reduced to NO^-_2 and finally to NH^+_4 . Additionally, during "anaerobic ammonium oxidation" (anammox), NO^-_2 and NH^+_4 are directly converted into nitrogen (N_2) and water. In long-term anoxic sediments, denitrification is decreased or completely suppressed due to lack of $NO3^-$ [Rysgaard et al., 1994] (otherwise produced by nitrification in oxic parts of the sediment), while in the transition zone between anoxic and oxic water regions, denitrification can be enhanced.

The majority of in-situ GHG N_2O is produced through sediment denitrification; hence, shallow coastal environments like estuaries, intertidal and vegetated environments emit small quantities of N_2O to the atmosphere. Decreased oxygen concentrations are expected to increase N_2O emissions linked to denitrification, following changes in marine vegetation and the pollution of coastal waters [Murray et al., 2015]. Additionally, changes in denitrification also affect the capacity of the ocean to sequester atmospheric CO_2 via the biological pump [Codispoti et al., 2001]. The amount of lost fixed nitrogen from the biosphere through these two processes is linked to the severity of the low oxic or anoxic conditions and strongly impacts the marine nitrogen budget and N_2 emissions. With growing predicted ocean oxygen loss, the volume of water with occurring denitrification and anammox can lead to an increased marine nitrogen loss and increased out-gassing of nitrogen-based GHG [Laffoley and Baxter, 2019].

A strong redoxcline exists in the Baltic Sea between the oxic surface and anoxic, sulfidic deep water. In the Baltic proper nitrification was found to be strongest near the oxic-anoxic interface and is spatially separated from processes reducing nitrate to N_2. Chemolithotrophic denitrification, producing N_2 is limited to water layers featuring nitrite or nitrate and sulfide at the same time. When deep, ammonium rich water mixes with oxygenated water, nitrification occurs, when anoxic conditions re-establish denitrification re-installs. Sedimentary denitrification at shallower oxic areas is lower, but relatively constant in time [Hietanen et al., 2012]. Here, sulfide was often found to be the only electron donor for respiration, and denitrification is driven in some situations by organic matter alone [Dalsgaard et al., 2013].

Overall, one third of the total natural N_2O emissions originate from the ocean [ArevaloMartinez et al., 2015, Battye et al., 2017, Pajares and Ramos, 2019]. Hot spots of these emissions are found in low-oxic upwelling zones at the edge of hypoxic to suboxic conditions and within some coastal areas [Nevison et al., 1995, Codispoti et al., 2001, Nevison et al., 2004, Naqvi et al., 2010, Walker et al., 2010, Orif et al., 2023, Resplandy et al., 2024]. Denitrification (under suboxic conditions) and nitrification (under oxic conditions) contribute to decreased oxygen concentrations in the water column and can ultimately amplify global warming due to the production of N_2O [Gruber et al., 2008].

Phosphorus cycle

In the following, we shortly sum the marine **phosphorus** (P) cycle; for an in depth review, see Paytan and McLaughlin [2007] or [Mackey and Paytan, 2009].

Phosphorus (P) is essential to all life, it is, e.g., present in DNA, RNA and ATP molecules and plays a crucial role for photosynthesis (orthophosphate (PO_4^{3-}, HPO_4^{2-})). In contrast to nitrogen, phosphorus is not abundant in the atmospheric reservoir but is naturally

supplied by continental weathering and run off (i.e., as the 11^{th} most abundant mineral) and atmospheric deposition. Due to this supply, it is seen as the ultimate limiting macronutrient (ULM) over geologic time scales [Tyrrell, 1999]. The P turn-over time in the surface ocean has been found to be 1-3 years, whereas in the deep ocean its turn-over time is similar to the ocean mixing time of ∼1500 years. Deposition and burial in marine sediment is the dominant oceanic sink for phosphorus in the form of particulate organic matter or P associated with iron oxyhydroxides (and other metal oxides, orthophosphate bound to e.g. Ca^{2+}, Mg^{2+}, Fe^{2+}, Fe^{3+}, and Al^{3+}) or hydroxides. Hence, marine sediments are the main reservoir in the oceanic phosphorus cycle. Nevertheless, most P in both organic matter and metal oxides deposited at the sediment surface is remineralized and released back to the water and only a smaller fraction is permanently buried. Under oxic conditions, organic P is remineralized to iron-bound P or inorganic poly-phosphorus [Diaz et al., 2012].
Under **low oxic to anoxic conditions**, phosphorus stored in the sediment can be released through dissolution mediated by two redox reactions. Phosphate (PO_4) and iron (Fe(II)) can be liberated by microbes from iron oxyhydroxides (FeO(OH)) and ferric phosphate (strengite, $FePO_4 2H_2O$) under reducing conditions [Jensen et al., 1995, Conley et al., 2009b]. Alternatively, sulfur-reducing bacteria can reduce iron phosphate ($FePO_4$) to iron sulfide (Fe(II)S), sulfur (S) and PO_4^{3-} [Mackey and Paytan, 2009, Carstensen et al., 2014b, Wilfert et al., 2020]. Regardless of the specific process, the amount of phosphorus retained in the sediment decreases under low oxic to anoxic conditions [Mortimer, 1941]. When this dissolved inorganic P reaches the surface waters, phytoplankton growth can be stimulated, enhancing primary production and acting as a positive feedback on eutrophication, further increasing oxygen loss from the system [Puttonen, 2017].
In the **Baltic Sea** environment, especially in the salt-stratified part of the Baltic proper, eutrophication worsens due to internal phosphorus release from the anoxic sediment [Conley et al., 2009a, Stigebrandt and Andersson, 2020, Kouts et al., 2021]. Here, the oxygen dynamics strongly dictate the internal release of P to the water column which ultimately further fuels eutrophication [Gustafsson, 2010, Puttonen, 2017]. The amount of methane (CH_4) and N_2O ocean-air emissions has been shown to be strongly influenced by the amount of vegetation and corresponding water biogeochemistry linked to eutrophication, as discussed in section 1.3 and 1.2.1. Hence, the internal loading of P in the Baltic Sea has an indirect impact on its total emissions of GHG to the atmosphere. The specific dynamics and overall impact still needs to be assessed in future work.

Hydrogen sulfides

Sulfur is released from rocks and subsequently reaches the ocean, mainly through run off (see reviews of sulfur cycle Jørgensen and Kasten [2006], Sievert et al. [2007], Jasinska et al. [2012] or Callbeck et al. [2021]).
Marine sediment is a major sulfur (S) pool and the S cycle is pronounced in waters with direct contact to the bottom sediment. Sulfur is assimilated into amino acids by microbes and plants which is then released when organic matter is remineralized under anoxic conditions. Specialized bacteria respire S or sulfate (SO_4) and release toxic hydrogen sulfide H_2S within the sediment [Hansen et al., 1978]. In the presence of dissolved oxygen, S is recycled back to sulfate (SO_x) by sulfide-oxidizing bacteria, with a small amount removed by pyrite formation.

If the organic matter input is largely increased due to highly eutrophic conditions or if **anoxic conditions** prevail (≤ 0.05 mg/L [Rabalais et al., 2007]), sulfate reduction at the water–sediment interface is increased and resultant enhanced sulfide production can overrun the bacterial capacity of removal. This ultimately leads to sulfide accumulation in the sediment and subsequently to its release to the water column. Sulfide is released via passive molecular diffusion which fuels a further decrease of oxygen concentrations and the reduction of nitrate (NO_3) to nitrogen gas (N_2), nitrite (NO_2) and ammonium (NH_4). This in turn increases the anammox reaction, producing more nitrogen gas and fueling nitrification which consumes even more oxygen. Furthermore, it promotes the release of phosphorous to the water column from its iron-bound form, further fueling the production of organic matter in the upper water column. Under suboxic conditions within the sediment, first the electron acceptors NO_x, Mn, Fe are respired since oxygen is unavailable. Below this zone, sulfate reduction is the dominant process for organic matter decomposition, extending meters down into the sediment. When large amounts of H_2S accumulate, euxinic zones form [Krapf et al., 2022].

Summary

Shallow coastal areas, e.g., continental shelves, estuaries, deltas, fjords and lagoons, can be areas of high sea-air emissions of greenhouse gases carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) [Bange, 2006, Resplandy et al., 2024]. All three count as Longlived greenhouse gases (LLGHGs) because they are chemically stable and persist in the atmosphere over time scales of a decade to centuries or longer. Hence, their emissions have a long-term influence on climate [Solomon et al., 2007]. Literature on the European shelf seas shows that systems with freshwater influence emit larger amounts of N_2O compared to ”normal” saline shelf waters. This makes the European coastal water a net source of climate-impacting N_2O coming majorly from estuarine/river systems, contributing up to 26% of global oceanic emissions. European fjords and estuarine systems also represent a net source of CH_4 to the atmosphere, contributing significantly to its global oceanic emissions [Bonaglia et al., 2022]. Total emissions of CH_4 and N_2O are dependent on i) the degree of global warming and respective warming of the ocean as well as on ii) future nutrient pollution and the respective severity of eutrophication and deoxygenation of these coastal zones [Bange, 2006, Resplandy et al., 2024]. Coastal upwelling regions in the global ocean, featuring a shallow oxygen deficient zone, represent hot spots of N_2O production and significant emissions. With future scenarios predicting expansion end intensification of these zones, an increase in N_2O emissions from the ocean is equally expected [Naqvi et al., 2010].

[Vigouroux and Destouni, 2022] reviewed 832 studies related to coastal eutrophication in the Baltic Sea and found that only a few studies overall investigate the sources of nutrient loads and possible solutions for their mitigation, as well as pressures and resulting impacts together. Hence, due to the very complex nature of the controlling processes, the links between eutrophication, relative changes in biogeochemical cycles and resulting sea-air fluxes of toxins and greenhouse gasses are not completely understood nor comprehensively researched.

Even though internal loading of nutrients like phosphorous has no direct effect on greenhouse gas emissions, the indirect influence on eutrophication and changes in the controlling biogeochemistry can lead to enhanced emissions of CH_4 and N_2O. Corresponding harmful algal blooms can be associated with the production and diffusion

of marine toxins in the atmosphere which are negatively impacting human and aquatic ecosystem health[MedinaPerez et al., 2020].
Large parts of the **Baltic Sea** have been intermittently hypoxic since 1900 until today. With increasing populations and the expansion and intensification of the agricultural and forest industry since the 1940's, enhanced inputs of nutrients and organic matter have contributed to a growing volume of hypoxic, anoxic and euxinic water in the region [Zill´en et al., 2008]. Even after nutrient run-off management and limits were implemented, deoxygenation of the Baltic characterized by increasing hypoxic and anoxic volumes [Hansson and Viktorsson, 2023] continues to increase. Sporadic major Baltic inflow events (MBI), which bring oxygenated, fresh water from the North Sea to the deep Baltic, do not suffice in maintaining oxic conditions throughout the Baltic [Gustafsson and Stigebrandt, 2007, Rolff et al., 2022] and, by nature, are spontaneous and hence not a reliable solution to reinstall good ecosystem health in the lox oxic regions of the Baltic. The variable spatial distribution of oxygen concentrations majorly influences CH_4 [Schmale et al., 2012] and N_2O [Hietanen et al., 2012] concentrations in the water column [Myllykangas et al., 2017]. Under oxic conditions, water quality is maintained as phosphate concentrations substantially decrease, ammonium concentrations remain low and nitrate concentrations increase in the deep, sub-halocline, water. Conversely, during anoxic conditions nitrate is depleted and phosphate and ammonium concentrations accumulate in the deep water. Future climate scenarios feature increasing water temperatures, enhanced freshwater inputs, additional nutrient loads, and stronger thermal stratification; these conditions will lead to further decrease of oxygen concentrations and stronger internal loading of phosphorus in the region [The BACC author team, 2008, Gustafsson, 2010, Carstensen et al., 2014a]. Furthermore, upwelling events of deep water from the Baltic proper at the Swedish coast can lead to additional increases in CO_2 and CH_4 sea-air fluxes [Humborg et al., 2019] which will contribute further oceanic deoxygenation and the climate crisis.

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Appendix 2. Preliminary risk assessment of linear diffuser equipment to fit new marine environment

1. Risk Assesment

"The impacts of these so-called harmful algal blooms (HABs) amount to approximately 8 $billion/yr globally, due to mass mortalities in finfish, harvesting bans preventing the sale of shellfish that have accu- mulated unsafe levels of HAB phycotoxins and unavoided human health costs. […] pre-emptive, ecosystem-based approaches are preferable to reactive physical, chemical or microbiological control measures aiming to remove or neutralise HABs and their phycotxins." Brown et al., 2020

The intended environmental impact of the proposed artificial oxygenation using a linear diffuser system is to increase the oxygen content of the respective water body from anoxic/hypoxic to oxic conditions by pure oxygen injection (POI). In the Baltic Sea environment this is inevitably linked to the significant reduction of the internal phosphorus loading from sediment which is driving the "vicious cycle" of eutrophication in the Baltic Sea. Eutrophication is a serious problem and all risks evaluated in the following should always be valued relative to the risks of further deterioration of the Baltic Sea environment. The increase of oxygen and reduction of phosphorus is expected to greatly improve the water quality and impact local and regional ecosystem functioning, including the present microbial communities, spawning and distribution of fish (e.g. Cod), the local recreational values and the overall greenhouse gas production and emissions of the water body (methane and nitrous oxide). This will have a positive impact on the economic value of the water body and the properties around it. The first pilot (within the pilot site) before upscaling the system long-term environmental effects of artificial oxygenation need to be monitored. In October 2021, HELCOM published the Guidelines for Sea-Based Measures to Manage Internal Nutrient Reserves in the Baltic Sea Region. Following these guidelines, artificial oxygenation is a viable measure with strong contribution and relevance to HELCOM's Baltic Sea Action Plan as well as the UN SDG-goals 7,13,14 and 17.

As research shows, the deterioration of the Baltic Sea, due to eutrophication and oxygen loss is already impacting local economy on the scale of billions (10^9) of Euros. When coupled to green hydrogen production, artificial reoxygenation have the double advantage of improving the state of the ecosystem and decarbonization of transport and industry through the produced hydrogen.

Oxygenation can have a positive influence on biogeochemical processes in the sediment such as the coupled iron-phosphorus cycling, oxidization of previously toxic reduced sulphur compounds and an increase of the coupled nitrification-denitrification, i.e. permanently removing of nitrogen into the atmosphere (nitrogen cycle), counteracting eutrophication (Rantajaervi et al. 2012). The desired results would include recolonization of the bottom habitat by animals, which would further improve the cycling of iron in sediments (Boyle et al. 2014) and enhance denitrification (**Appendix 1**). For further reading an elaborated risk assessment can be found as well in Rantajaervi et al. 2012 in the final report of the PROPPEN project and at Eriksson et al., 2013 for the BOX-WIN project. One has to keep in mind that a significant number of risks defined for the PROPPEN and the BOX WIN project are directly linked to the method of aeration of the deep water through pumping of aerated winter mixed layer water. These risks are non-existing or low due to the technique of pure oxygen injection through a linear diffuser proposed, here.

There are several environmental, technical, and socio-economic risks related to artificial oxygenation.

- The **environmental risks** include all potential unwanted changes happening during or post artificial oxygenation within the ecosystem and range from biogeochemical to physical changes.
- The **technical risks** are related to design, construction, installation, operation, maintenance and decommissioning of a pilot experiment. The risks depend on the nature of the system, e.g. a pure oxygenation injection system without coupling to hydrogen production onshore, or an oxygenation system integrated into a hydrogen producing offshore platform.
- The **socio-economic risks** are rather centred around public acceptance and permitting processes and can involve major costs and time-lags if not accounted for.

Some of the below collected risks are recognized, but the exact probability is hard to predict. Studying and analysing the exact impact of artificial oxygenation is one of the objectives of a following fjord-scale pilot implementation project as typically risks increase according to physical dimensions of the water body and the infrastructure implemented.

1.1. Environmental Risks

To reduce, determine and monitor most environmental risks, a solid pre-oxygenation hydrographic, biogeochemical and ecosystem monitoring to hold baseline knowledge about a system is crucial. During the active phase of artificial oxygenation, close spatial and temporal monitoring of water quality changes and the evaluation of changes and of the oxygen input rate are key to monitor the achievement of the objectives of reoxygenation and to detect and prevent unwanted changes to the system. Additional measures are collected in the prevention of risk or the planned mitigation actions columns of the following table. The effective probability of the environmental risks is up to date unknown, is dependent on the actual installation site and must be subject to analysis of the monitoring during the implementation of the actual fjord-scale pilot experiment.

In the case of the Baltic Sea, some risks concerning the sediment surface oxygenation and following changes in biogeochemical cycles could be imagined dependent on the actual sediment structure and material. The increase of the oxygen concentration in the bottom waters does not forcibly have to lead to a decreased release of nutrients from the sediment such as phosphorus through sufficiently high rates of iron oxidation following the formation of iron sulphides instead and blocking of the iron cycle (Caraco et al. 1989, Caraco et al. 1993, Gaechter et al. 2003). In regions like the Gulf of Finland, even modest oxygen concentrations do not suffice in summer to keep the sediment oxidized, though experiments increasing oxygen saturation in the bottom water of Lännerstasundet showed that the ventilation removed hydrogen sulfide and decreased the sub-pycnocline water pools of phosphorus and ammonium. In another Fjord, Sandöfjärden, ventilation did not prevent formation of anoxia and the release of nutrients probably due to insufficient oxygen supply during the experiment (Lehtoranta et al. 2022). The exact reaction of the sediment to artificial oxygenation will be dependent on the sediment structure, with either high iron-phosphorous stored or high organic matter sedimentation (Lehtoranta et al. 2009). In general, the penetration of oxygen into the sediment is based on diffusion which is a relatively slow process compared to the oxygen input – hence a lag time between the onset of artificial oxygenation and reduction of phosphorus loading will have to be accounted for. Additionally, the supply of oxygen must be high enough to induce a sufficiently large transport through the diffusive layer (Rantajaervi et al. 2012).

Table 1. Environmental risk collection

Type		Risk title	consequence	Prevention of risk	planned mitigation actions
Environmental risk		Disturbance or failure in species reproduction (regional, COD, Mackerel, Herring)	- negative influence or AO on species reproduction due to - changed oxygen conditions - changed biogeochemical cycles - decrease in fisheries - decrease of economic value of waters	- Long-term base data available - Previous high frequency monitoring of the ecosystem - Hoh high is the sensitivity of the species to changes in the biogeochemical parameters	- Monitoring to understand the reasons and environmental feedbacks on reoxygenation - Which nutrients are released - Increase of oxygen supply - If persistent: - Interruption of experiment
		Changes in nutrient ratios/cycles	- Increased release of nutrients to water column from sediment - e.g. accumulation of nitrates, and less removal by denitrification than expected	- Long-term base data available - Previous high frequency monitoring of the interesting parameters	- Monitoring to understand the reasons and environmental feedbacks on reoxygenation - Which nutrients are released - Increase of oxygen supply
			- temporary Increase of eutrophication		- Increase of oxygen supply - If persistent: - Interruption of experiment - Monitoring to understand the reasons and environmental feedbacks on reoxygenation
			- Continuous Increase of eutrophication		- Interruption of experiment - Monitoring to understand the reasons and environmental feedbacks on reoxygenation
		Harmful interaction with seawater pulses	- eutrophication gets worse - harmful substances get released - fish stocks are negatively impacted - An anoxic water pulse may also impede all oxygenation efforts		- Interruption of experiment - Monitoring to understand the reasons and environmental feedbacks on reoxygenation
		Bottom stays anoxic	- AO has no effect at all - no change in - ecosystem - biogeochemistry - oxygenation can be stopped - oxygen volume not sufficient - increase oxygen input		- augmentation of oxygen input - biogeochemical measurements to understand the reason for the increase in oxygen demand
		Sediment stays anoxic			
		Release of toxic substances from polluted sediment or WW1/WW2 munition	- negative change in ecosystem - intoxication of fisheries - danger to the public	- Thorough study of contaminants and pollutants in water column and sediment - Screening for WW munition	- Interruption of experiment - Adaptation of reoxygenation depth
	Hydrographical risks	Physical changes of deep waters – temperature - warming	- changes in stratification - changes in local mixing - changes in local species distribution - changes in anoxic and hypoxic area distribution - need for reevaluation of physical state through observations	- Adaptation of bubble size to water body system parameters (depth of anoxia, MLD) - Choice of oxygenation technology adapted to keep to a strict minimum	- Dependent on the severity of warming - Interruption of experiment - Adaptation of bubble sizes to future conditions
		Physical changes of deep waters - salinity			
		Physical changes of deep waters - currents			
		Physical changes of deep waters - mixing			

1.2. Technical Risks

The proposed pilot installation will rely almost exclusively on known technology, either from the freshwater environment implementation of the proposed technology or from proven designs from the maritime and offshore sector. Completely new and unknown technology will be avoided to minimize the risk of pilot installation failure.

The technical risks listed in **table 2** are not beyond the risks already resolved by the offshore, maritime and wind power industry. To counter those risks related to oxygen handling during transport and operation, operators will have to be trained to deal with O_2. Project delays due to the delay in installation of infrastructure must be mitigated trough a thorough preparation of permitting and preparation of the actual infrastructure construction. These delays can either prolong the project or increase the costs significantly or both. The Work program and preparation has to be adjusted accordingly. According to the risk analysis presented in the PROPPEN project report, general difficulties in site setup, or damages or the infrastructure during assembly can lead to shorter delays and can be fixed with a medium effort. On the other hand, major delays can be related to delays and concerns during the permitting and implementation process due to local stakeholders, landowners and permitting agencies, which can inhibit the project implementation completely.

Table 2 Technical risk collection

Type		Risk title	consequence	Probability of failure	Severity category	Frequency category	Prevention of risk	Planned mitigation actions
Technical risk	Oxygen related not flammable/ essential for combustion / may cause increased risk of ignition and rapid combustion/ high O2 concentration can cause burning at explosive rates	- Explosive/flammable risk due to presence of oxygen. (storage, piping, compressor)	- Enriched O2 atmosphere (leaks) can induce fires because UEL (upper explosive limit) rises, and ignition temperatures are lower - In an oxygen system - oxidizer is oxygen and the system fire hazard increases with increasing concentration, pressure, temperature, and flowrate - flammable fuels are the materials of construction (metals, non-metals, and lubricants) or potential contaminants like particulates, oils, or greases. - ignition sources include particle impact, compression heating, frictional heating, and others	medium	high	medium	- surveillance of structure - ***Oxidizer***: oxygen conditions of service with respect to fluid purity, composition, gas velocity, pressure, temperature, and dew point - **Fuel:** conscious selection of metal and non-metal components (burn resistance) - **Potential ignition mechanisms:** gas velocities, sites that could contribute to particle impact ignition, frictional heating, or rapid-opening components such as valves (producing adiabatic compression heating) must be optimized to oxygenation system demands - the AO open air on land system had to be sufficiently protected from weather and	- Visual and sounding alarm - emergency stop at any suspicious activity

							other environmental influences (storms, thunder, waves etc.) - regular maintenance - hazardous area classification - System must be degreased - If system in **closed area/unit**, requires (<23% of O2): - air fans for ventilation - O2 detectors - precise study of O2 dispersion	
		- piping specific damages and explosive risk	- frost damage - atmospheric corrosion - ignition through lightning - ignition static electricity - Damage from casual surface construction - shifting due to unstable soil, - - backfill damage to the external surface of pipe or the coating - damage from aboveground loads such as vehicles or equipment moving over the path of the pipeline. - damage from anchoring ships or fishing gear	medium	large	medium	- piping and pipeline routed as far away from other equipment containing hazardous fluids in oxygen environment - Oxygen lines should not be exposed to external forces causing failure/dangerous situation (hot gas or steam vents, vibration from external sources, leaking oil dripping onto the line) - adequately bury pipeline to protect from external damages - aboveground carbon steel piping painted to an approved specification to protect against atmospheric corrosion - aboveground piping and pipelines shall have electrical continuity across all connections, except insulating joints (could be either flanges or monobloc) and shall be earthed at suitable intervals - porous pipe in the water - anchoring and ground fishing prohibition - mark surface water area with buoys	
		- Explosive/flammable risk due to presence of oxygen – compressor specific	- condensated water can damage instruments - working hazard - noise	medium	high	medium	- compressors must be isolated from the rest of the site, either in an enclosed area	

							or with a fire wall - dry gas - evacuation of condensates at every compression stage - wear personnel protection gear identified	
	Supply related	Traffic risk of truck loaded with oxygen when no oxygen production at location	- trucks as ignition source - explosion of oxygen infrastructure - damaging or destruction of infrastructure due to traffic accident -	Medium	High	medium	- Certification of operators for oxygen handling and transport - Operation manual for infrastructure - On site training for the operators	- Replacement of damaged or destroyed parts - Exchange of operators - Stop of oxygenation
		Problems with energy supply	- Artificial oxygenation of the water body stops - unknown consequences - loss of safety and control devices	medium	medium	medium	- Secure good grid connection of pilot area - Installation in safe position - Critical safety equipment - Genset as a backup - Emergency lighting	- Stop of oxygenation - Anticipation of predicted energy outfalls - Maintenance of backup energy supply
		Not enough oxygen supply		low	low	low	- Anticipation and ordering of oxygen in advance - Adaptation of storage capacity to the oxygen needs per day/ week - Screening of potential alternative oxygen suppliers	- Reordering - Use alternative oxygen supplier
	Infrastructure related	Complete technical failure		low	high	low	- Long term proven technology from freshwater adapted to marine environment in use - Adaptation of infrastructure to the specific marine environment (corrosion, biofouling, depth etc.)	- Stop of oxygenation
		Concept not adapted to site - Destruction/Movement due to strong inherent oscillations	- no or only partial improvement of oxygen concentrations and ecosystem functioning - oxygenation has to be stopped or interrupted	low	high	low	- Long term proven technology from freshwater adapted to marine environment in use - Adaptation of infrastructure to the specific marine environment (corrosion, biofouling, depth etc.)	- Stop of oxygenation

							- Adaptation of infrastructure to specific site	
		Destruction/Movement of infrastructure through fishing gear	- Change of oxygen flow through crushing or displacement - Infrastructure severely damaged - Artificial oxygenation of the water body stops	high	high	high	-	- Stop of artificial oxygenation - Maintenance of subwater infrastructure
		Destruction/Movement of infrastructure through natural disaster (Icing of infrastructure, crushing of piping through horizontal sea ice drift, Flooding of land based infrastructure, internal movement of water body (internal waves, tidal waves) …)	- Complete stop of pilot oxygenation	low	high	Low	- Intensive site study to implement infrastructure the most secure way - Design site adequately - Winterization philosophy – adapt infrastructure to low temperatures and potential presence of sea ice - Hazardous Area Classification	- High temperature sensor outside - Pressure monitoring - Hazardous Area Classification
		Strong Biofouling on underwater structure	- Corrosion of infrastructure - Can lead to complete stop of oxygenation - Changes of oxygenation rate over time	medium	Medium	medium	- Basis of design - Biofouling inhibitor - Inspection / prevention maintenance	- Regular maintenance and monitoring -
		Destruction of land based infrastructure through vandalism	- Complete stop of pilot oxygenation - Destruction of crucial infrastructure	Low	High	Low	- Fencing and site protection - Regular surveillance - Include local stakeholders in pilot study	- Repair destroyed or affected infrastructure - Stop reoxygenation
		Corrosion of Infrastructure	- Corrosion of infrastructure - Can lead to complete stop of oxygenation	medium	Medium	medium	- Basis of design - Corrosion inhibitor - Inspection / prevention maintenance	- Exchange of corroded parts - Regular maintenance

1.3. Socio-economic Risks

Table 3 Socio-economic risk collection

Type	Risk title	consequence	Probability of failure	Severity category	Frequency category	Prevention of risk	planned mitigation actions
Socio-economic risk	No acceptance in local society	- public resistance - slowing or prevention of project - negative publicity	medium	high	medium	- Thorough Information of local stakeholders about the project - Collaboration with local industry (oxygen) - Collaboration with local universities - Implementation of an elaborated monitoring plan to secure objectives of project are met - Open discussion rounds with local stakeholders to lower eventual fears or concerns	- Regular information about status of project - Final open access reporting of monitoring and observation results - Open data policy to involve public academic and policy stakeholders
	No acceptance in local industry		low	low	low		
	No acceptance in local environmental organizations		medium	high	medium		
	Legislation not ready for chemical sea-bed measures	- unclear political and legislative ground to build on - slowing or prevention of project	low	high	low	- Information of stakeholders previously to project funding application to secure support - Elaborate scientific and societal needs that could be met with project - Underline future economic interests	
	Cross-border collaboration fails (permitting, observations etc.)		low	high	low		
	Conflicts with other users of the marine space	- political resistance - sector resistance - slowing of permitting and installation	Medium	Medium	medium	- Inform about measures taken and risks prevented and monitored - Include stakeholders in citizen science projects for monitoring (e.g fish)	
	Difficulties in obtaining funding	- project not feasible - slowing of the project	medium	high	medium		

Appendix 2 References:

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Appendix 3. Results of first-phase pilot screening

The results of the first-phase screening are shown in Table 1 below. In the data table, the “Surface area”, “maximum depth”, “volume” and “mean depth” data were obtained from the SMHI Vattenwebb (SVAR data), or, for some areas, estimated from online depth charts (e.g., based on eniro.se). The “Pycnocline depth” and “depth of hypoxia” were estimated from summer monitoring data as the middle depth of the density stratification. Below pycnocline and hypoxic sediment areas (<2 mg oxygen per litre), “hypoxic volume” and “mean depth hypoxic volume” were estimated from depth info as above. A crude estimate of the oxygen demand was made as the amount of oxygen needed to be added to increase the concentration from 0 to 10 mg/l over a period of two months. For some areas with sufficient monitoring data, it was possible to calculate oxygen consumption from the seasonal decline of (volume-weighted) oxygen amounts in the deep water (hydrogen sulphide converted to negative oxygen in the calculation).

Table 1. Data on 19 sites identified in the first-phase screening of POI pilot sites.

Name	Areacode	StnID	Municipality	Lat/Lon	Surface (km2)	Max depth	Volume (Mm3)	Mean depth	Sill depth	Pycnocline depth, middle (m)	Below pycnocline volume (Mm3)*	Below pycnocline area (km2)*	Mean depth bottom-to pycnocline	Consistent Anoxia in summer
Edsviken	EDS	S19	Sollentuna/ Danderyd	59 24.71 17 59.91	3,44	18	26,7	7,7	4-5 m	6	10	2	5	
Kyrkfjärden	KYR		Österåker	59 26.00 18 11.40	2,15	15	14,8	6,9	2	6	5	1	5	Yes
Säbyviken	SAB	S73	Österåker	59 25.99 18 14.10	1,73	23	16,2	9,4	4	7	7/4 (Total/Western area)	1.0/0.5	7/8	Yes
Skarpösundet	SKA	S86b	Värmdö	59 20.52 18 43.65	0,14	27			4	7	1,05	0,085	12	Yes
Kanholmsfjärden	KAN	S86	Värmdö	59 20.03 18 46.16	34,87	101	2000	57	90m to Möja Söderfjärd	55	450 (below 55m)	17	27	D, Y
Farstaviken	FAR	S102c	Värmdö	59 19.52 18 22.64	0,54	17			6	8	1,1	0,24	5	Yes
Lännerstasundet	LAN	S81	Nacka	59 17.90 18 13.33	2,29	26	24,8	10,8	2-16m depending on sub-area	8	10/6.6	0.7 (Western area)	9	Yes
Grisslingen	GRI	S96	Värmdö	59 18.16 18 25.75	2,52	19	25,3	10		8	8	1,6	5	J, D
Vårgärdssjön	VAR	S101b	Nacka	59 15.78 18 18.34	0,38	15	2,7	7,1	2	7	0,5	0,17	3	Yes
Våmfjärden	VAM	S94d	Värmdö	59 16.49 18 35.11	1,51	24	20,4	13,5	2	9	9	1,1	8	
Kalvfjärden	KAL	S105	Tyresö	59 12.77 18 20.57	3,25	28	34,5	10,6	2	7	17	1,9	9	J, D
Björnöfjärden	BJO	S98c	Värmdö	59 14.12 18 31.71	1,56	23	16,4	10,5	2	8				Yes
Kaggfjärden	KAG	S131	Botkyrka	59 05.08 17 44.53	5,06	39	81,4	16,1	11	12	33	3,4	10	J, D
Nynäsviken	NYN	S116	Nynäshamn	58 51.41 17 54.81	6,04	32	70,7	11,7	2	10	25	3,3	8	Most Y
Fjällsviksviken	FJA	S84b	Värmdö	59 20.01 18 42.57	ca 0.4	14			2	7				Yes
Lembötebergen	LEM	Ål2	Åland	60 05.31 19 58.89		34								D, Y
Slottssundet	SLO	Ål8	Åland	60 12.80 20 04.76		17								Yes
Kvarnboviken	KVA	Ål13	Åland	60 16.17 20 01.28		26								D
Byfjorden	BYF		Uddevalla							10				Yes
				sampling location										* No or less anoxia in July (J) , (sometimes) only very deep anoxia (D), or some years without anoxia (Y)

Depth hypoxia* (m)	Hypoxic volume (Mm3)*	Hypoxic sediment area (km2)	Mean depth hypoxic volume	Hypoxia persistence	O2 demand ton/day (adding 0-10mg/l 2 months)	O2 demand ton/day (data O2 consumption)	H2S in bottom water in August mg/l	Monitoring programme	Typical Salinity Deep water	Contaminants	Water body in SVAR	Potential installation site and access	Comment
8	5	1,4	4		0,8			SKVVF Jul-Aug + EVVS	3		Yes	Small marina	P precipitation planned
8	3[V]	0,7	4		0,5	0.5-1	12 (1-28)	SVOA (monthly Apr-Oct)	3,5	?	Yes	Small marina	
8	5.8/3.5 [EV] (Total/Western area)	0.9/0.46 (Total/Western area)	6/7	Anoxic Jul-Aug all years 2010-23	1.0/0.7		11 (2-25)	SKVVF Jul-Aug	5,1	?	Yes	Marina	
12	0,66	0,08	8		0,1	0.05	14 (6-27)	2012-2018 SKVVF Jul-Aug	5,9		No, part of Kanholmsfj.	Small Marina	
60	346	14,3	24		58	6 (-3-17) (Jul-Aug)	0-9	SKVVF Jul-Aug	8,5		Yes		
9	ca 0.9	ca 0.2	4		0,13		ca 20	SVOA (monthly Apr-Oct)	5,5	High	No, part of Baggensfj.	Marina	
10	7.2[V] /4.5[E] (Total/Western area)	0.6[E] (Western area	7.5 (western area)	Anoxic Jul-Aug all years 2010-23	0.8 (Western area)	2-3 (Western area, Apr-Aug)	12 (2-23)	SVOA (monthly Apr-Nov), SKVVF (Jul-Aug)	4	High	Yes ("Skurusundet"), but contains sub-areas	Small marina	
11 (-14)	4 (-1)	1	4		0,7		2 (0-5)	SKVVF Jul-Aug	5,5		Yes	Marina	
8	0,3	0,15	2		0,05		10 (3-24)	SKVVF Jul-Aug	5,4		Yes	Very limited	Good surface water quality
17 (-20)	1,5	0,36	4		0,3		6-10		5,4		Yes	Very limited	
11	10[EV]	1.4[E]	7		1,7		1.4 (0-5)	SKVVF Jul-Aug	5,5		Yes	Marina 1.5 km	
9								SKVVF Jul-Aug	5,5		Yes	Marina 1.5 km	P precipitation done
17	17[EV]	3.4[E]	5		2,8		0-2	SKVVF Jul-Aug	6,4		Yes	Marina	
15 (1-5 mg/l)	12[V]	1,5	8		2	0.6-1.6 (Jul-Aug)	0 (oxygen minimum 1 mg/l)	SKVVF Jul-Aug	5,9		Yes	Very limited	
7								SKVVF Jul-Aug	4,9		No, part of Älgöfj.	Very limited	
20	ca 1	ca 0.3	4?		ca 0.2		?	Mar/(Jul)/Aug*	6			Small marina >1.5km	
10	ca 0.7	0,35	2?		ca 0.1		?	Mar/(Jul)/Aug*	5,6			Limited	
15	1,5	0,3	5?		ca 0.25				5,3			Limited	
ca 15	63				9	2-3*			32				
*<2mg/l	*in August				O2 10 mg/l in 2 month from 0 mg/l			*Jul only surface					
	**SMHI hypso or depth chart						5-15						
	V= SMHI Vattenweb					* Stigebrandt pers. Comm.							
	E= Eniro depth chart												

The 19 identified potential pilot sites are further elaborated below (listed in no particular order of interest):

1. **Edsviken.** Edsviken is an 8 km elongated bay in the inner archipelago of Stockholm, connecting to Lilla Värtan near central Stockholm. It is sampled by SKVVF (station S19) in the deepest spot. There is monthly monitoring within the local organization Edsvikens vattensamverkan. In most, but not all years (in the period 2010-23), there is anoxia from 10 meters depth in August and only some years in July. The area deeper than 10 m is mainly restricted to the central Edsviken, and only a small area of the bay is deeper than 15 m. The bay is currently being investigated for phosphorus precipitation by aluminium treatment. Due to the influence of freshwater from Lake Mälaren in central Stockholm, the salinity is low.

2. **Kyrkfjärden.** Kyrkfjärden is located in the inner archipelago of Stockholm and has a narrow and (10 m) shallow (2 m) connection to the water area Stora Värtan. Due to the influence of freshwater from Lake Mälaren in central Stockholm, the salinity is low. There is a sewage treatment plant (Rydbo STP) with discharge in the area, and there is a control programme (reported by SVOA) with monthly monitoring for part of the year. SKVVF has no sampling station in the area. There is regular seasonal anoxia at 10 meters and deeper. Depth-integrated and volume-weighted monitoring data was used to estimate the oxygen consumption in the deep water during summer.

3. **Säbyviken.** Säbyviken is an elongated bay which is deepest (23 m) in the inner part, where the SKVVF monitoring station (S73) is located. In all investigated years, there has been well-developed anoxia in July and August. Sampling in the winter and spring of 2023 and 2024 showed permanent anoxia in this period. It has previously been observed to be fully mixed in September. Probably, the variation of H_2S concentrations in summer depend on if there has been mixing in autumn (and perhaps spring) or not. Volumes and potential oxygen demand were estimated for the whole area (which is an official water body) and for the inner, western part separately.

4. **Skarpösundet.** Skarpösundet is a small, narrow bay with a deep central part (max depth 27 m), with consistent anoxia in summer at depths from 15 meters. It has been included in the SKVVF sampling for a few years only. For four years (2012-2015), it was sampled intensively in a research project (BalticSea2020). This data was used to estimate oxygen consumption from the oxic conditions in late winter (three years, one year not mixed) to developed anoxia in early June (H_2S not available). Due to the small volume of the deep water, the oxygen consumption is one of the smallest of the investigated areas, ca 50 kg/day. There is a small marina in the area.

5. **Kanholmsfjärden:** This is a very large and deep basin, with the maximum depth of 102 meters. It is the only area that has a deep halocline. The area has many wide connections to surrounding areas, and there is a high water exchange of surface water due to surface currents. The deep water is renewed irregularly by inflows of often anoxic deep water from the Baltic Sea via the sound east of Möja island (Ekeroth, Kononets, Walve, Blomqvist, & Hall, 2016) (Walve, 2020). Winter mixing can more or less ventilate the deep water. Currently, there is monitoring in July and August (SKVVF programme), but previously, there was monthly sampling within the SVOA programme.

6. **Farstaviken:** Farstaviken is a small bay that is part of the large official water body Baggensfjärden. It has a maximum depth of 17 meters, but large parts are <13 m deep. SKVVF has no sampling station in the area, but there is a control program run by SVOA, with monthly sampling for part of the year. Hypoxic volumes and areas were estimated using available online bathymetry (https://kartor.eniro.se/m/ebKIy, area 6). Due to previous industrial activity, the area has highly contaminated sediments (high Cu, Cd, Pb, and TBT, data from Värmdö municipality). The water is relatively clear in summer, and purple sulphur bacteria have been observed in the sulfidic waters near the thermocline (Jakob Walve, personal observation).

7. **Lännerstasundet**. Lännerstasundet is an elongated bay with three sub-areas. The official water body name is Skurusundet, after the sound in the north connecting the area to water bodies strongly influenced by the runoff from Lake Mälaren. There is a mean surface water flow through the area towards the water body Baggensfjärden, via the Baggenstäket canal. Due to the salinity stratification in the area, the deep water can remain permanently anoxic for long periods. The western part is the largest and deepest (max 25 m) and has SKVVF and SVOA monitoring stations (sediment data SGU report). The eastern sub-area (18 m) is separated from the other sub-areas by a 7-meter sill. Even though there is often permanent anoxia, mixing in spring is observed some years. Interpolated and volume-weighted data showed that oxygen consumption was for >10 m depth in the period April to October in four investigated years, 2-3 tons/day for the western sub-area. The salinity is also relatively low in the deep water.

8. **Grisslingen.** Grisslingen has a maximum depth of 20 m, but the depth of its central area is mostly 14-16 m. In July, there is usually hypoxia from 15 m depth, and in August, there is anoxia from 12 m depth, but some years deviate with higher oxygen concentrations.

9. **Vårgärdssjön**. Vårgärdssjön is a small bay connected to Baggensfjärden via a shallow (2 m) and narrow (4 m) canal. There is a special bathymetry map for this area. It has a maximum depth of 15 m, but the volume below the pycnocline is small. It is anoxic in summer from 10 m depth. The surface water is relatively clear in summer, but high concentrations of purple sulphur bacteria are regularly observed in the sulfidic waters near the thermocline. There is virtually no space for any on-land installations.

10. **Våmfjärden.** Våmfjärden is a small and deep (max 25 m) bay with a narrow (3 m) and shallow (1.5 m) inlet. It is normally not monitored, but anoxia has been observed from 19 m depth, i.e. most of the water below the pycnocline is toxic.

11. **Kalvfjärden**. Kalvfjärden receives freshwater inputs from the river Tyresån. The bay has a maximum depth of 26 m. In July, most of the deep water is hypoxic but not anoxic, with some exceptional years of oxic conditions. In August, there is normally anoxia 15 m and deeper, but with some exceptions. A marina in the southwestern part of the bay is located 1 km from the deep central area. The surface water quality is relatively good in the bay.

12. **Björnöfjärden.** The area has been subject to a phosphorus precipitation experiment (2012-2013) (Rydin;Kumblad;Wulff;& Larsson, 2017). Phosphorus concentrations have decreased, but there is still anoxia in the deep water in summer. Due to the aluminium treatment of the sediments, the area is less suitable for oxygenation experiments as the biogeochemical conditions have been altered in the bay.

13. **Kaggfjärden.** This relatively large bay is normally not hypoxic in July, but in August it is often anoxic from 20-25 m depth. The deepest part is in the south (38 m), but most of the central area is 20-25 meters deep.

14. **Nynäsviken.** This is a relatively large (9 km) and deep (31 m) elongated bay. It connects with a shallow canal in the southwest and a shallow sound in the southeast. This area is normally not hypoxic in August. However, it has had deteriorating oxygen conditions over the last years. For this area, it was possible to calculate oxygen consumption based on the July and August SKVVF data.

15. **Fjällsviksviken.** This small bay is a part of the large official water body Älgöfjärden. It connects to the main Älgöfjärden via two narrow canals. The bay is normally anoxic from 8 m depth in August. The bay has been a reference area in the BalticSea2020 project for

16. **Lembötebergen.** This fjord is located east of Mariehamn on Åland. It has a maximum depth of 35 m, but most of the deep area is 20-25 meters deep. It is often anoxic from 20-25 meters depth.

17. **Slottssundet.** This Åland site is a small, elongated bay with a maximum depth of 17 m, but most of the deep area is 12-15 m deep. In summer it is anoxic from 10-12 m depth.

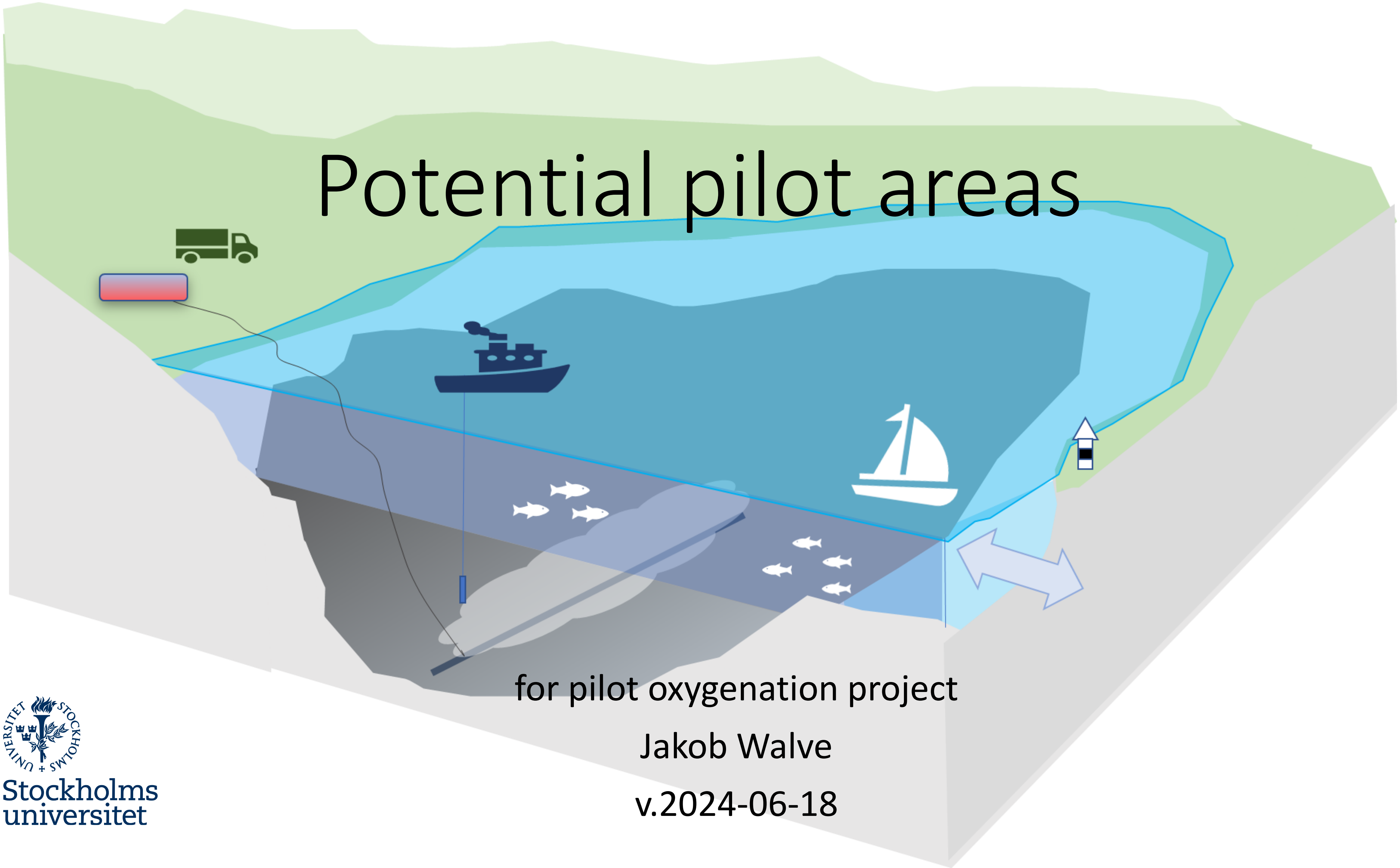
18. **Kvarnboviken.** This elongated bay on Åland has a deep central area (maximum depth 26 m). Oxygen conditions are variable between years, with an anoxia depth of 12-20 meters.

19. **Byfjorden.** This is a deep bay on the west coast of Sweden, with a maximum depth of 46 m. It is monitored monthly in the local control programme. It is stratified at 10-15 meters depth and has more or less permanent anoxia in the deep water, even though there is

variability due to natural inflows of deep water. It is currently subject to a second experiment with ventilation to increase deep water.

Maps and further data on the sites can be seen below.

Potential pilot areas



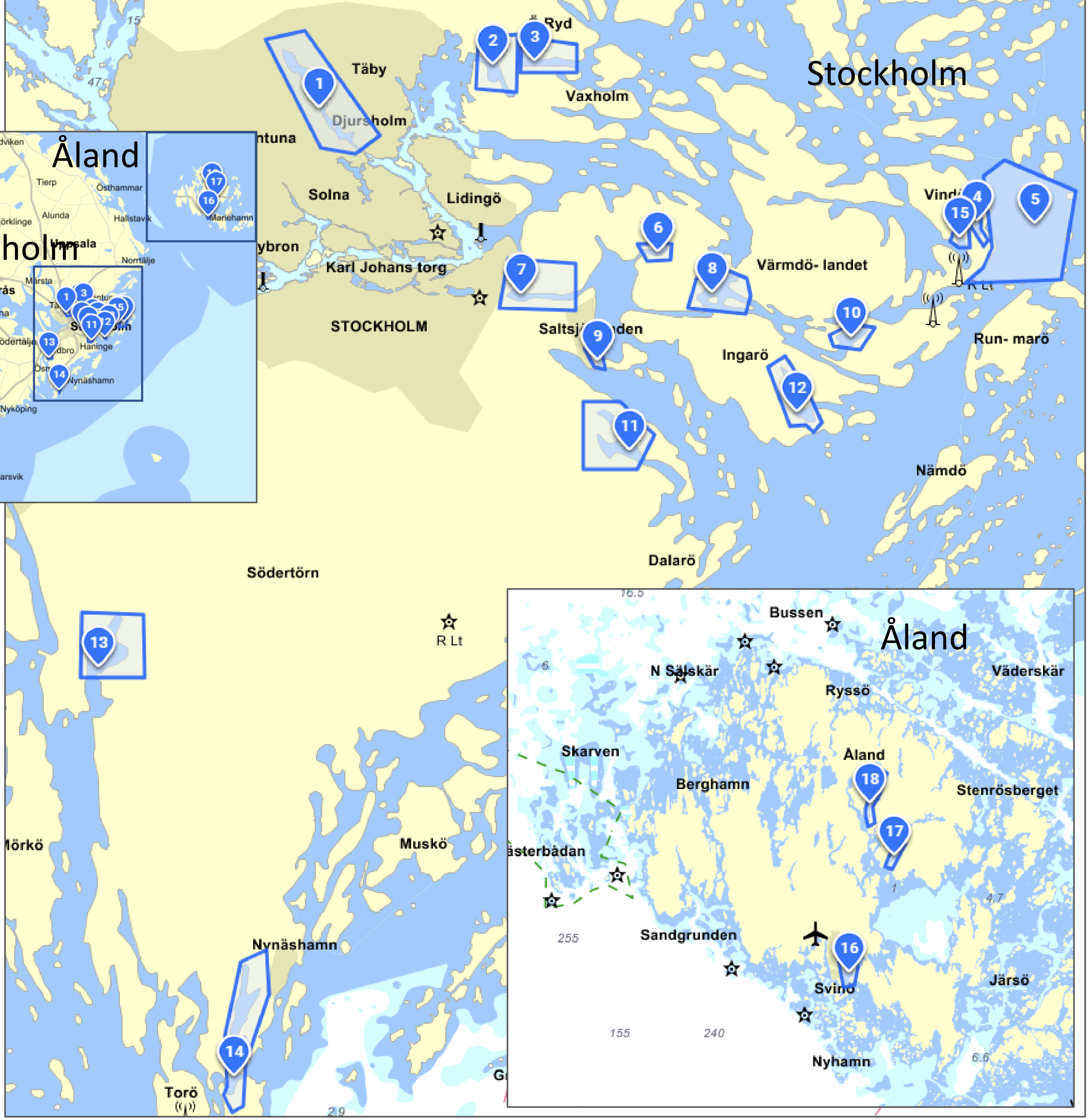
for pilot oxygenation project

Jakob Walve

v.2024-06-18

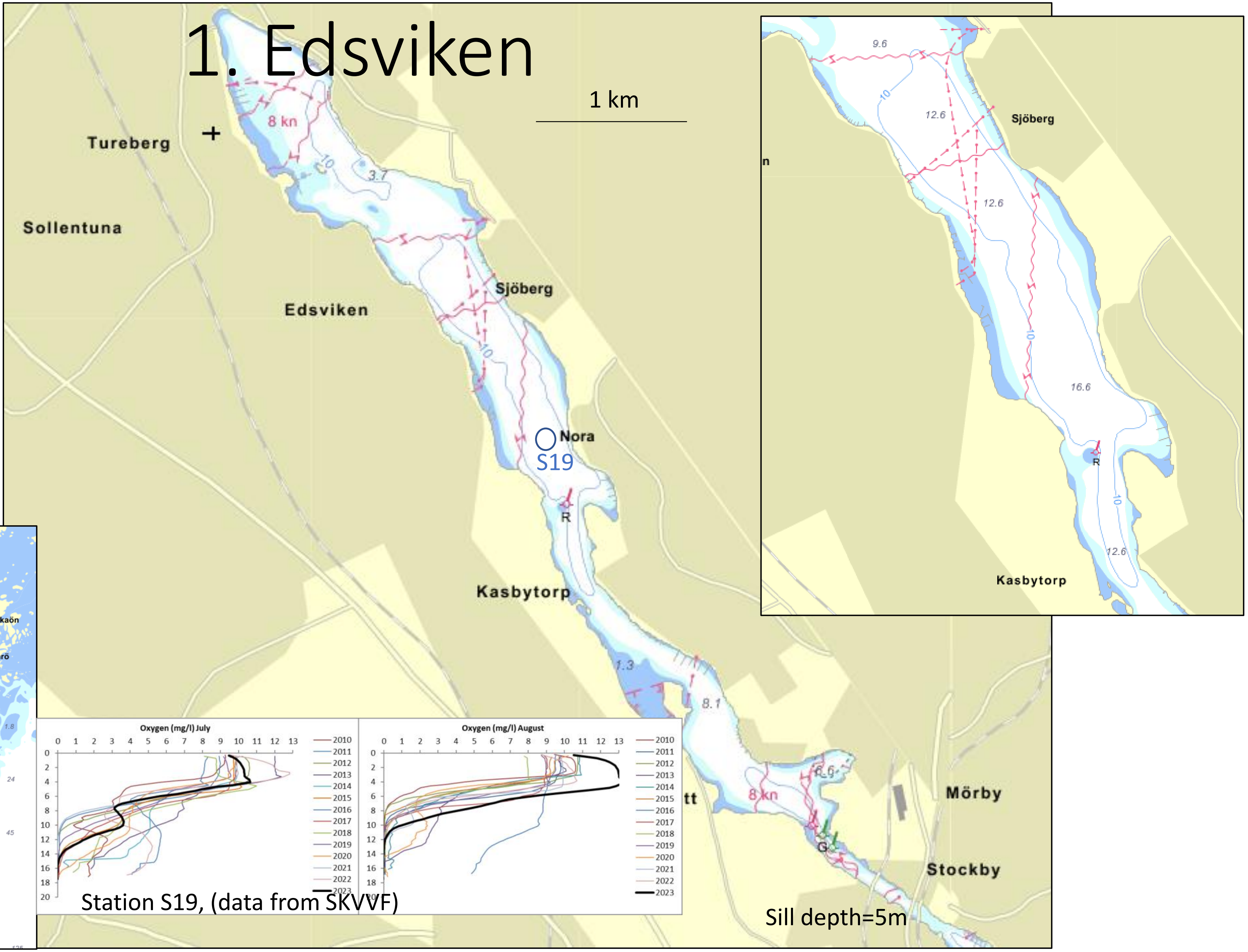
Stockholms universitet

1. Edsviken
2. Kyrkfjärden
3. Säbyviken
4. Skarpösundet
5. Kanholmsfjärden
6. Farstaviken
7. Lännerstasundet
8. Grisslingen
9. Vårgärdssjön
10. Våmfjärden
11. Kalvfjärden
12. Björnöfjärden
13. Kaggfjärden
14. Nynäsviken
15. Fjällsviksviken
16. Lembötebergen
17. Slottssundet
18. Kvarnboviken
19. Byfjorden



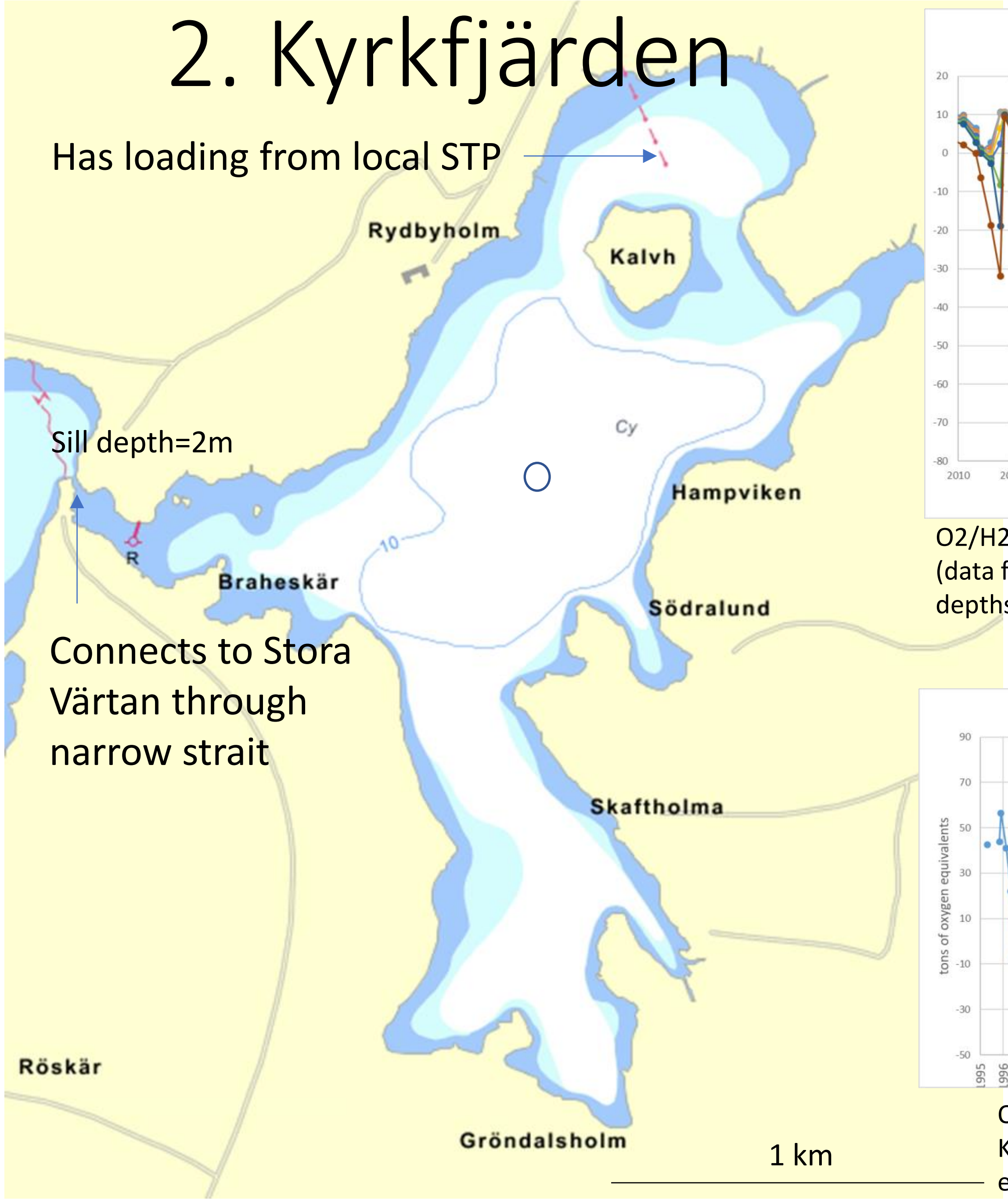
https://kartor.eniro.se/m/ebKIy

1. Edsviken



Station S19, (data from SKVVF)

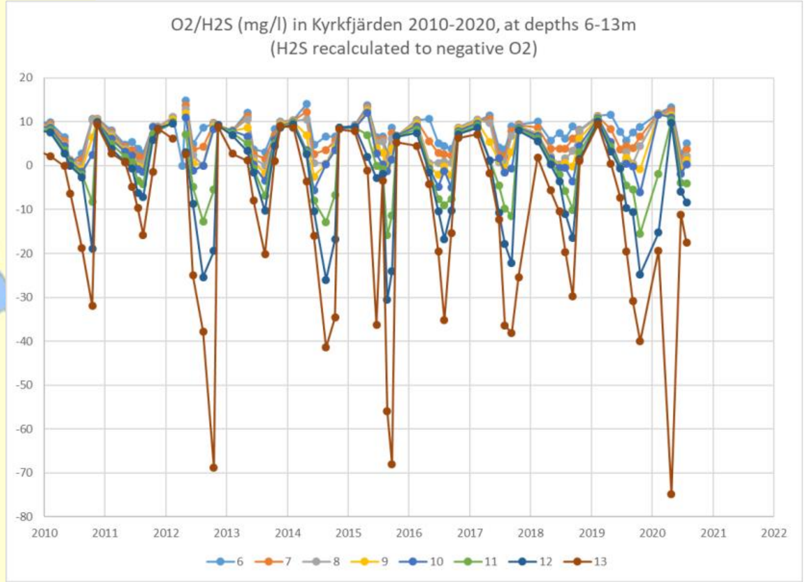
2. Kyrkfjärden



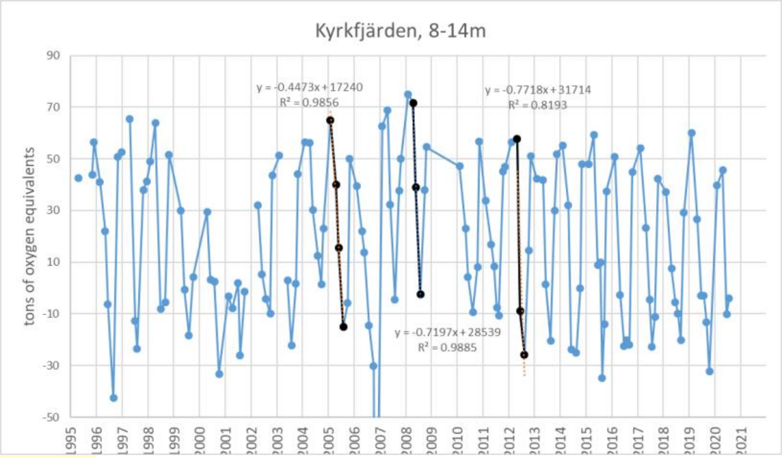
Has loading from local STP

Sill depth=2m

Connects to Stora Värtan through narrow strait

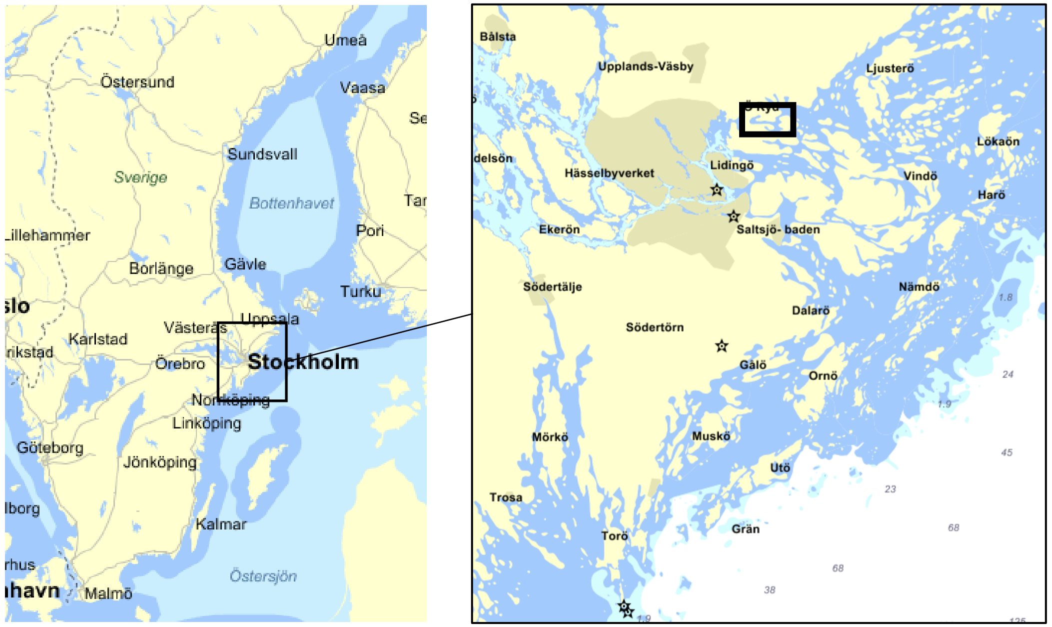


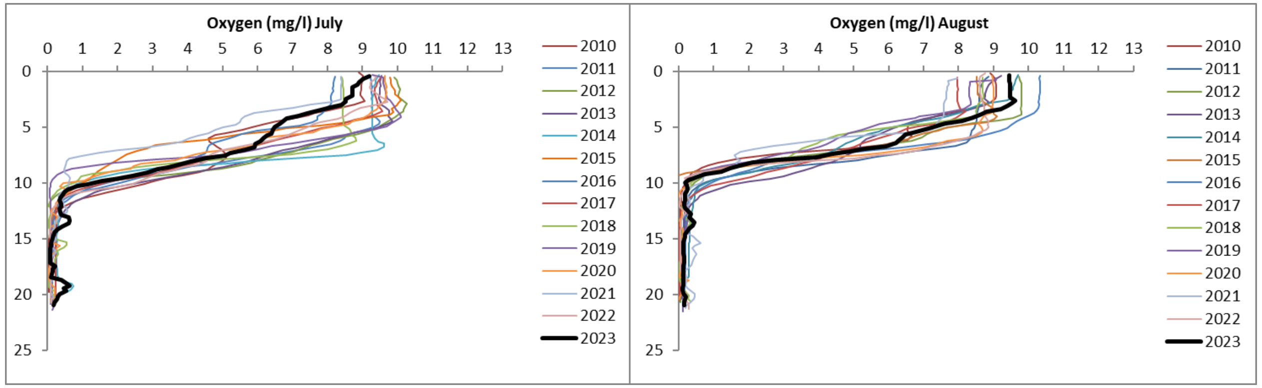
O2/H2S (mg/l) at station Kyrkfjärden, Feb-Nov 2010-2020 (data from SVOA, at 6, 8, 10, 12 and bottom 13-15m, other depths interpolated)



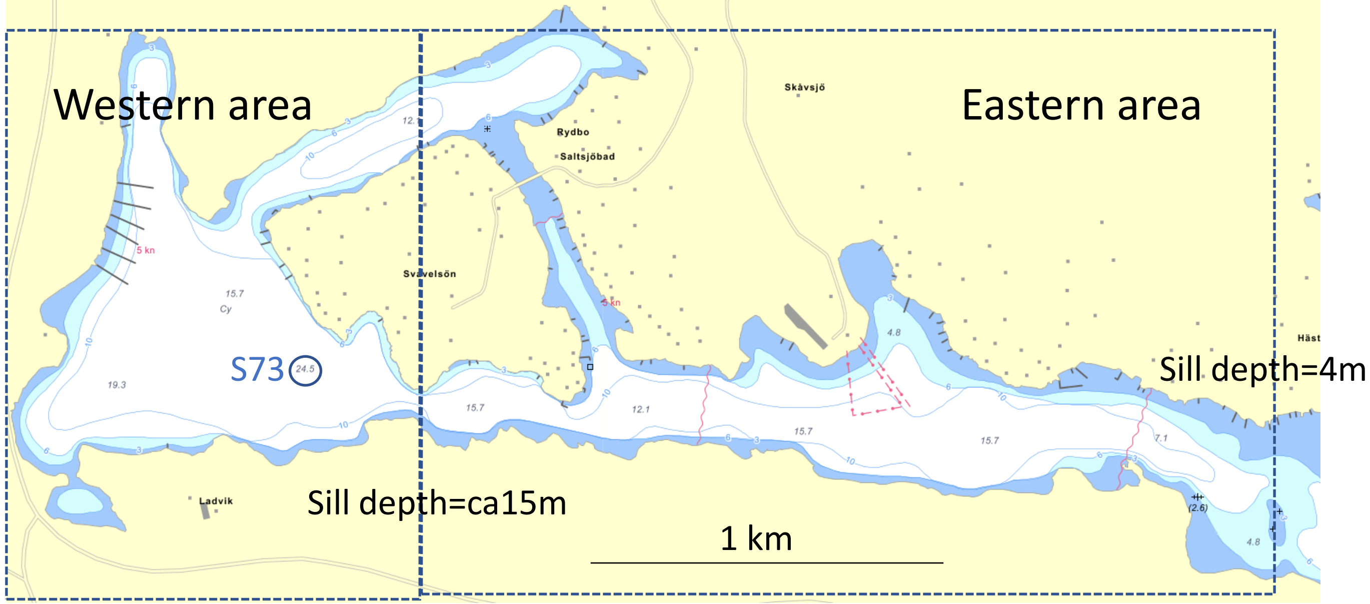
O2/H2S (tons O2 equivalent) below 8 meters depth in Kyrkfjärden, Feb-Nov 2010-2020. Three examples of estimated O2 consumption is shown (linear regression)

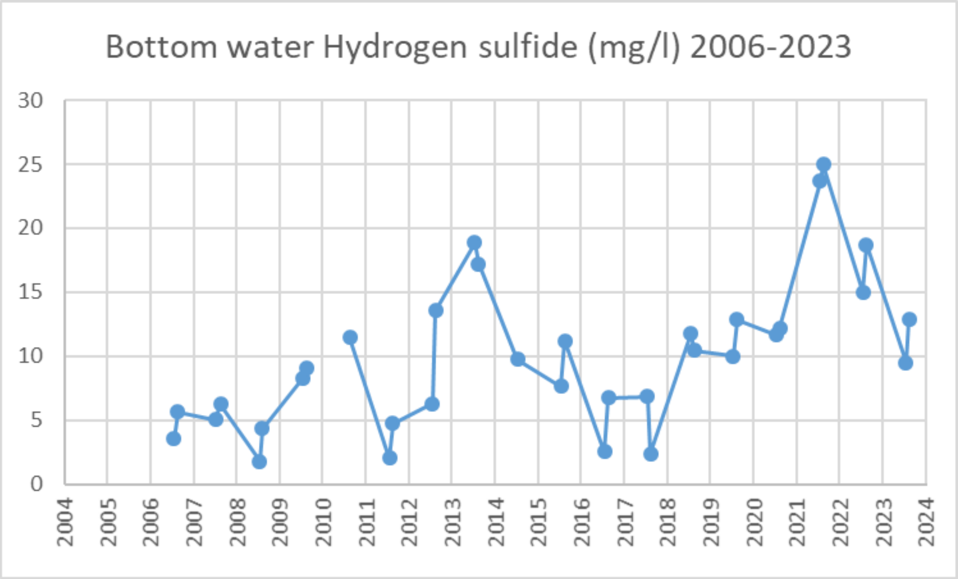
3. Säbyviken



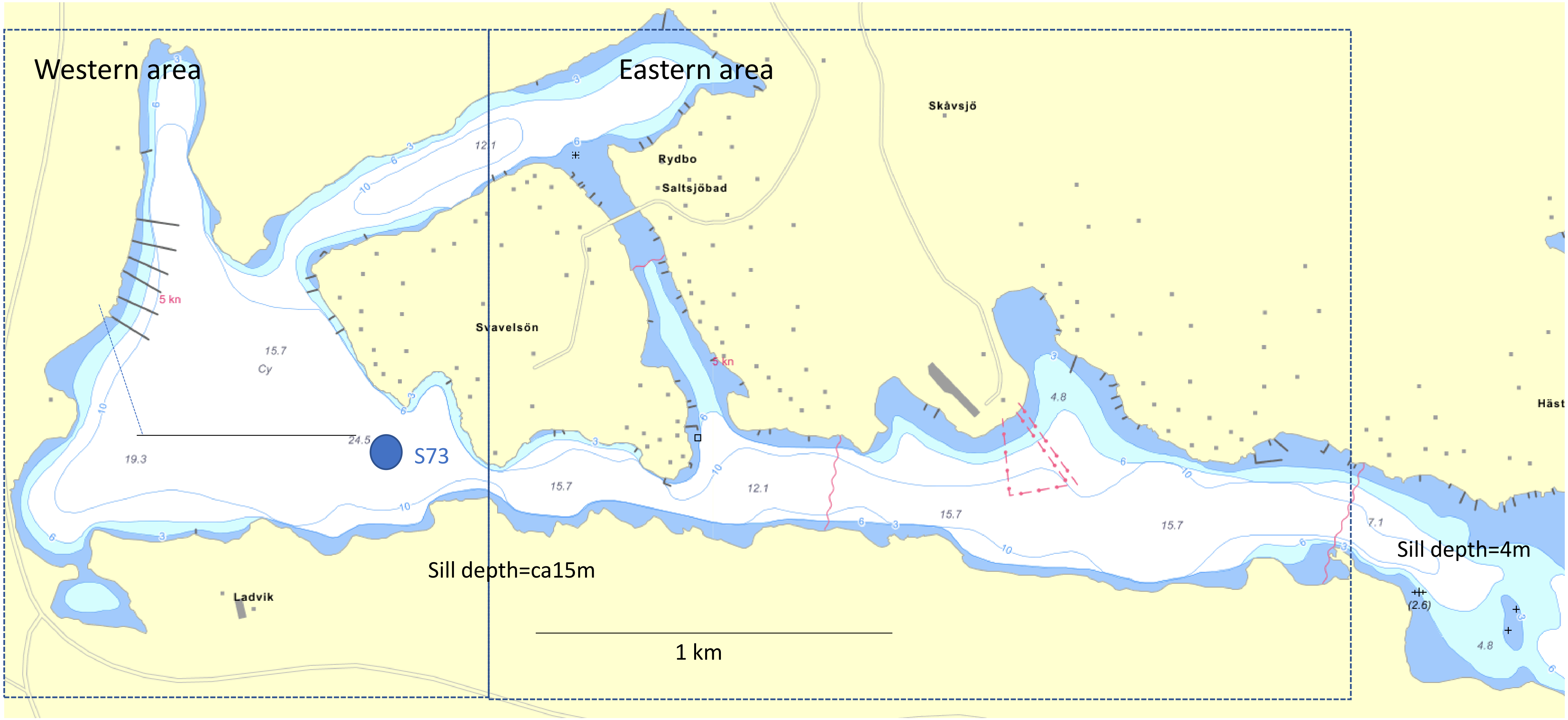


Western area
Station S73, (data from SKVVF)





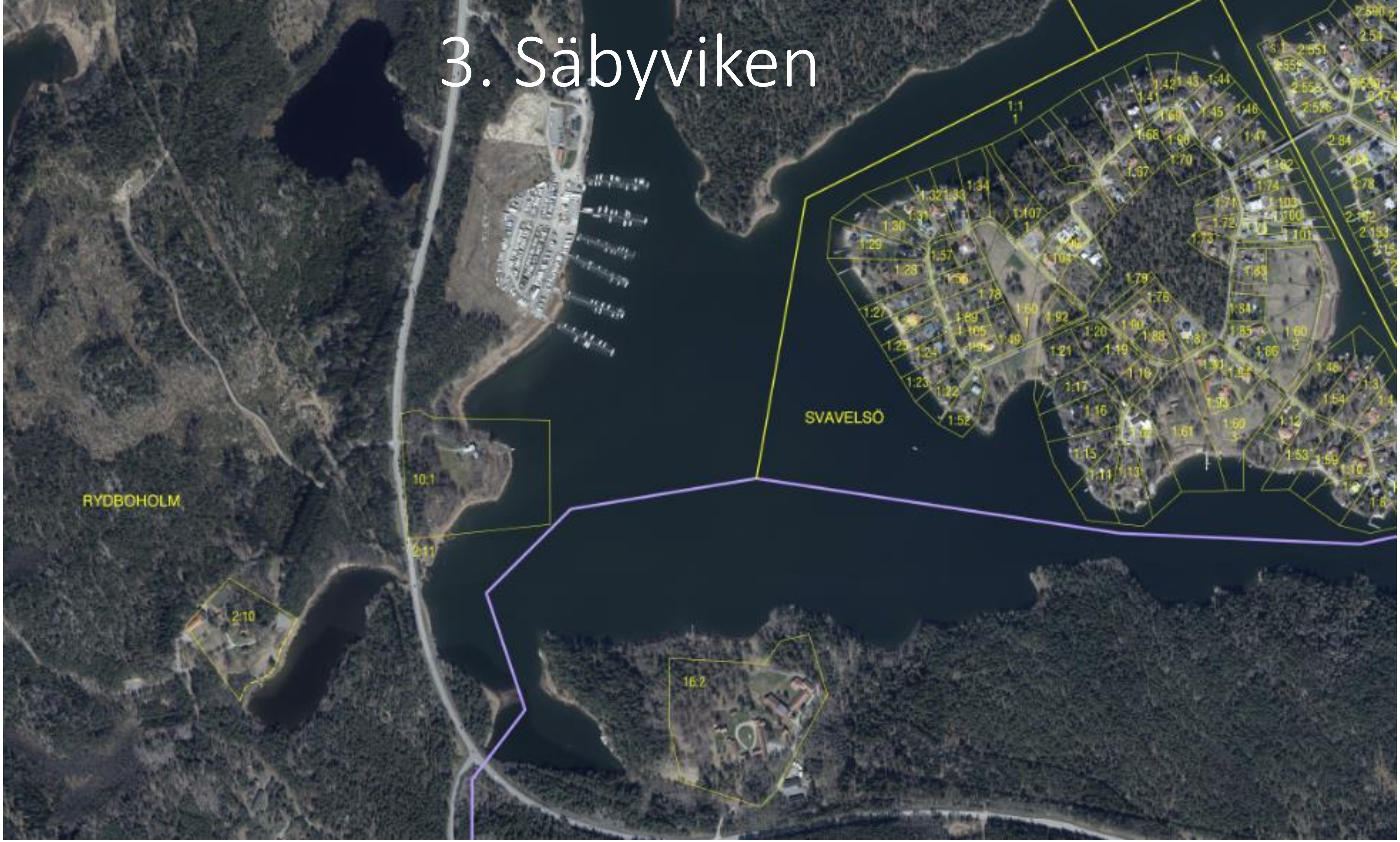
3. Säbyviken



Ca 1 Ton O2/day

3. Säbyviken

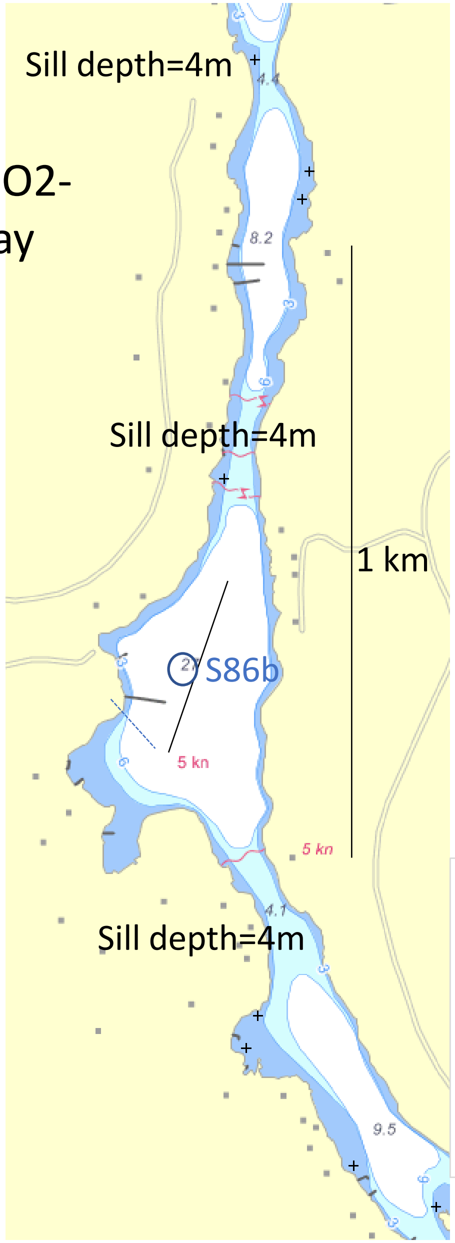
3. Säbyviken

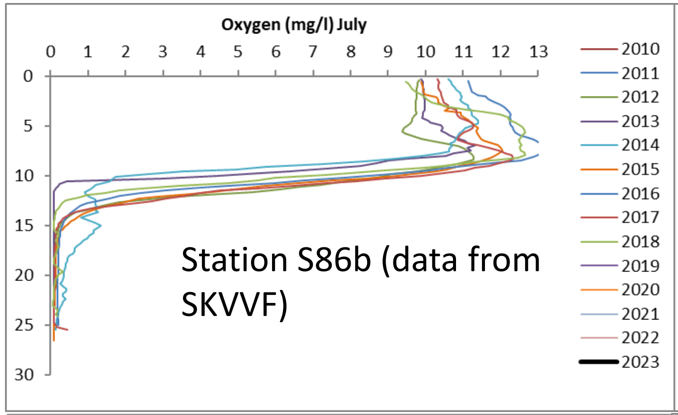


[Min Karta (lantmateriet.se)](#)

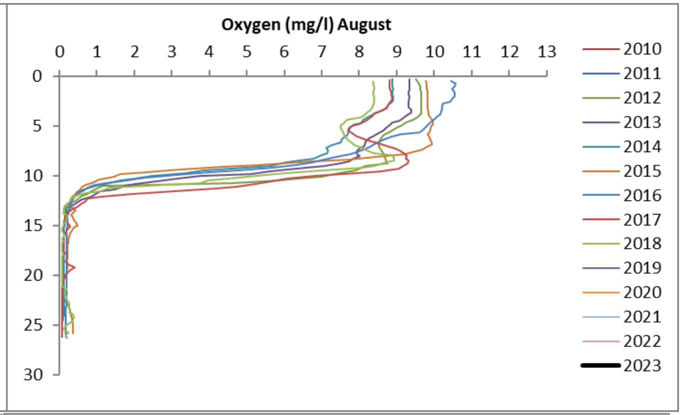
4. Skarpösundet

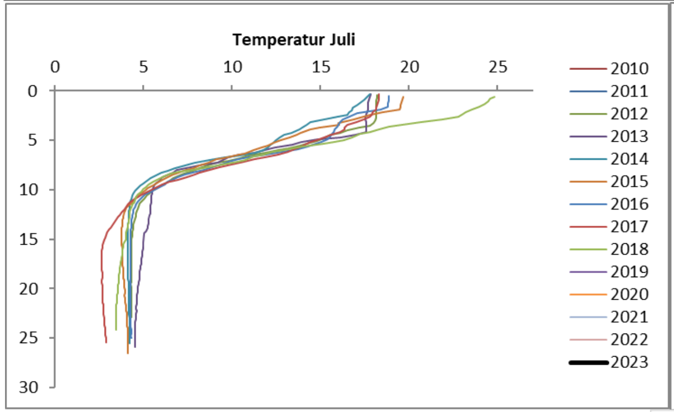
O2-consumption calculation from O2-data: 0.05 ton/day

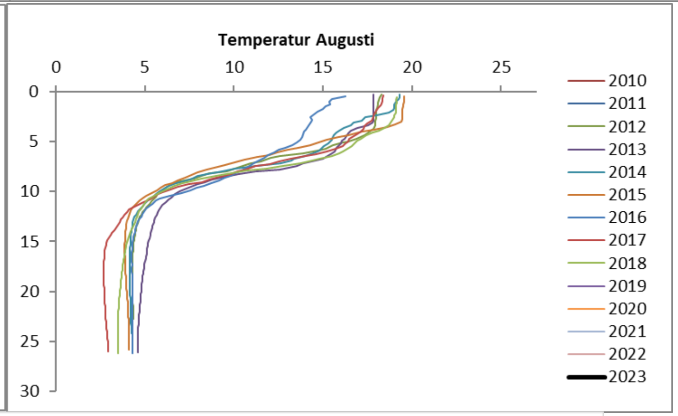


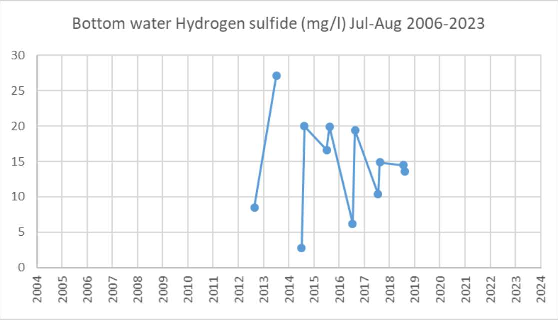


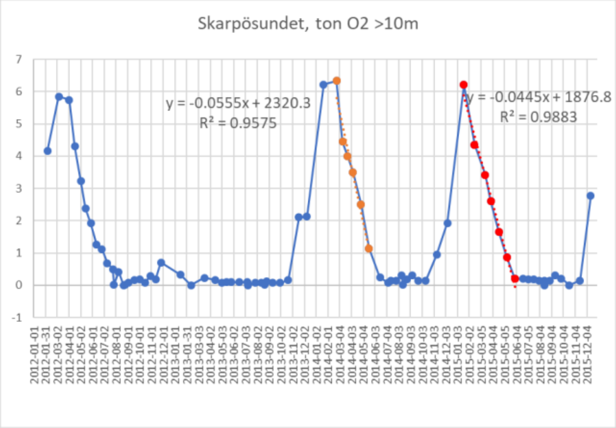
Station S86b (data from SKVVF)



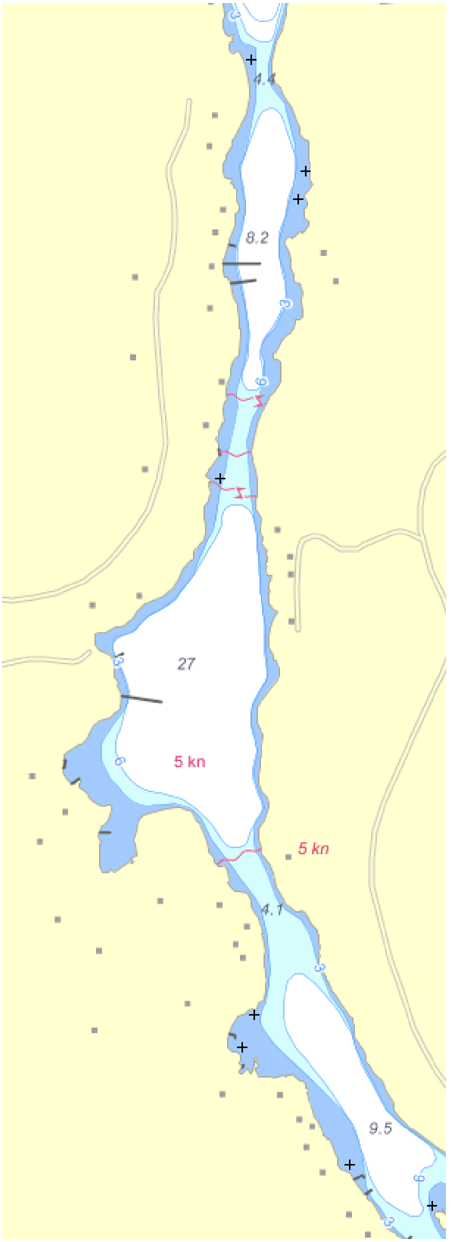




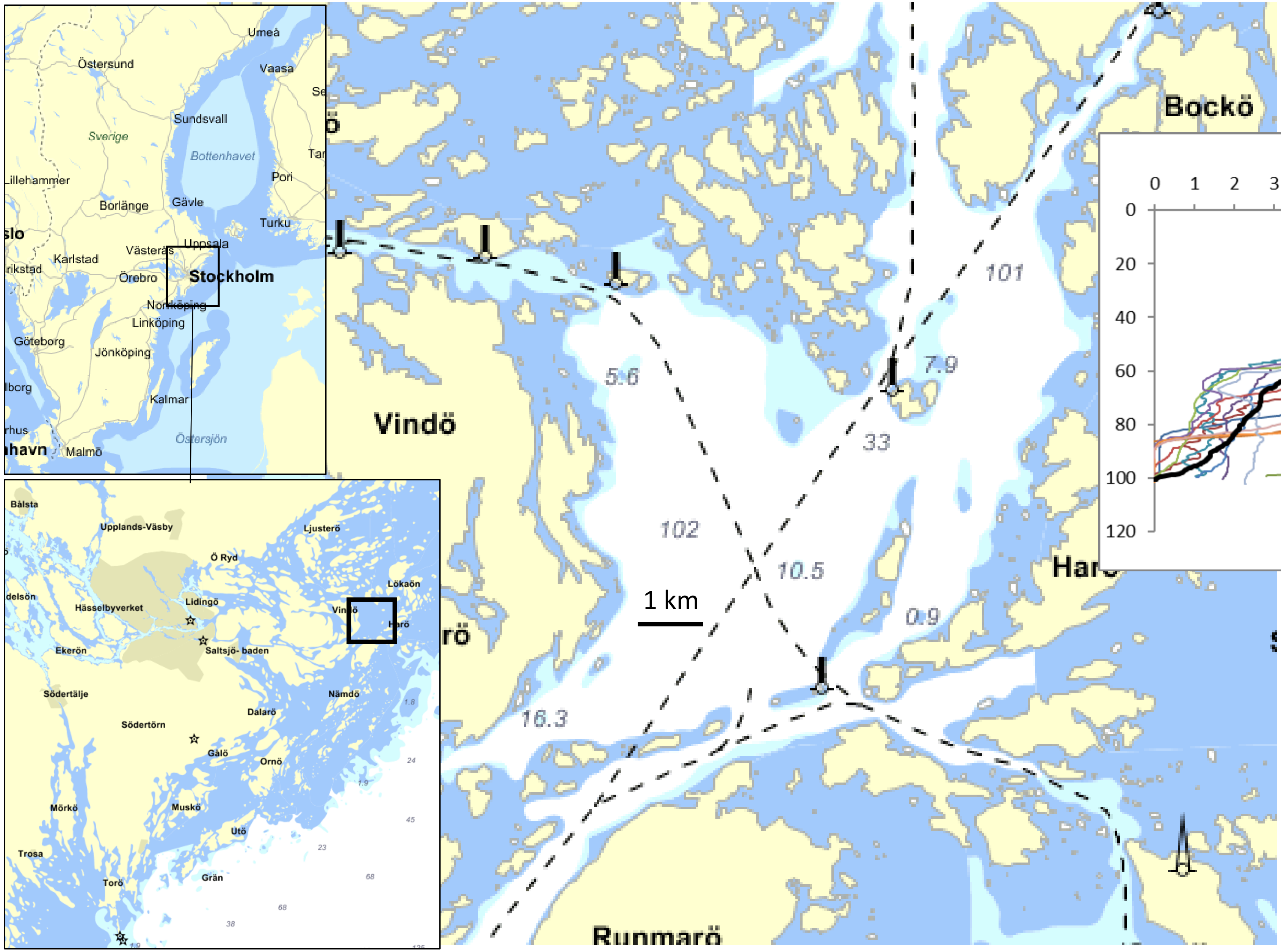


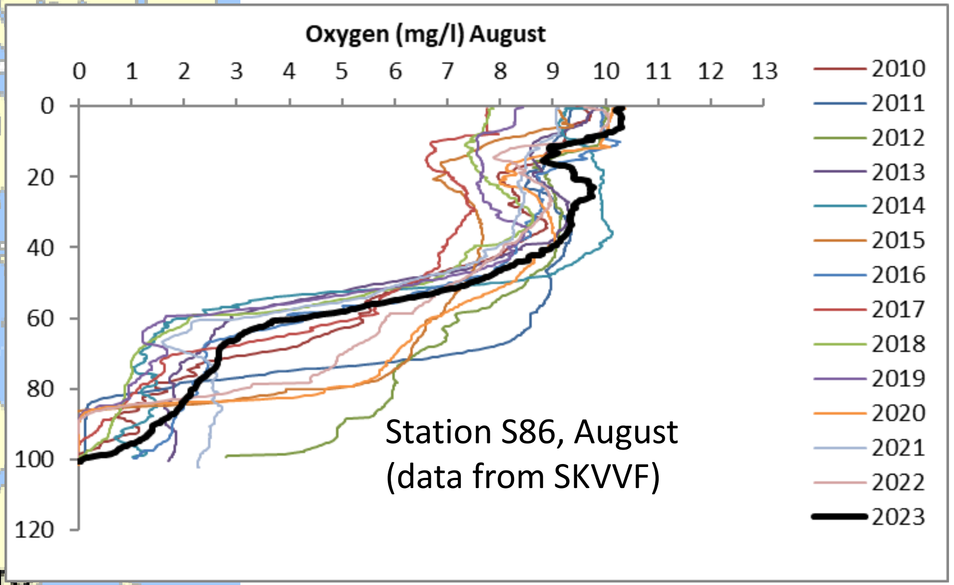


4. Skarpösundet

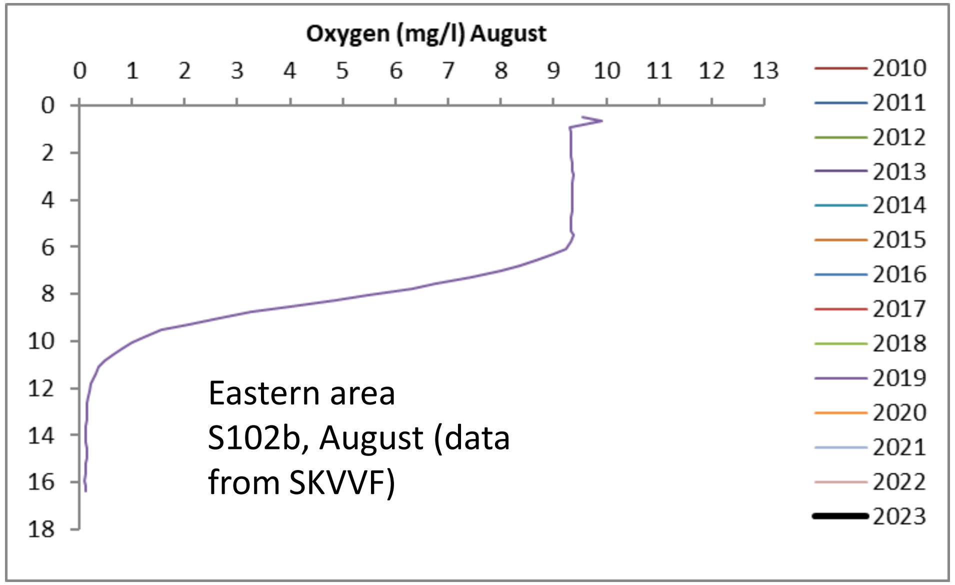


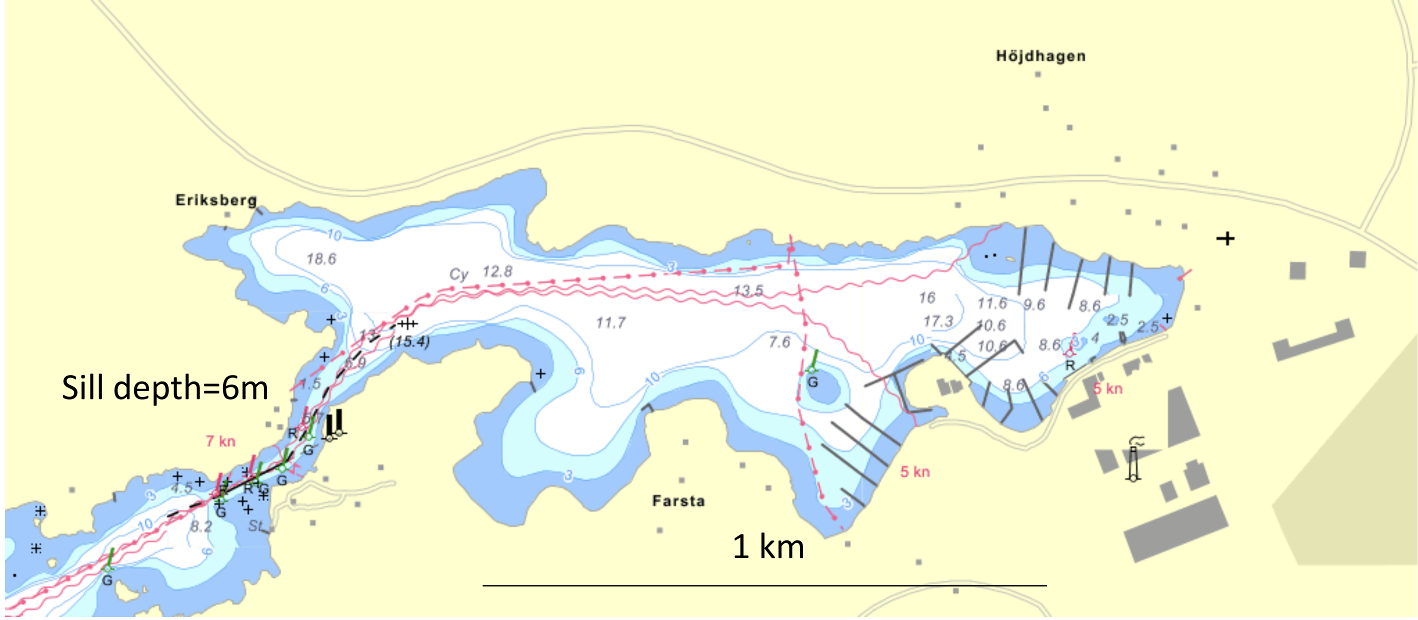
5. Kanholmsfjärden

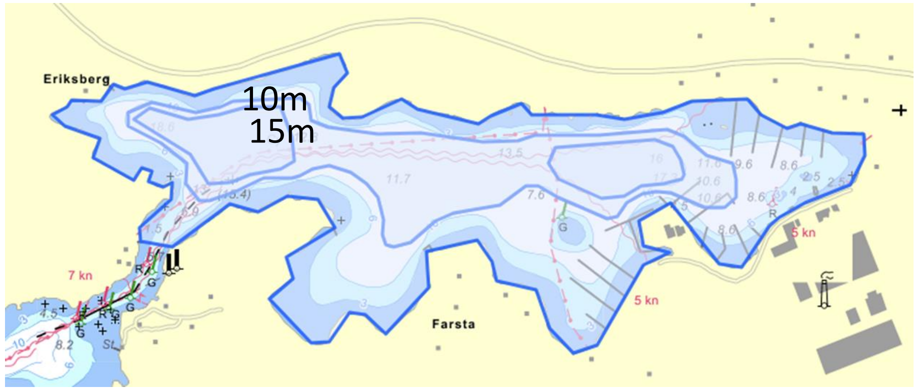




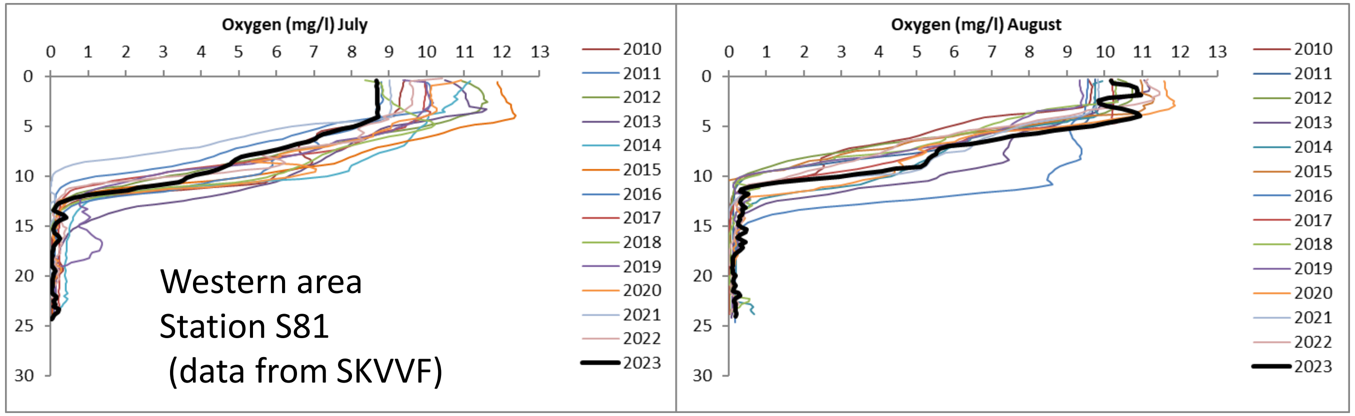
6. Farstaviken

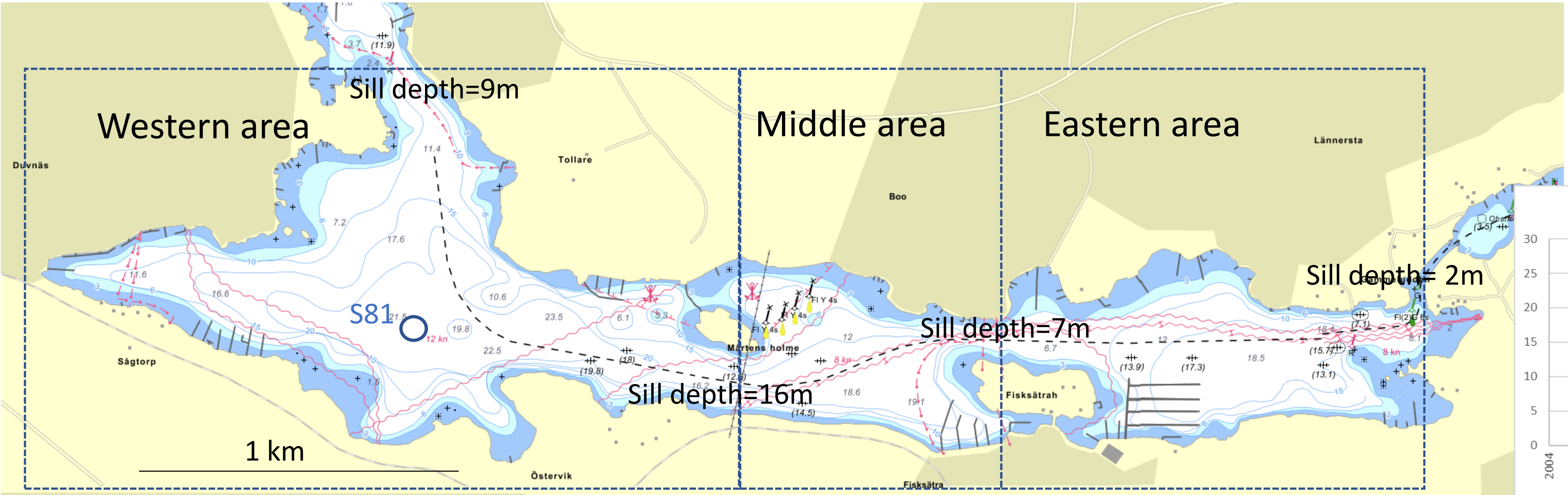


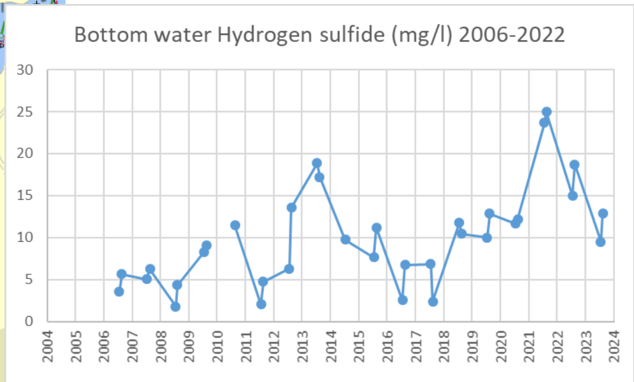




7. Lännerstasundet







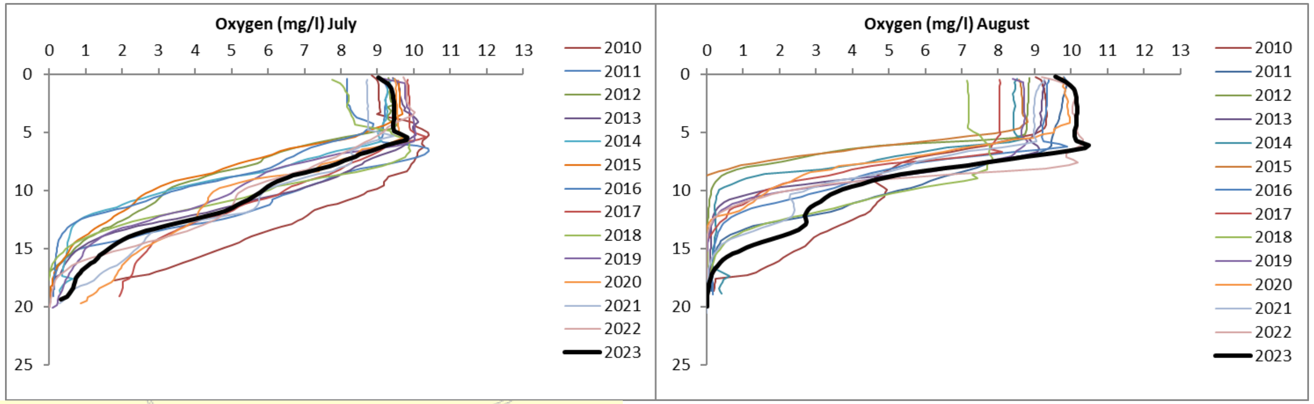
7. Lännerstasundet

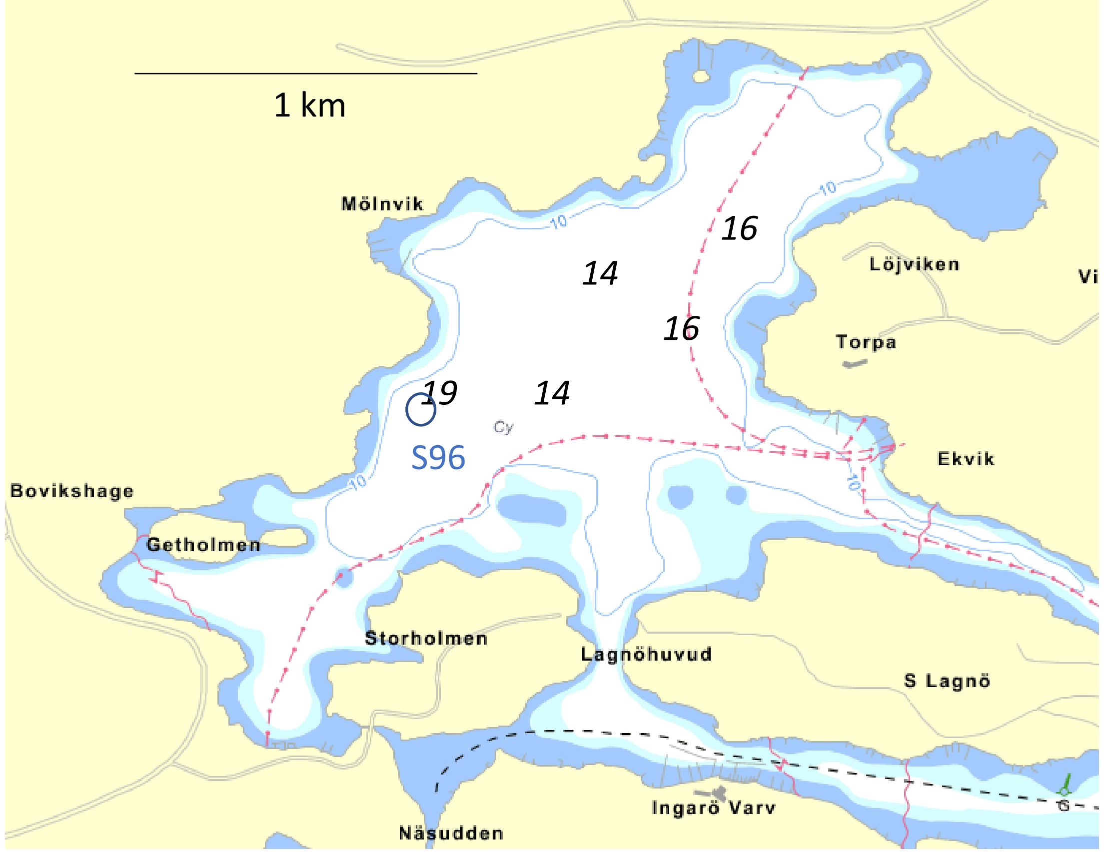
7. Lännerstasundet

depth	W Area km2	M Area km2	E Area km2
>10m	0.5866	0.1880	0.2145
>15m	0.3794	0.1096	0.1235
>20m	0.2187		

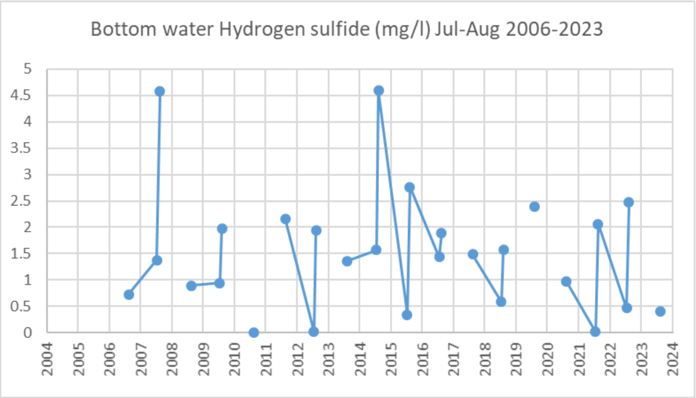
https://kartor.eniro.se/m/OY4Lu

8. Grisslingen

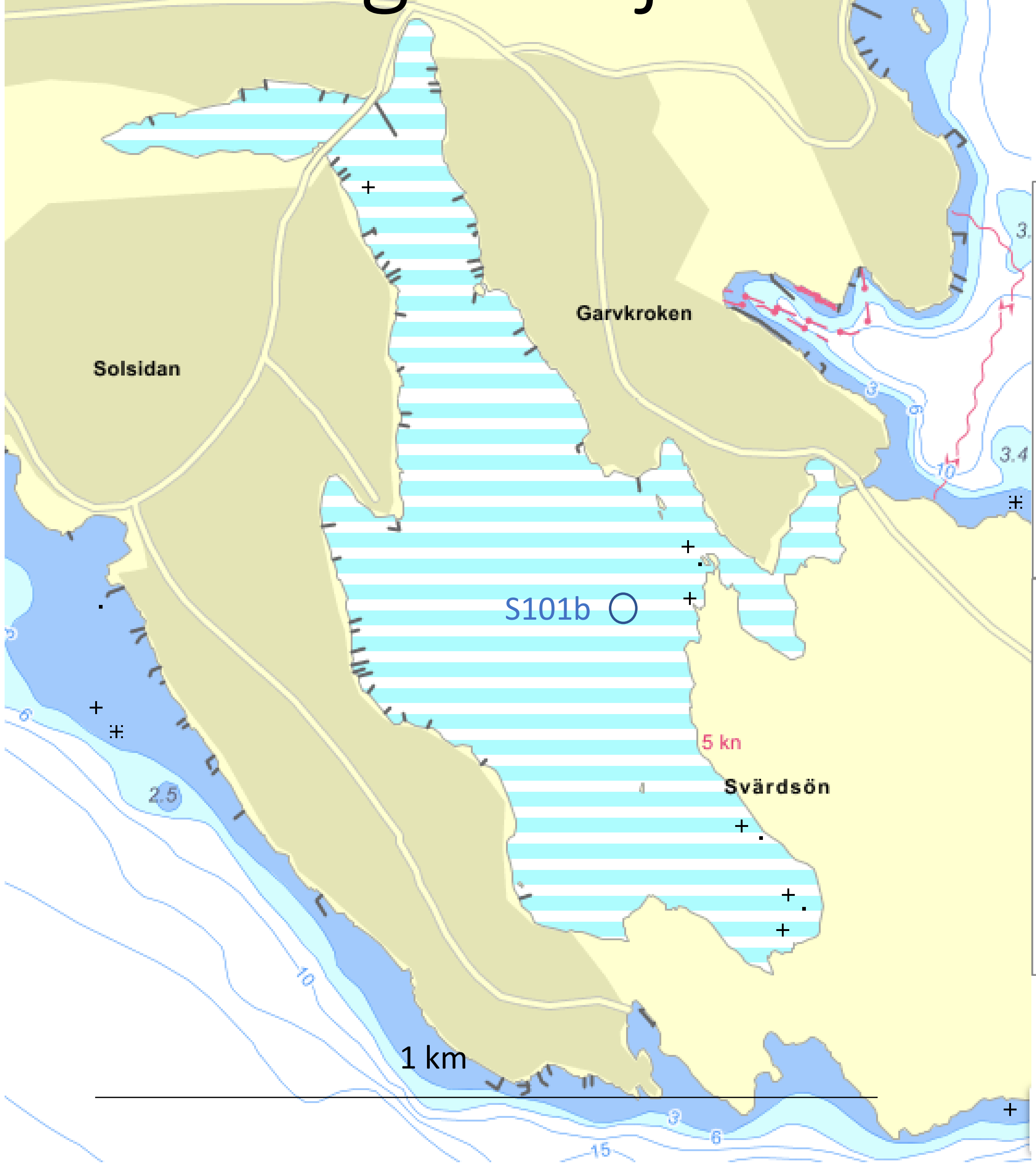


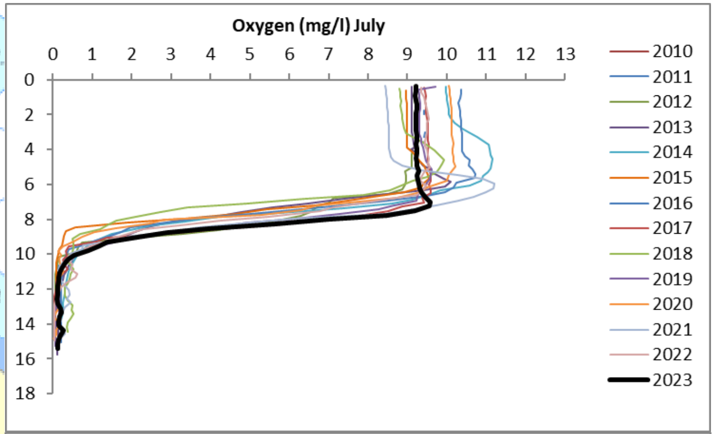


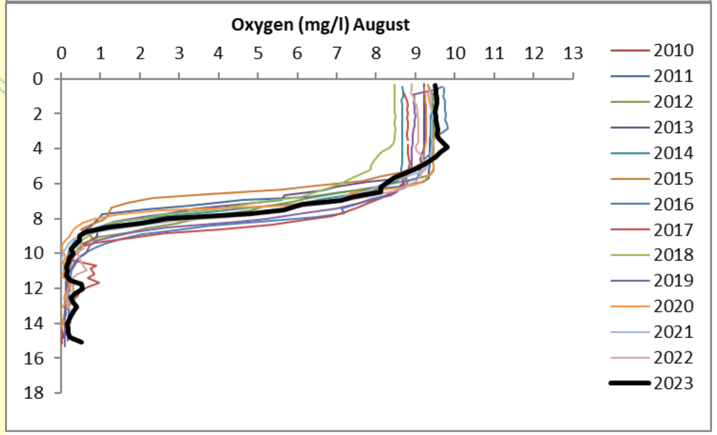
H2S at 19m depth



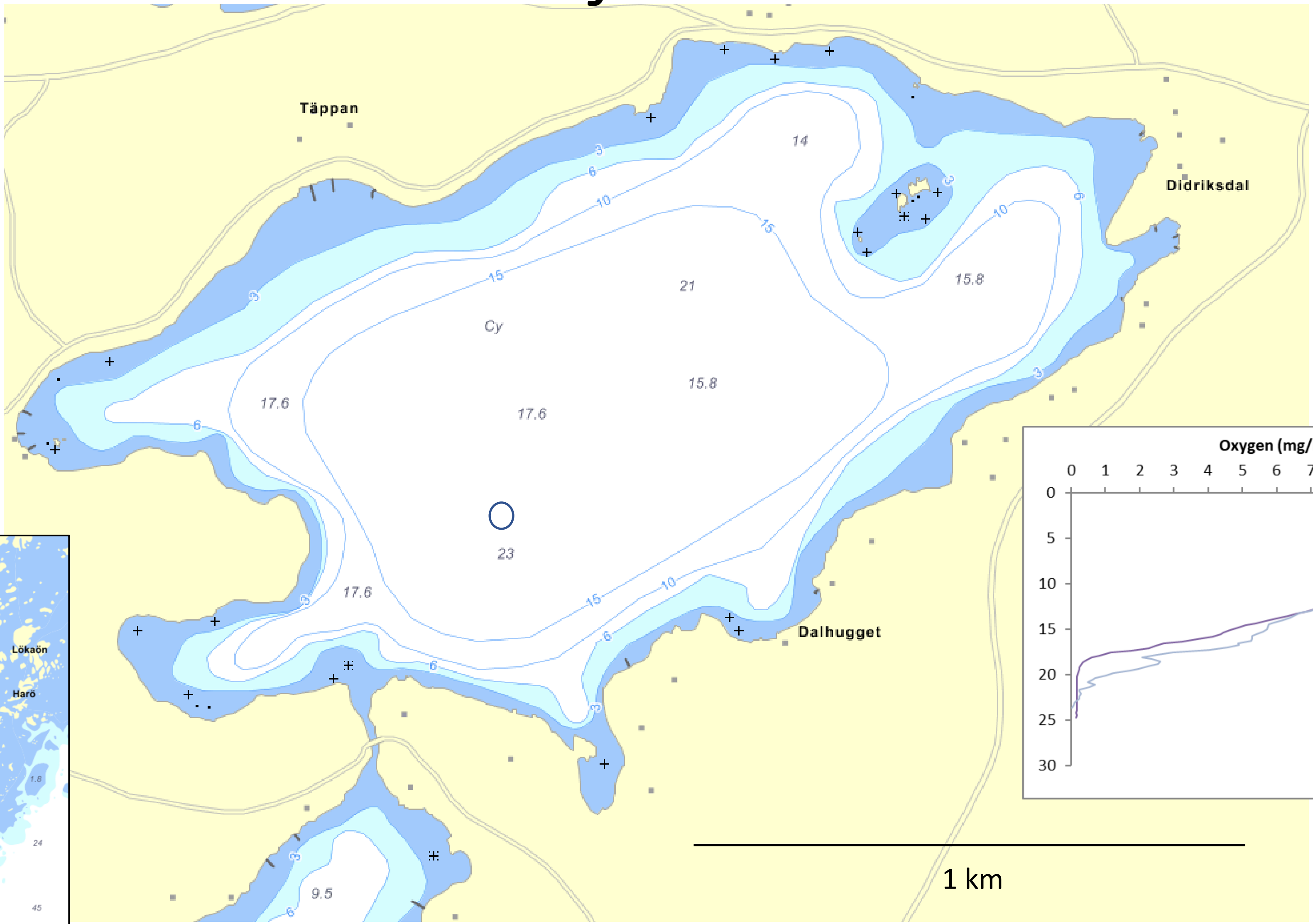
9. Vårgärdssjön

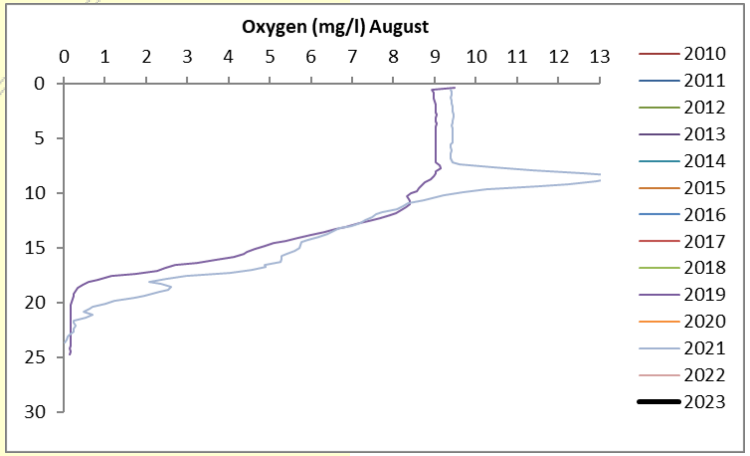




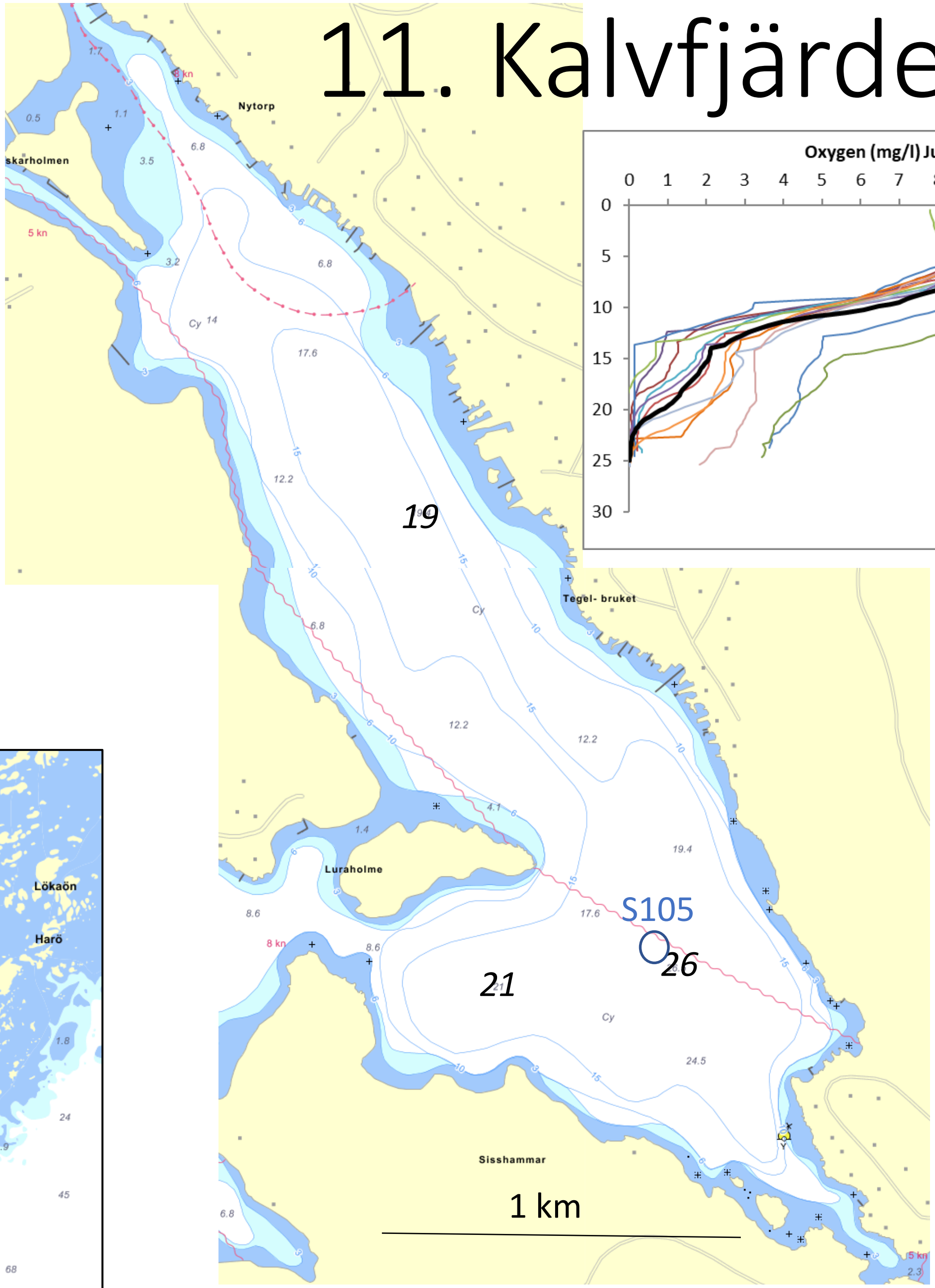


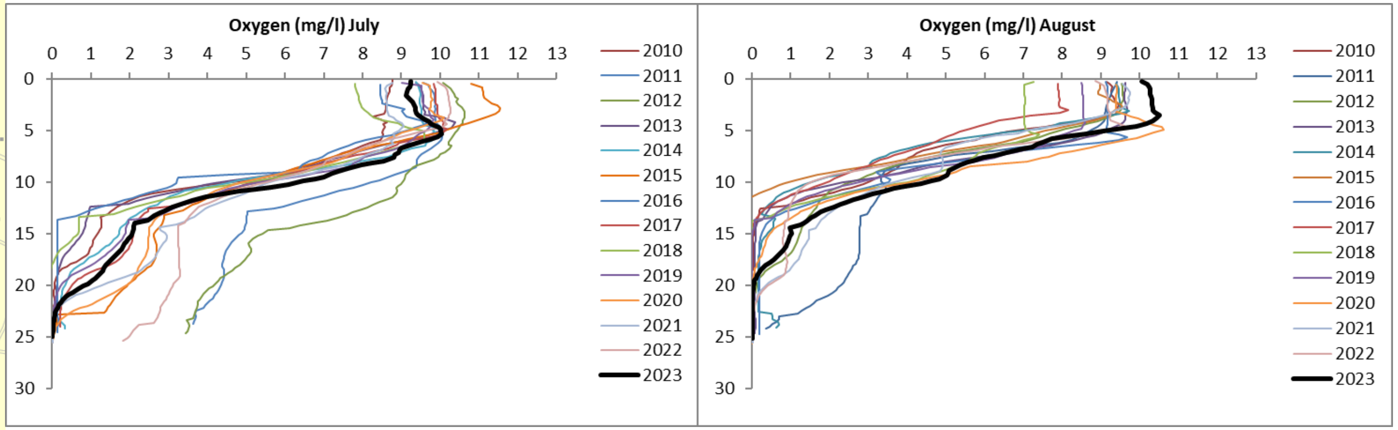
10. Våmfjärden



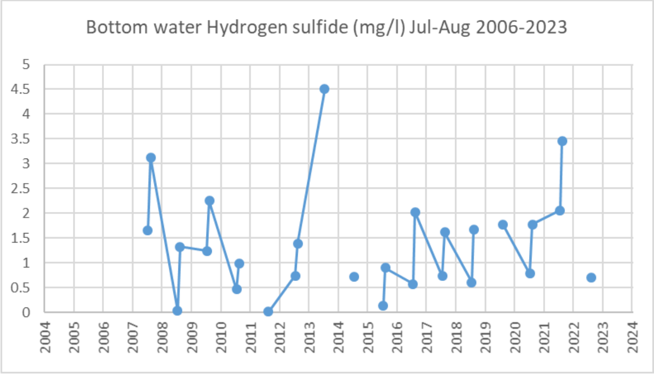


11. Kalvfjärden



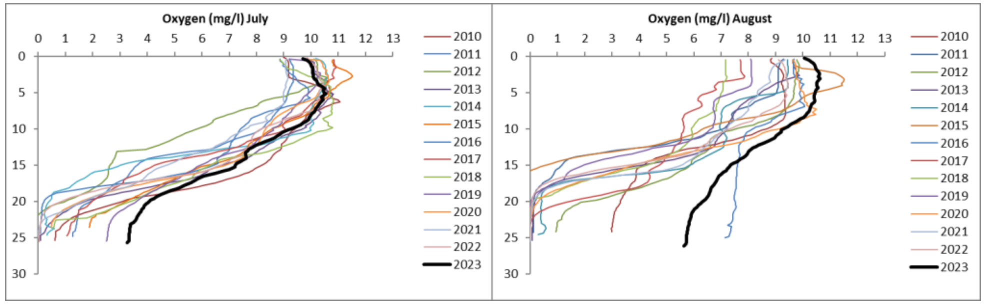


Station S105 (data from SKVVF)

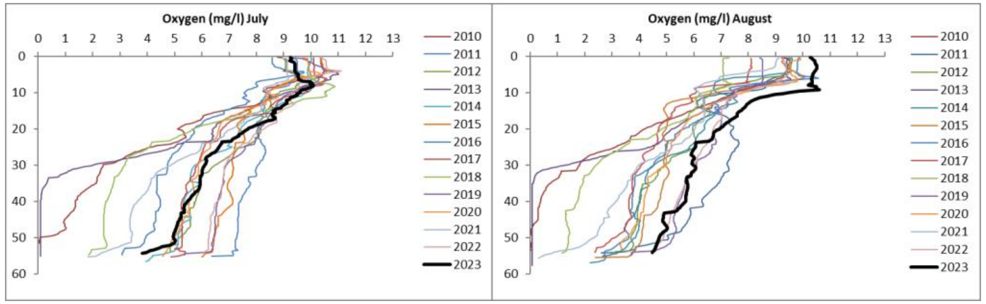


Stations close to 11. Kalvfjärden

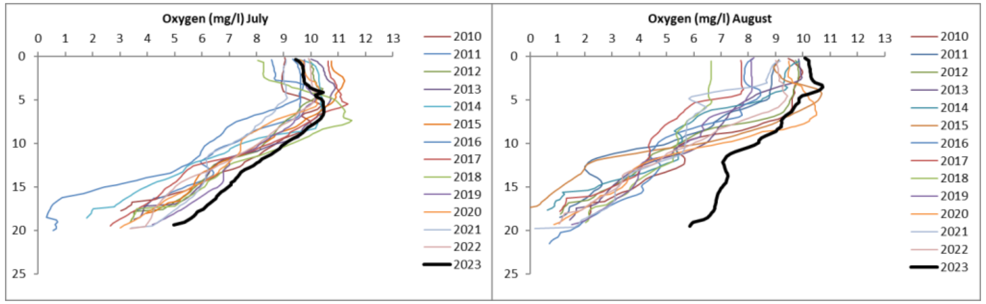
S103



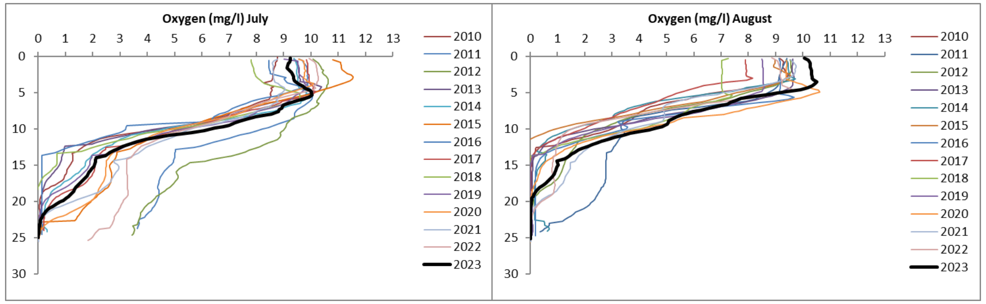
S102



S104

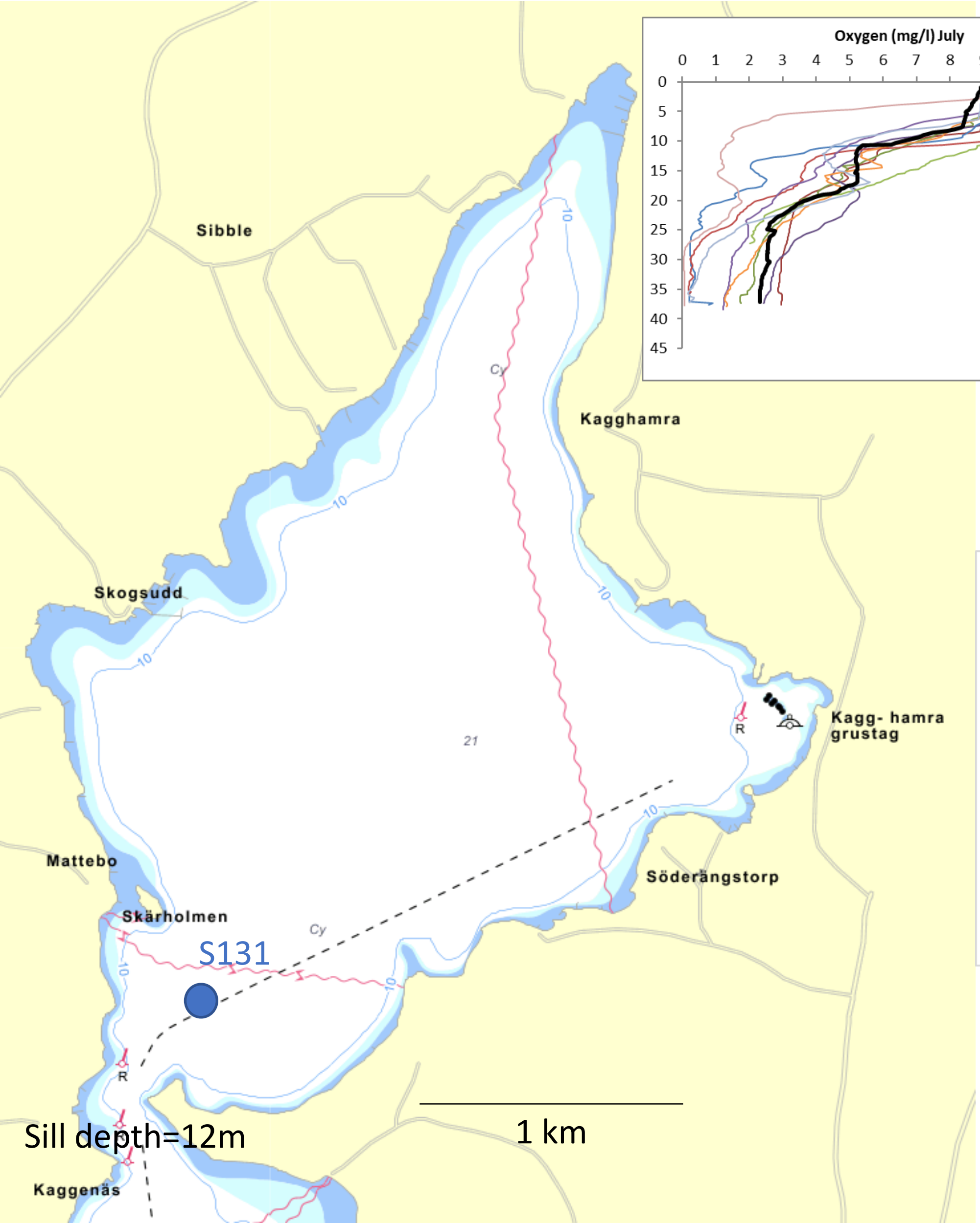


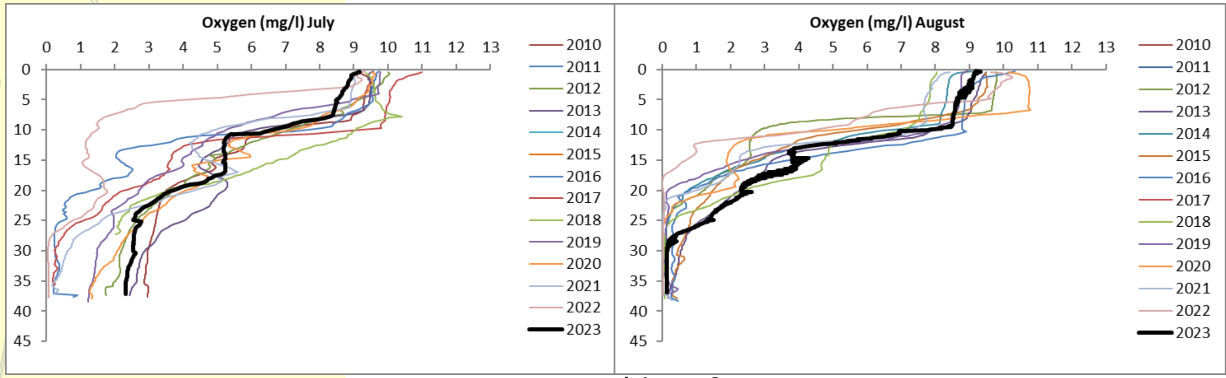
S105



12. Björnöfjärden

13. Kaggfjärden





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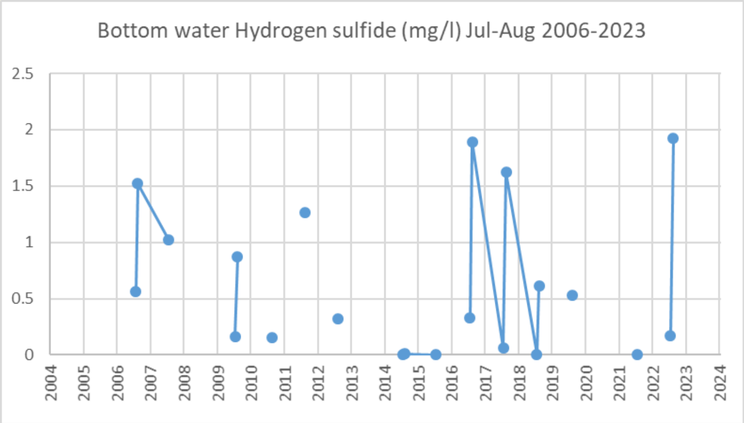
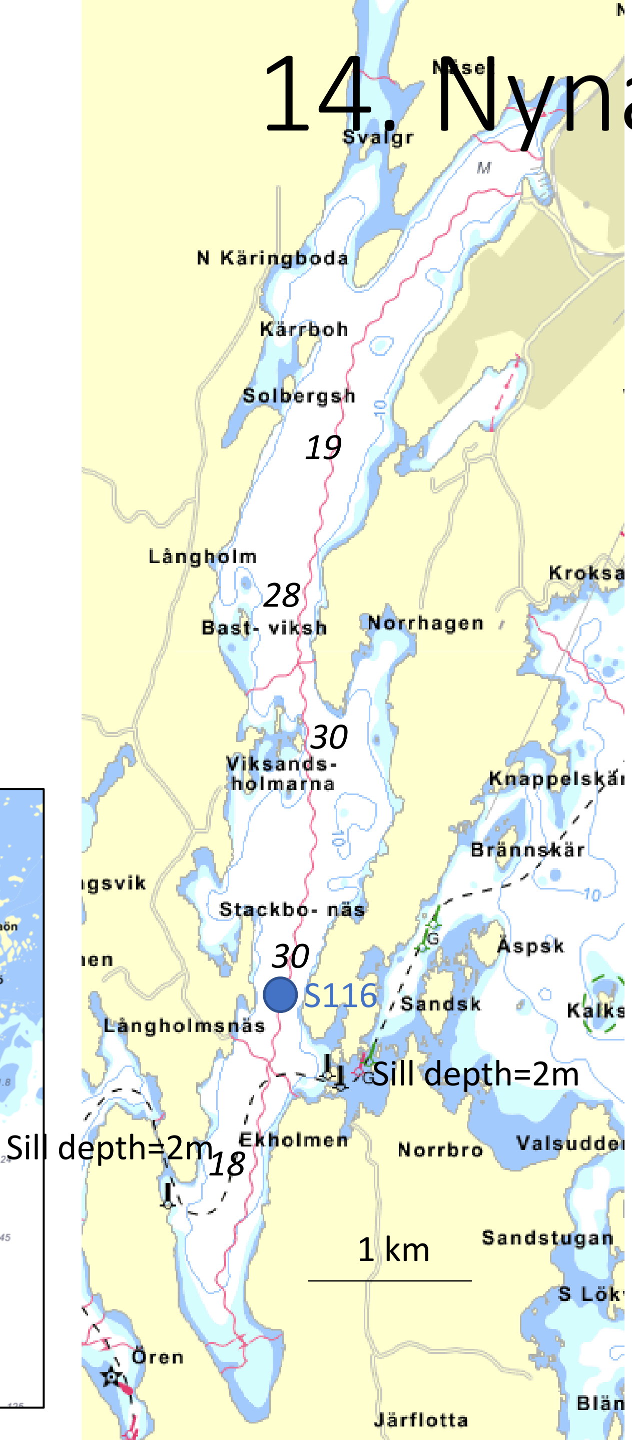
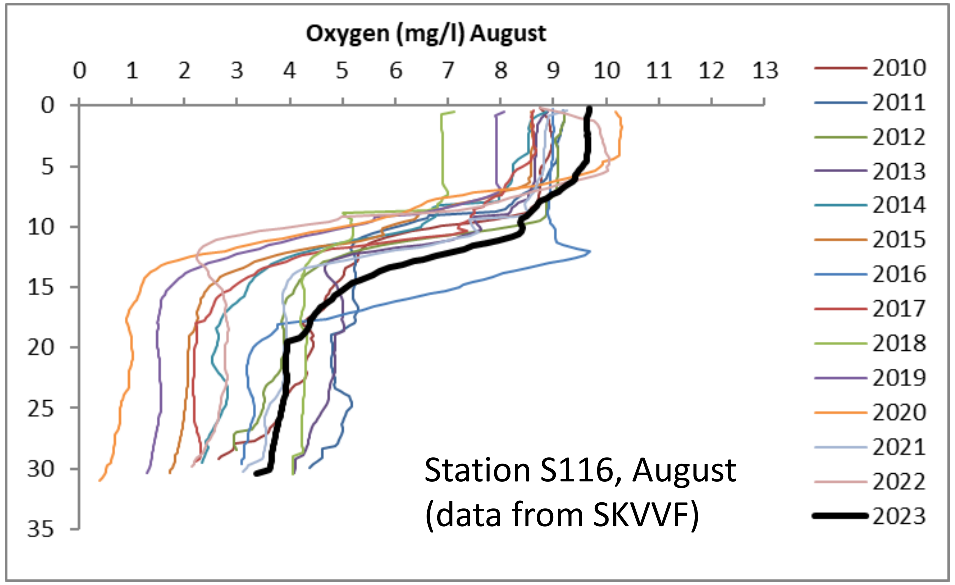


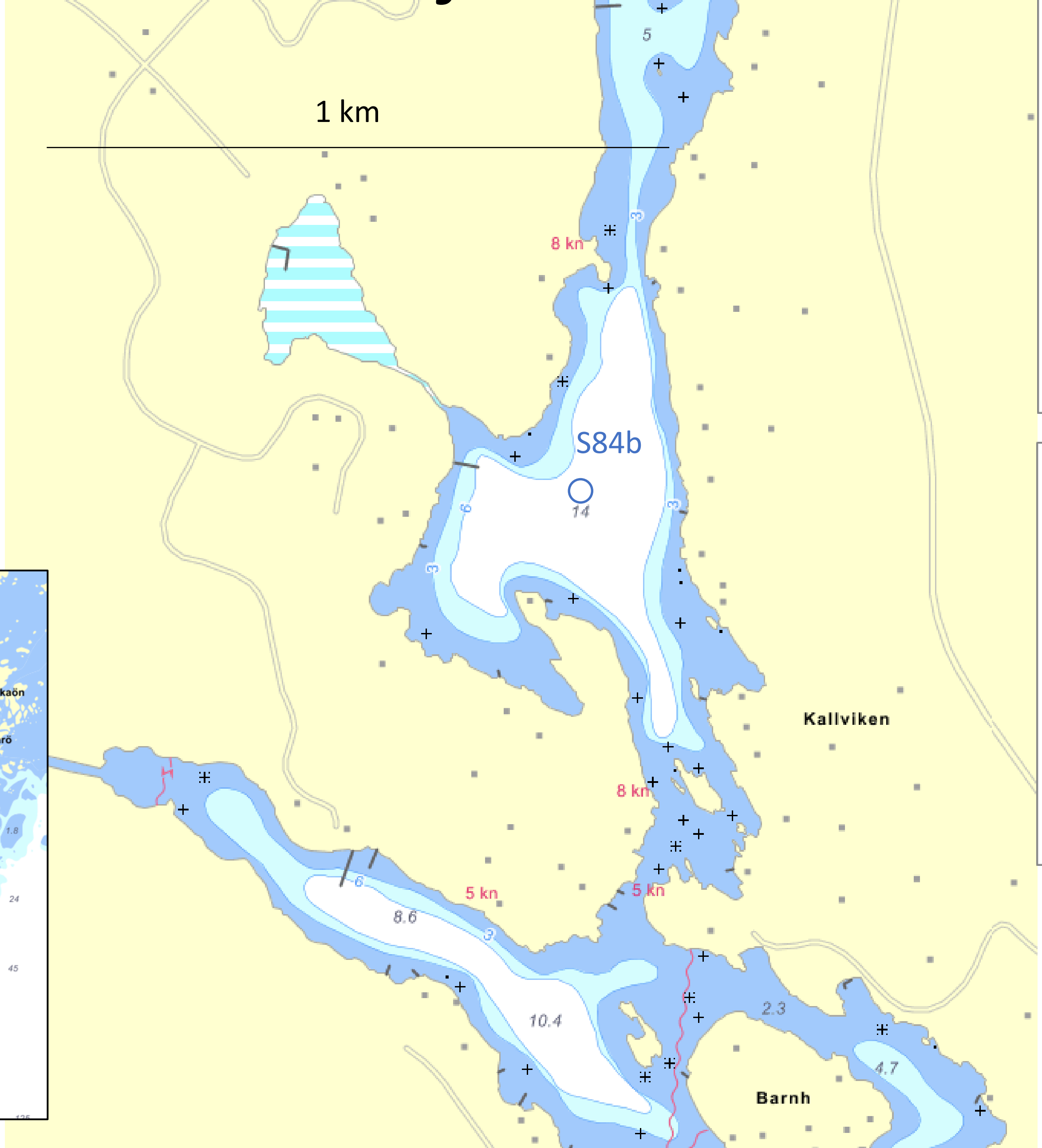
13. Kaggfjärden

14. Nynäsviken

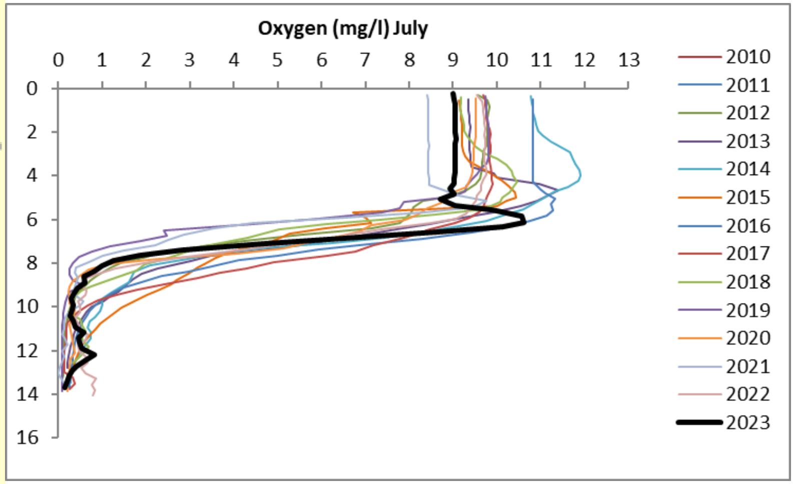


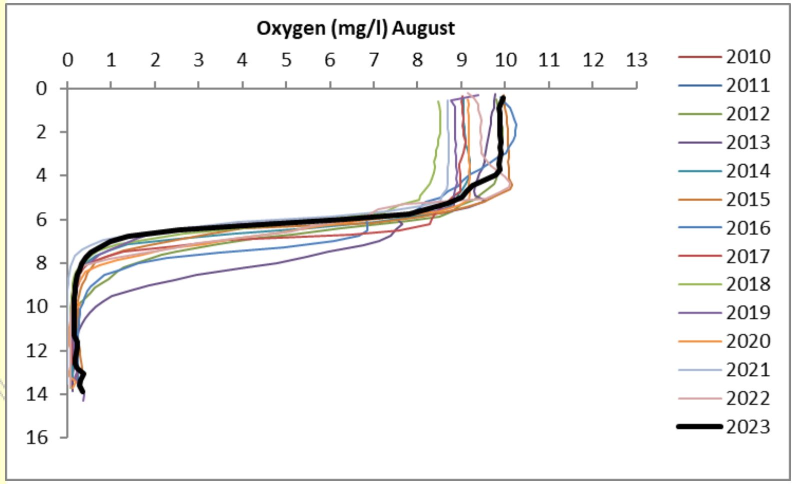


15. Fjällsviksviken

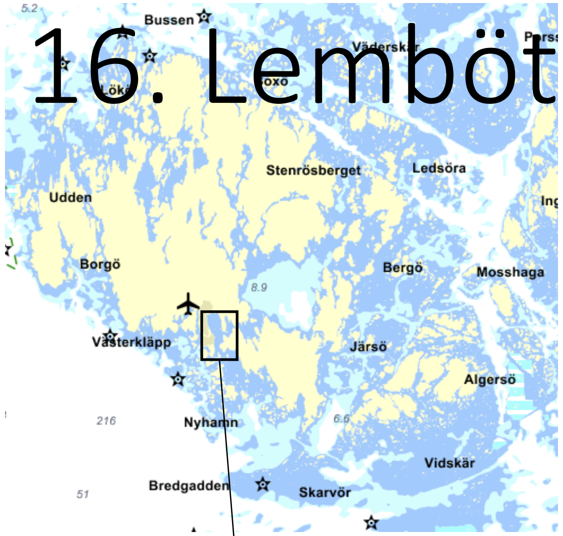


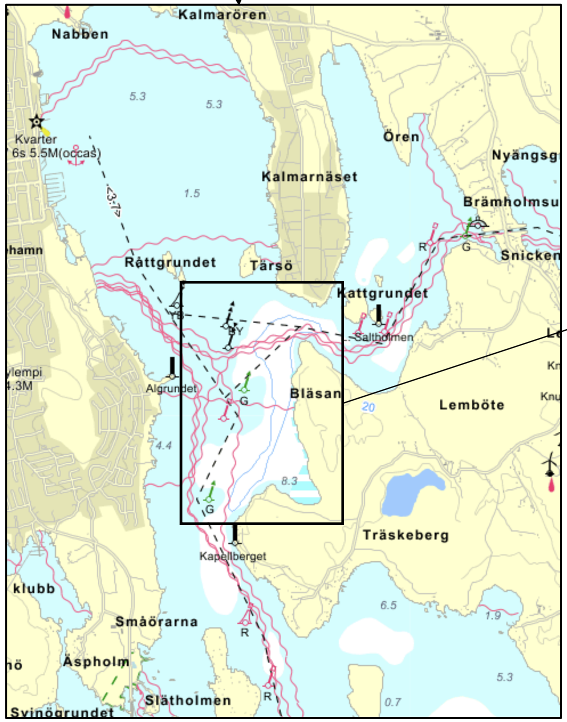
Station S84b (data from SKVVF)

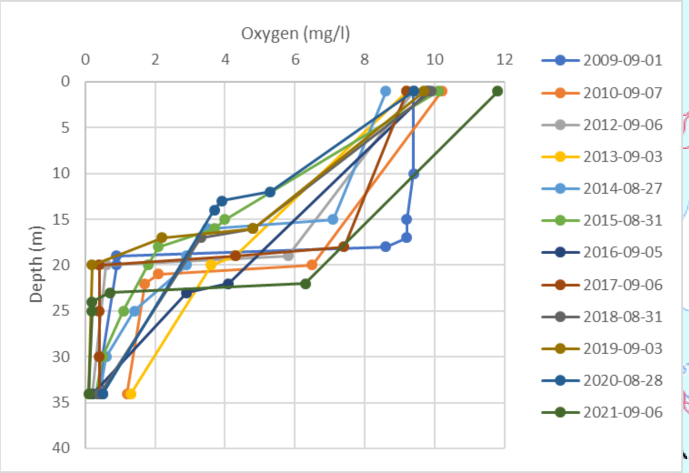


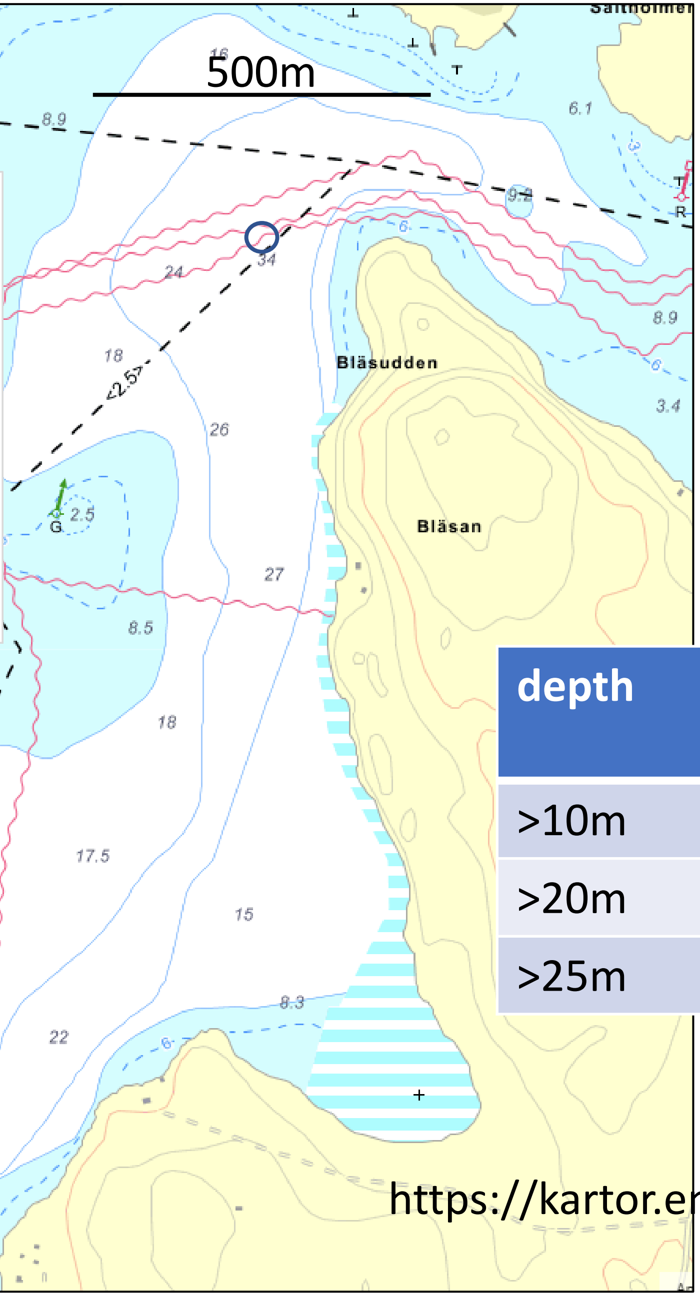


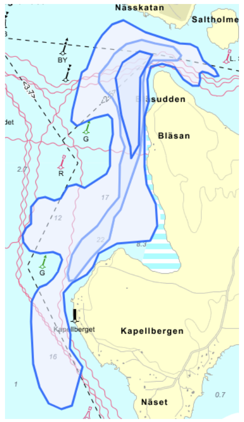
16. Lembötebergen (Ål2)







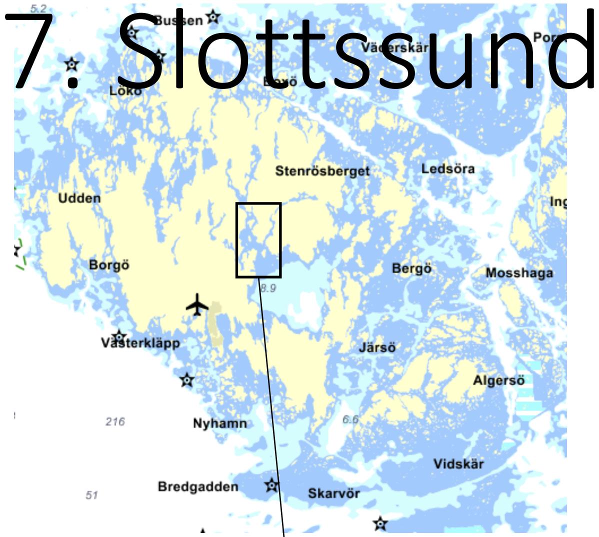


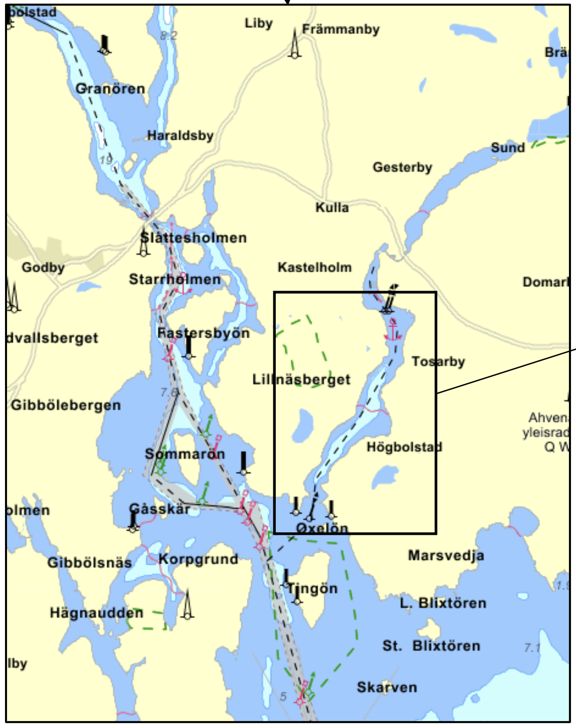


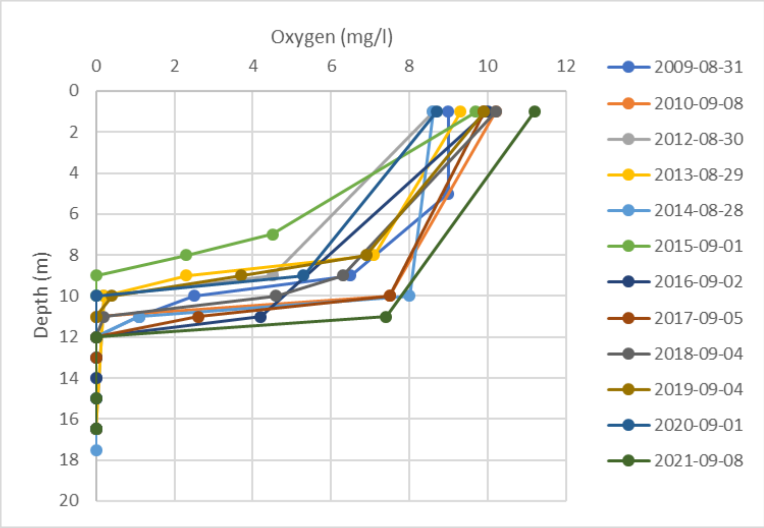
depth	Area km2
>10m	1.05
>20m	0.2647
>25m	Ca 0.08

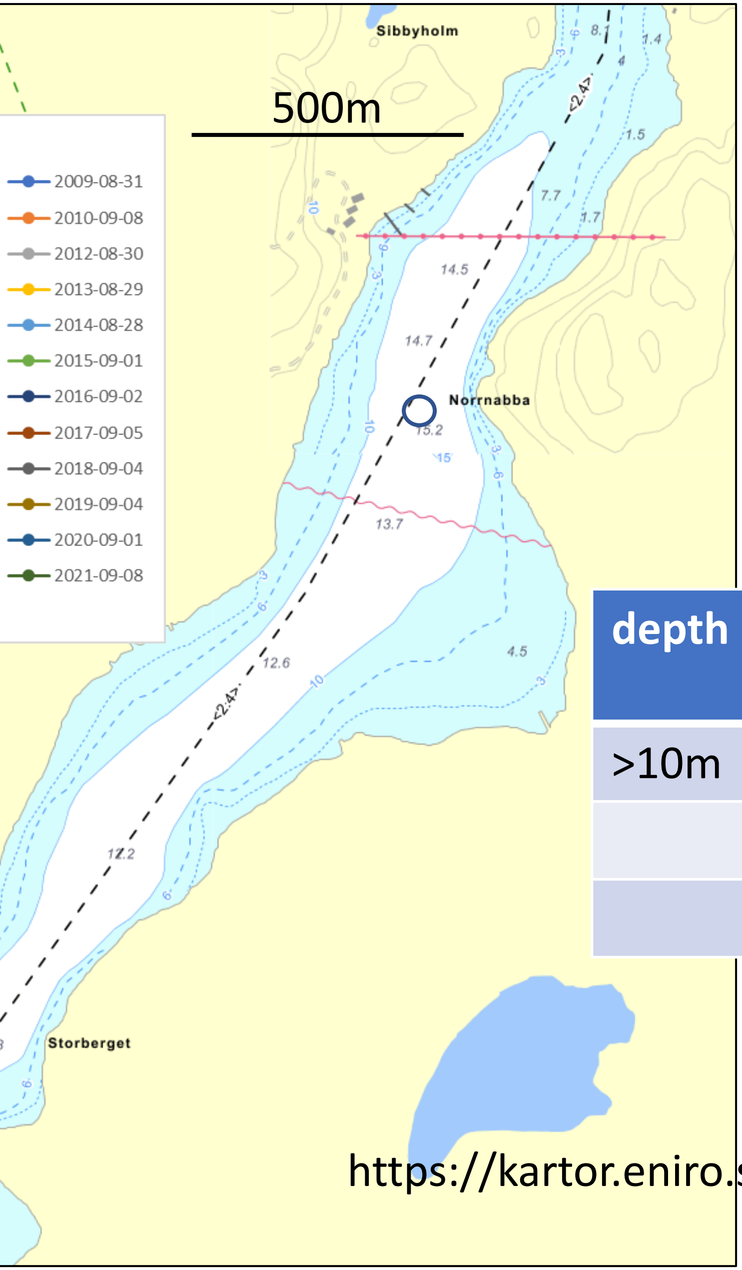
https://kartor.eniro.se/m/ijqOt

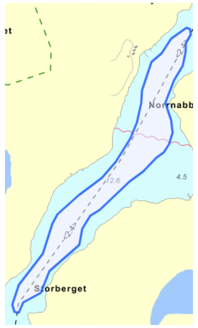
17. Slottssundet (Ål8)









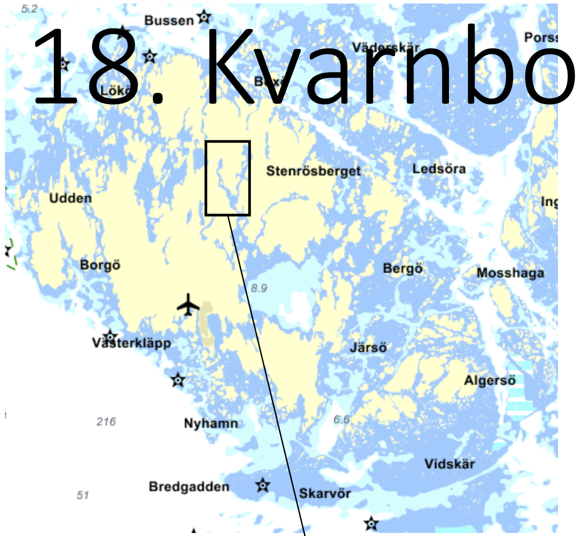


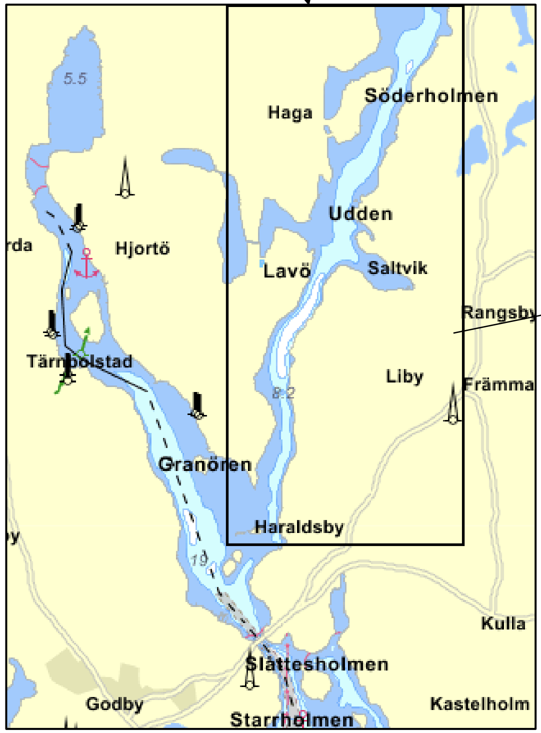
depth	Area km2
>10m	0.3515

https://kartor.eniro.se/m/geMLX

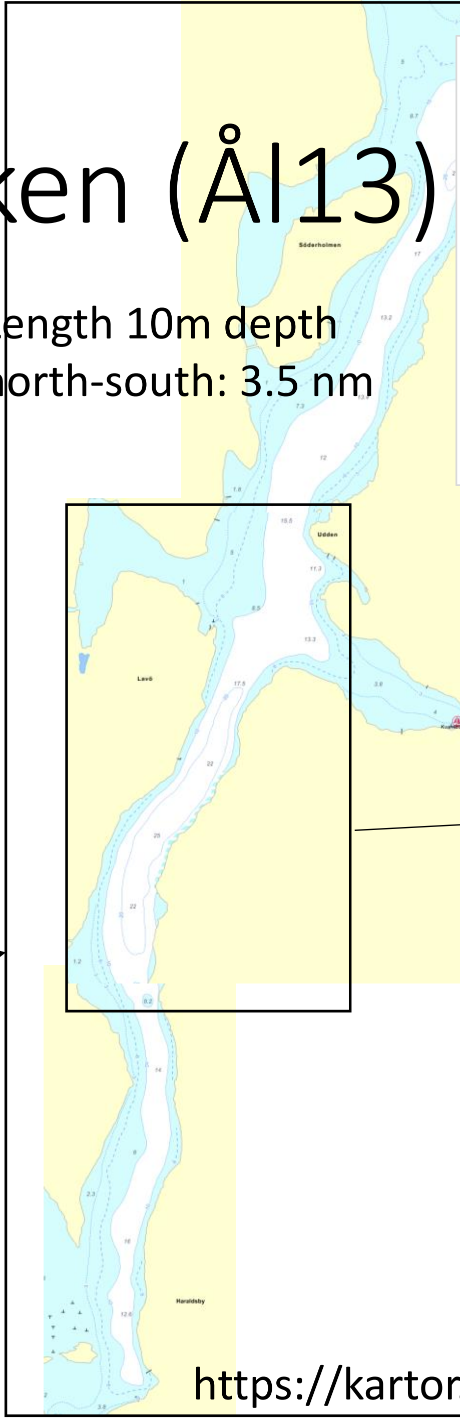
60º 16.27 N, 20º 1.44 E

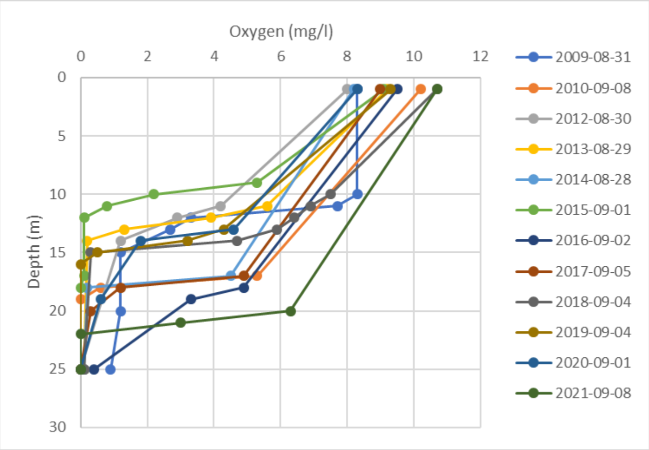
18. Kvarnboviken (Ål13)

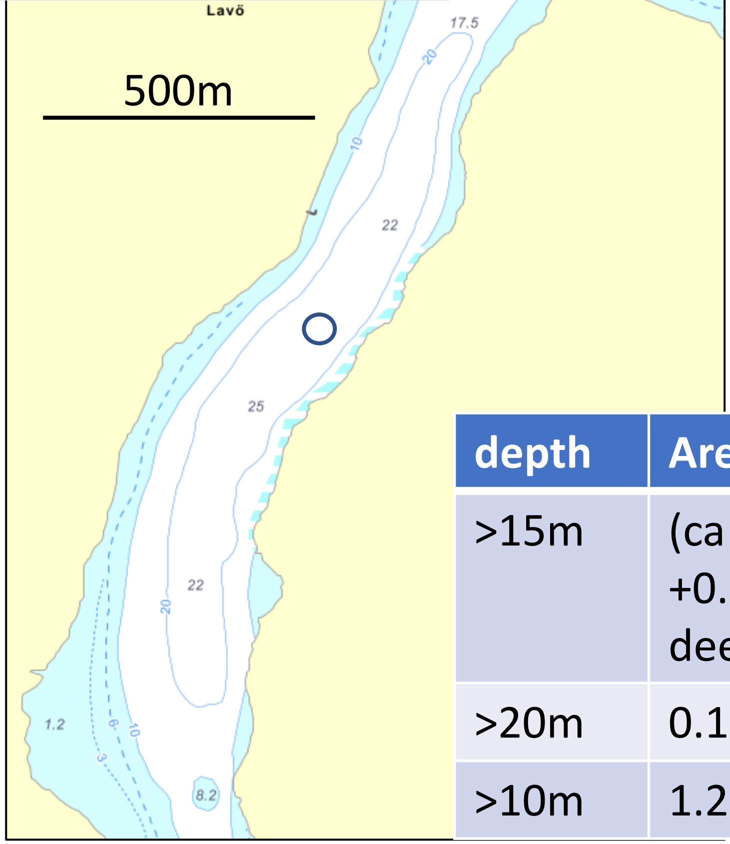


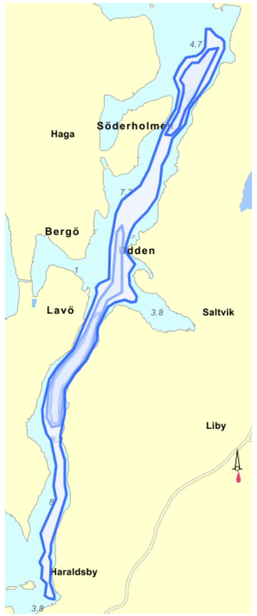


Length 10m depth north-south: 3.5 nm





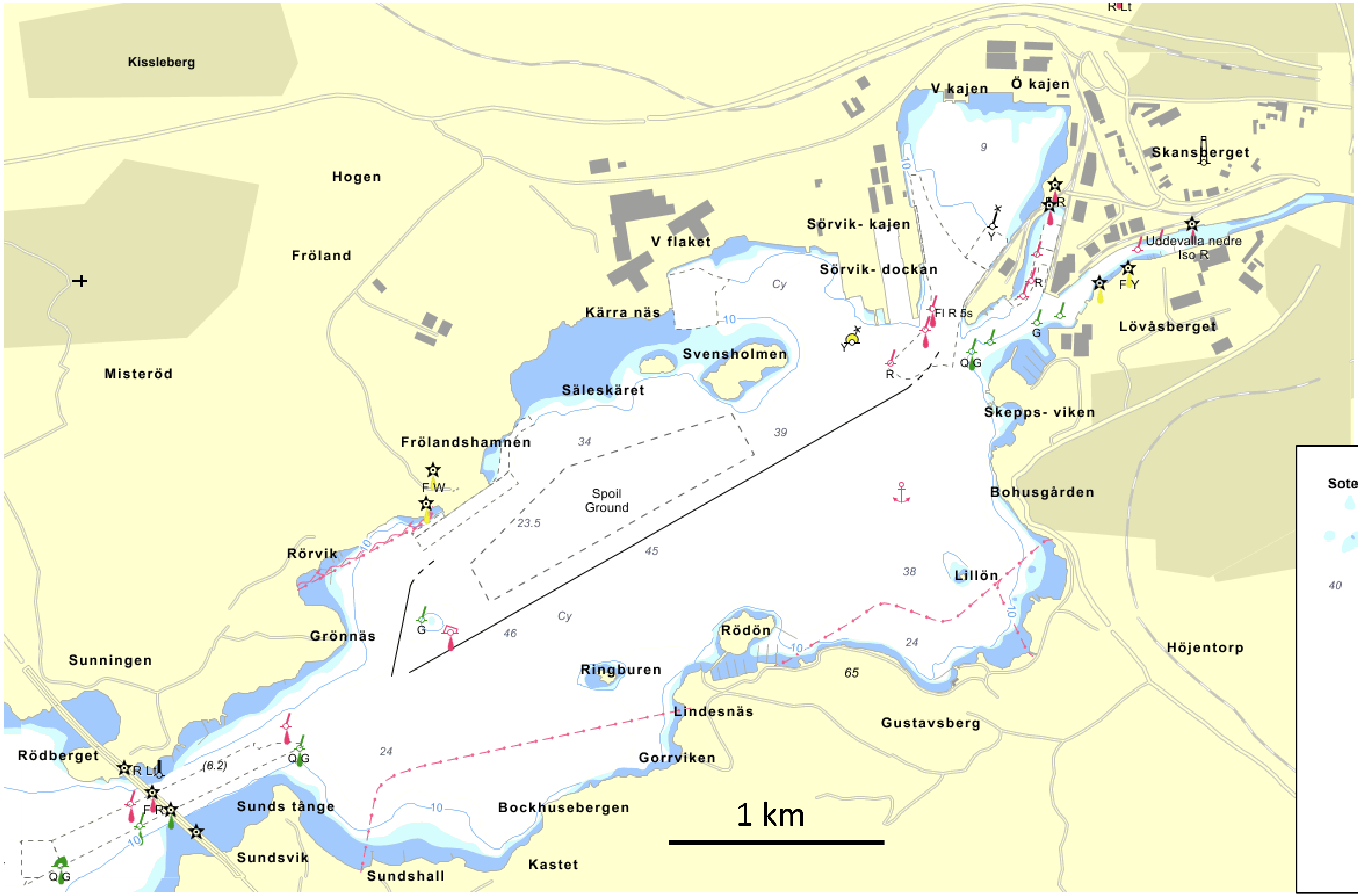


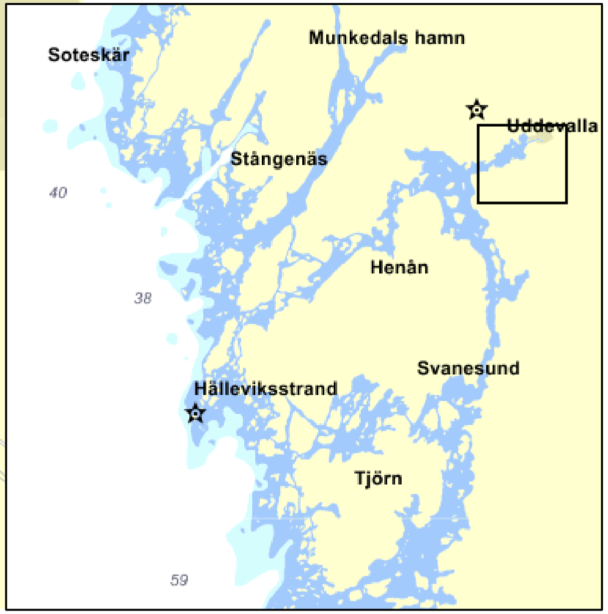


depth	Area km2
>15m	(ca 0.2876) +0.1308 (N deep area)
>20m	0.1335
>10m	1.21

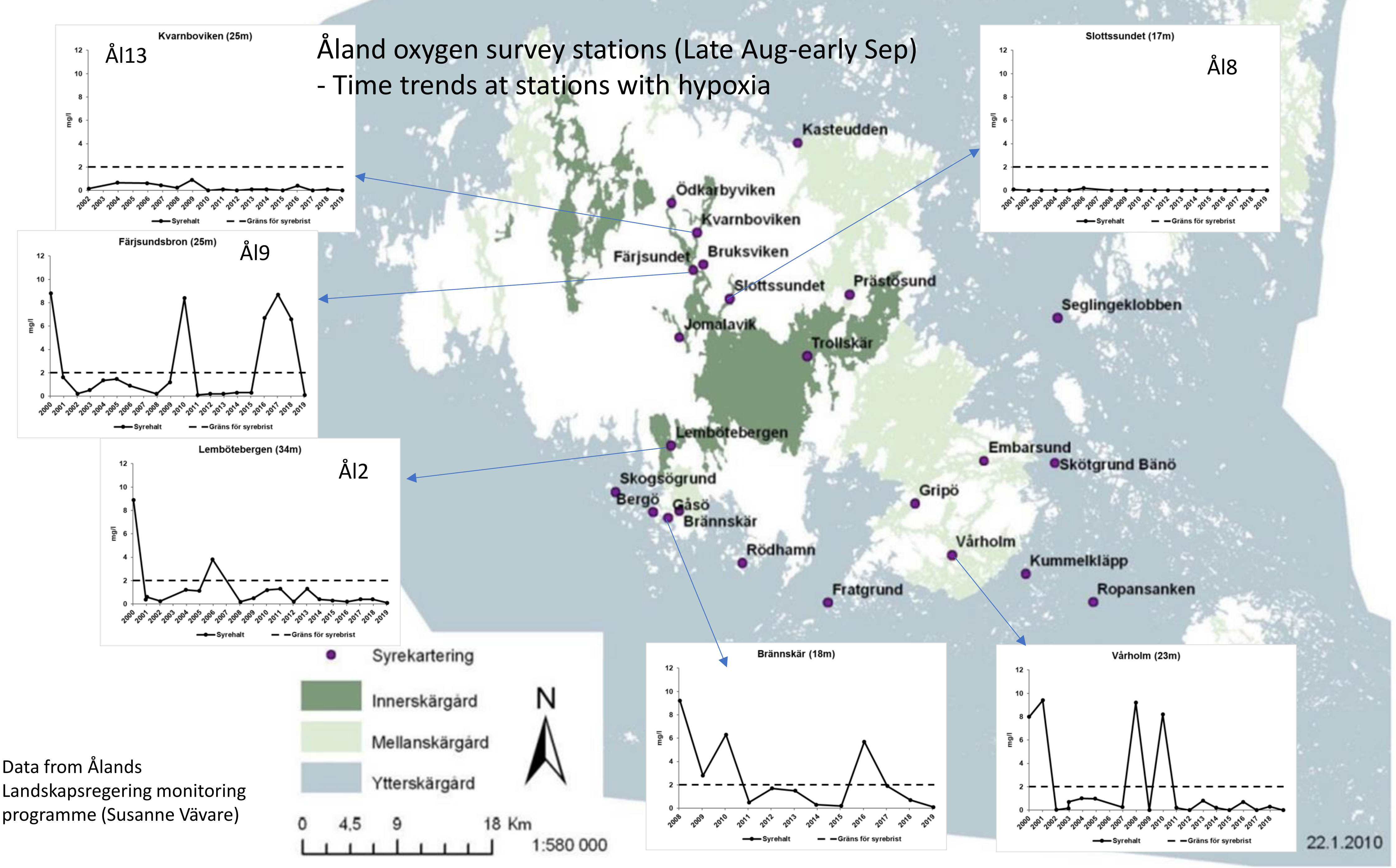
https://kartor.eniro.se/m/sCgoL https://kartor.eniro.se/m/Gx6ha

19. Byfjorden



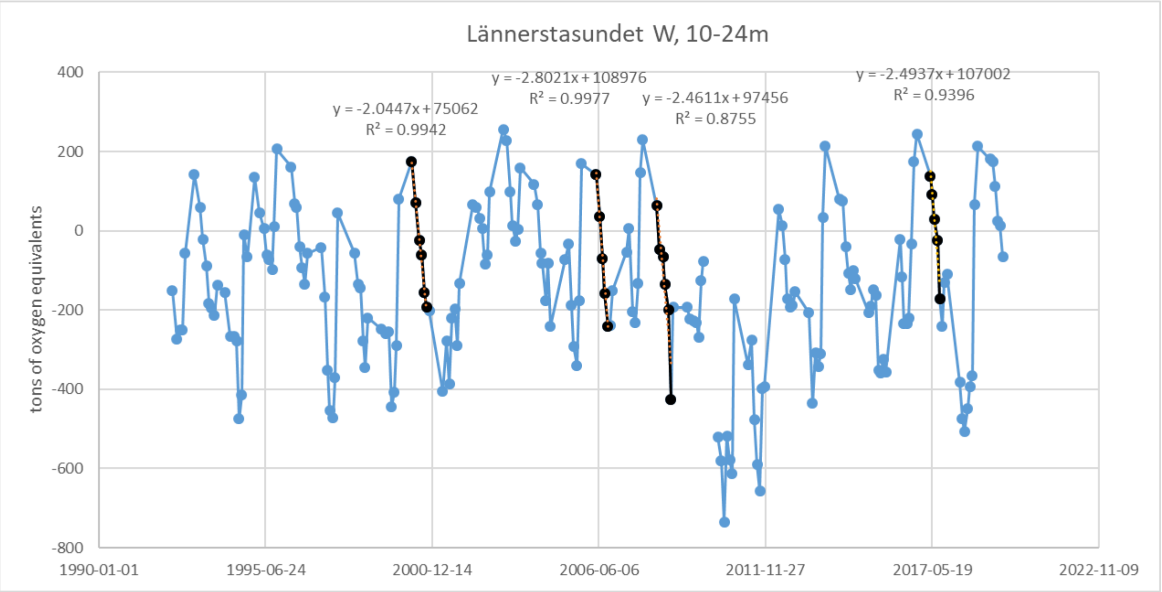


Åland oxygen survey stations (Late Aug-early Sep)
- Time trends at stations with hypoxia

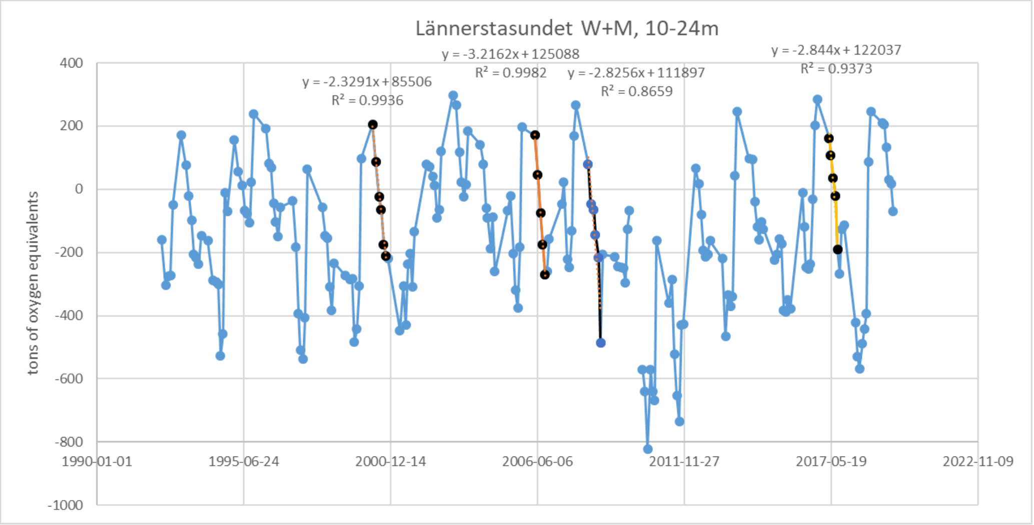


Data from Ålands Landskapsregering monitoring programme (Susanne Vävare)

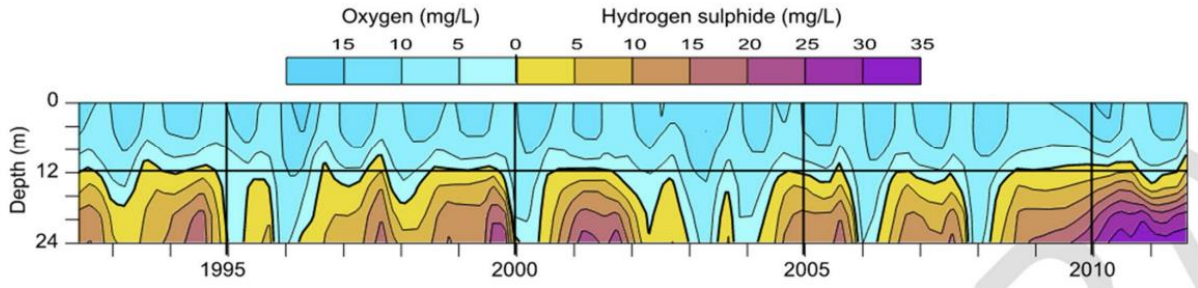
Oxygen consumption in Lännerstasundet



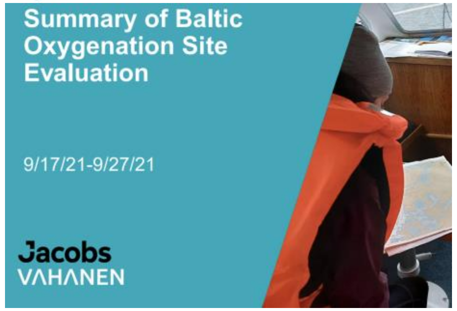
Consumption rate 2-3 tons O2 per day
(based on basin volumes and depth interpolated O2 and H2S data, for each 1m depth layer, summed for 10-24m)



Pilot Sizing Basis of Design



- Initial Feed Rate: 30 mg/L H2S Consumption in 30 Days
  - Oxygen Demand: 8,000 kg/d
  - Design Flux Rate: 27 kg/d/km
  - Active Diffuser Length 300 m of diffuser
- Maintenance Dose: SOD of 1 g/m/d
  - Oxygen Demand: 870 kg/d
  - Design Flux Rate: 5 kg/d/km
  - Active Diffuser Length 160 m of diffuser



Appendix 4. Electrolyser projects data

Table 1. Electrolyser projects under development that were evaluated in the desktop study. Red text indicates that the project has been cancelled since the evaluation was first conducted.

Country	#	Company	Project name	Site	Coordinates (WGS84 lat-long)	End-product	ELZ type	ELZ capacity
Finland	1	Green NorthH2 Energy		Naantali	60.466358, 22.030678	H2 & NH3		280 MW
Finland	2	P2X Solutions		Harjavalta	61.314182, 22.146549	H2		20 MW
Finland	3	P2X Solutions	Green reindeer - GHP02	Joensuu	62.592077, 29.785309	H2 & e-fuels		30-50 MW
Finland	4	Fortum & SSAB		Raahe	64.685016, 24.486809	H2		700 MW
Finland	5	Flexens	Flexens Kokkola	Kokkola	63.852623, 23.043137	H2 and NH3		300 MW
Finland	6	Flexens		Lempäälä	61.313605, 23.757935	H2		2.5 MW
Finland	7	Nordic Ren-Gas Oy		Lahti	60.978104, 25.670929	H2 & P2X		120 MW
Finland	8	Nordic Ren-Gas Oy		Mikkeli	61.687918, 27.271156	H2 & P2Gas		40 MW
Finland	9	Nordic Ren-Gas Oy		Kotka	60.464496, 26.94191	H2		60 MW
Finland	10	Nordic Ren-Gas Oy		Tampere	61.493215, 23.786774	H2 & P2Gas		60 MW
Finland	11	Neste Oy	SHARC	Porvoo	60.391809, 25.685349	H2		120 MW --> 360 MW later
Finland	12	St1	St1-Power-to-Methanol	Lappeenranta	61.053633, 28.22525	Methanol		17-35 MW
Finland	13	PlugPower		Kokkola	63.852623, 23.043137	H2 & NH3	PEM	1 GW
Finland	14	PlugPower		Kristiinankaupunki	62.275111, 21.375618	H2	PEM	1 GW
Finland	15	PlugPower		Porvoo	60.391809, 25.685349	H2	PEM	200 MW
Finland	16	Prime Capital AG		Kristiinankaupunki	62.275111, 21.375618	H2		200 MW

Finland	17	Raahen Monivoima & Kokkolan Energia		Raahe	64.685016, 24.486809	H2		5,7 MW
Finland	18	ET Fuels		Ranua	65.928414, 26.516876	Methanol		500 MW
Finland	19	Blastr Green Steel	Inkoo Green Steel Plant	Inkoo	60.045989, 24.004784	low CO2 steel & integrated H2 facility		
Finland	20	OX2	Långnäs Mega Grön Hamn	Lumparland (Åland)	60.116861, 20.297306	H2 & marine fuels		< 3 GW
Finland	21	Helen		Helsinki	60.186598, 24.966431			2 MW
Finland	22	Vantaa Energia		Vantaa	60.289875, 25.044022	Power 2 Materials/chemicals		100-500 MW
Finland	23	Vantaa Energia		Vantaa	60.289875, 25.044022	Power 2 gas		22 MW
Finland	24	UPM Kymmene Oy		Lappeenranta	61.053633, 28.22525	Biorefinery H2		20 MW
Finland	25	EPV Energia Oy	H-FLEX-E	Vaasa	63.097244, 21.626587	H2 & P2X2P		10 MW
Sweden	1	Ovako		Hofors	60.545464, 16.294785	H2		20 MW
Sweden	2	Uniper & Perstorp Group	Project Air	Stenungsund	58.062261, 11.843262	Methanol	Alkaline	30 MW
Sweden	3	Liquid Wind & Ørsted	FlagshipONE	Örnsköldsvik	63.300962, 18.705597	methanol		70 MW
Sweden	4	Liquid Wind	FlagshipTWO	Sundsvall	62.403096, 17.303467	methanol		140 MW
Sweden	5	Lhyfe		Trelleborg	55.375209, 13.160248	H2		5 MW
Sweden	6	Vattenfall,SAS, Shell, LanzaTech	HySkies	Forsmark	60.371787, 18.155594	SAF		200 MW
Sweden	7	Statkraft & Göteborgs Hamn		Gothenburg	57.721753, 11.988831	H2		4 MW
Sweden	8	Vattenfall & St1		West coast		eSAF		
Sweden	9	OKG		Oskarshamn	57.263079, 16.457005	H2		0,7 MW
Sweden	10	Svea vind Offshore		Gävle	60.675869, 17.141418	H2		7 MW
Sweden	11	Skyborn Renewables & Lhyfe	SoutH2Port	Söderhamn	61.300089, 17.034988	H2		600 MW
Sweden	12	RES		Alby	62.526101, 15.650883	H2		<500 MW
Sweden	13	Uniper & Sasol ecoFT	SkyFuelH2	Långsele	63.175937, 17.067776	SAF		300 MW

Sweden	14	Uniper, ABB & Luleå hamn	BotnialänkenH2	Luleå	65.585436, 22.164917	H2		100 MW
Sweden	15	H2 Green Steel		Boden	65.826407, 21.711731	H2		800 MW
Sweden	16	Grupo Fertiberia	Green Wolverine	Boden/Luleå		NH3		600 MW
Sweden	17	Lhyfe		Härjedalen	62.035055, 14.352951	H2		5 MW
Sweden	18	Karlstads Energi		Karlstad	59.378513, 13.500481	H2		20 MW --> 120 MW
Sweden	19	Liquid Wind	FlagshipTHREE	Sundsvall	62.403096, 17.303467	Methanol		140 MW
Sweden	20	SSAB	Hybrit	Luleå	65.585436, 22.164917	H2		400? MW
Sweden	21	LKAB	Hybrit	Gällivare/Kiruna		H2		70 + 800 MW
Denmark	1	Linde Gas A/S & Port of Aabenraa		Aabenraa	55.039041, 9.418716	H2 to NH3		100 MW
Denmark	2	Ørsted et al.	H2RES	Avedøreværket	55.610257, 12.475491	H2	N+1?	2 MW
Denmark	3	PlugPower		Holstebro	56.361827, 8.607788			100 MW
Denmark	4	European Energy / Vindtestcenter Måde		Esbjerg	55.466789, 8.462906			9 MW
Denmark	5	European Energy / Padborg PtX		Padborg	54.821953, 9.353313	e-fuels		150 MW
Denmark	6	Electrochaea / Biocat Roslev		Rybjerg				10 MW
Denmark	7	European Energy / Kassø PtX Expansion		Rødekro	55.069326, 9.346275			10 MW
Denmark	8	Ørsted et al.	Green Fuels for Denmark	Greater Copenhagen	55.684166, 12.532654	e-fuels		10 MW (2025) 100 MW (2027) 300 MW (2029)

								1,3 GW (2030)
Denmark	9	Everfuel		Holstebro	56.361827, 8.607788	H2		100 MW
Denmark	10	H2 Energy		Esbjerg	55.466789, 8.462906	H2		1 GW
Estonia	1			Tallinn/Paldiski				
Estonia	2			Saaremaa	58.427764, 22.312865			
Estonia	3			Narva	59.374781, 28.177703			
Estonia	4			Tartu	58.373748, 26.729252			
Estonia	5			Järvakandi	58.775079, 24.810405			
Estonia	6	H2Nodes?		Pärnu	58.389924, 24.489033	Hydrogen		
Latvia	1	Freeport of Ventspils & PurpleGreen Energy C		Ventspils	57.404727, 21.608617	H2		
Latvia	2	Riga airport		Riga	56.929426, 23.987670			
Poland	1	LOTOS		Gdansk	54.342166, 18.643327	H2		100 MW
Germany	1	HH2E		Lubmin	54.133714, 13.616646	H2	Alkaline	50 MW 2025 500 MW 2030
Germany	2	HH2E Werk Theirbach GmbH		Borna	51.122282, 12.493156	H2		100 MW 2025 1 GW 2030

Finland

At the time of writing (October 2024), Finland has the largest share of currently known electrolyser projects that match the criteria of this project. Most of them are located along the Western and Southern coasts. As the level of anoxia and hypoxia is the largest around the Baltic Proper, the most interesting projects in Finland would theoretically be located in the Southwest and on Åland.

F1 – Green North2 Energy is planning to build a 280 MW electrolyser in Naantali, that is set to be commissioned in 2026. The produced hydrogen will be further derived to ammonia that will be used mainly in the food industry and in the future also as fuel for marine vessels. The by-produced heat will be used in the district heating network in Turku. The initial investment cost is estimated to be EUR 600 million (Green North Energy , n.d.), and the company has been granted EUR 2.3 million in funding by Business Finland (Elomatic, 2022). Flexens has a minority share of Green North2 Energy.

F5: Flexens Kokkola – Flexens is planning to build a 350 MW electrolyser in Kokkola. The plant will produce hydrogen that will be further derived to ammonia and is planned to be ready for production in 2028. The investment cost of the plant is estimated at EUR 800 million. Other projects are also planned in the same region, for example, Plug Power´s 1 GW proton exchange membrane (PEM) electrolyser, expected to be ready by the end of this decade.

F20: Långnäs Mega Green Harbour – Another interesting project in Finland is OX2´s and the Bank of Åland´s (Ålandsbanken) plans on converting Långnäs harbour to what they describe as a "mega green harbour". The companies have together initiated a feasibility study of the concept. The electrolyser would have a capacity demand of 3 GW and is planned to source its electricity demand from the companies' potential offshore windfarms in the area (Pettersson, 2023). If this project gets realized, it could be ideal for the BOxHy project, considering it would produce hydrogen with electricity from offshore windfarms and would be located on one of the energy islands, Åland.

F21: 3H2 – Helen is planning to build a 3 MW electrolyser in Helsinki, that will produce hydrogen for the heavy transport sector, while the waste heat is to be used in Helen´s district heating network. The project reached its final investment decision (FID) in 2024 and is planning to start its production in 2027. The project has received EUR 8.25 million in investment support from the Ministry of Economic Affairs and Employment for large-scale demonstration projects in new energy technology (Helen, 2024).

Sweden

Sweden, like Finland, is at the forefront of the hydrogen economy and has many announced projects in the pipeline. Many of the projects are located along the East coast. Project S8 has not been included on the map in the figure as the location is not specified enough.

Based on the electrolyser locations in relation to the sub-basins with the highest oxygen demands in connection to Sweden (BY31, BY32, BY38 and BY05), for example, S6, S9 and S10 could be considered as interesting projects. However, they share different limitations making them unsuitable at this stage, such as already defined off-takers or limited information. Hence, more mature, and therefore suitable projects have been identified as the most interesting, S2: Project Air – Uniper and Perstorp Group are planning to build a methanol production facility in Stenungsund at the West coast of Sweden, from which the methanol is to be utilized in the chemical industry. Included in the facility is a 30 MW pressurized alkaline electrolyser. The water needed in the electrolysis process will be purified wastewater and the carbon dioxide needed for the methanol production will be captured from Perstorp´s other operations (Project Air, n.d.). The project received EUR 97 million from the Innovation Fund in 2023 (Project Air, 2023), and is planned to be commissioned in 2026.

S7 – Statkraft and the Port of Gothenburg (Göteborgs hamn) are planning a 4 MW electrolyser at the Port of Gothenburg, the biggest port in Scandinavia. The electrolyser will produce 750 tonnes of hydrogen per year to be used in the transport sector, both maritime and land based, either locally or exported for external use (Statkraft, 2021). The project got accepted by the County Board in late 2023 (Länsstyrelsen Västra Götaland, 2024).

S11: SoutH2Port – Skyborn Renewables, ABB, and Lhyfe are planning a 600 MW electrolyser in Söderhamn that will produce hydrogen. The electrolyser will be located next to Skyborn Renewables planned 1 GW offshore wind park outside the East coast of Sweden. ABB will explore the opportunities of using the produced hydrogen as an energy storage. If the projects get realized, it will make Skyborn, ABB, and Lhyfe one of the biggest hydrogen suppliers in Europe (Lhyfe, 2023).

Another project of interest in Sweden is by Gotlandsbolaget and H2 Green Steel that are exploring the options of producing hydrogen for consumption by a part of their future fleet. It is yet to be determined whether the ferries would bunker hydrogen on Gotland, in Nynäshamn, or somewhere else. H2 Green Steel will utilize the expertise gained from developing the S15 project in Boden. The electrolyser has an estimated capacity demand of 300 MW, and the goal is to have one ferry operating on hydrogen by 2030 at the latest (Gotlandsbolaget, 2023). In terms of the scope of BOxHy, this project could be ideal, especially if the hydrogen is to be produced on Gotland, also classified as an energy island.

Denmark

Denmark does not yet have as many projects as the other Nordic countries. In 2023, Denmark launched its own hydrogen and derivative tender totaling DKK 1,25 billion (EUR 168 million), with the same basic concept of the European Hydrogen Bank (EHB). At the end of the year, it was revealed that six projects with a combined capacity of almost 280 MW had been granted the subsidy. One single developer, European Energy, accounted for 80 % of the total awarded budget. All the awarded projects must have their facilities in operation within four years, that is 2027 (Hydrogen Insight, 2023). These projects are marked from D3 to D7 on the map in the figure. As seen, neither of these are coastal projects, although both D5 and D7 are within a 30 km distance from the port of Aabenraa. Other projects, that have more accessible information, are,

D1 – Linde Gas A/S and Port of Aabenraa have an ambition of installing a 100 MW electrolyser at Aabenraa, which has one of the deepest ports in the Baltic Sea. The energy will be sourced from offshore windfarms in the North Sea, and the produced hydrogen will be used to further produce other fuels (Linde Gas , 2021).

D2: H2RES - Ørsted and others are planning a demonstration project of a 2 MW n+1 electrolyser at Avedøreværket, that will use energy from two 3,6 MW offshore wind turbines. The electrolyser will produce around 365 tonnes of hydrogen per year that will be used in the road transport sector. The construction of the plant started in 2021, however, it remains unknown whether it has been put in commission.

D8: Green Fuels for Denmark – Ørsted and others are also planning to produce e-fuels in the Greater Copenhagen area. The plan is to increase the electrolyser capacity over the years, starting with 10 MW in 2025, 100 MW in 2027, 300 MW in 2029, after which it will reach its full capacity of 1.3 GW post 2030. During the first phase, the produced hydrogen will be used for heavy-duty road transport, while its use case will be extended to derivation to methanol for the maritime industry and kerosene for the aviation sector during phase 2. In phase 3 onwards, the production of methanol and kerosene will be increased, with the aim of producing kerosene for 30 % of the pre-pandemic jet-fuel consumption of Copenhagen airport, exceeding the total demand for Danish domestic flights (Ørsted, n.d.). More recent articles do, however, suggest that some these targets could be reached even quicker (Ørsted, 2022).

Germany

Germany has an ambitious hydrogen strategy, with an estimated demand of 2.7-3.9 million tonnes by 2030. They do, however, plan to import about 70 % of that (Hydrogen Central, 2023). Hence, they do not have too many public projects in the pipeline. There is, however, one company that is of particular interest.

G1 – HH2E is constructing an alkaline electrolyser in Lubmin, on the Northeast cost of Germany. The plan is for the electrolyser to be 50 MW in 2025, but to reach 500 MW in 2030. The site will be connected to and source its electricity from nearby offshore windfarms in the Baltic Sea. The site also already has connections to a gas pipeline in place. HH2E is planning a combined capacity of 4 GW from multiple production facilities around Germany and has already located over 15 interesting sites (HH2E, n.d.).

Germany has also participated in the EHB under the "auction-as-a-service" scheme, meaning that they have added EUR 350 million as an addition the EHB´s original EUR 800 million, only to be allocated to German projects (European Commission, n.d.). This indicates that Germany has serious projects in the pipeline.

Poland

There availability of information regarding hydrogen in Poland is scarce, however, at least one project is publicly available.

P1 – Lotos is planning to build a 100 MW electrolyser, from which the produced hydrogen will partly replace the grey hydrogen used in a refinery owned by Lotos´s parent company, PKN Orlen. The refinery is located in Gdansk and the electrolyser is planned to be built on the same site, estimated to be set in commission in 2027. The project has been granted EUR 158 million by the Polish government (Hydrogen Insight, 2023).

Estonia
Estonia has established a hydrogen valley concept, including 30 projects, ranging from renewable energy production to use cases. Hydrogen will be produced on at least six locations around the country and will be used in the transport and industrial industries. Other parameters of a hydrogen industry are also planned, such as fuelling stations and export/import terminals. There is around 7 GW of offshore power production potential, of which at least a part is planned to be used for hydrogen production, starting from 2029.

The available information on these projects is still limited, however, a few of the locations stand out.

E1 – Tallinn/Paldiski area.

E2 – Saaremaa.

E6 – Pärnu.

The common factor among these projects is that they all have coastal connections and are located near planned renewable energy production sites.

Latvia
The Latvian Hydrogen Association have compiled a map of their hydrogen projects around the country. Most of the projects still lack information.

La1 – Freeport of Ventspils and PurpleGreen Energy are planning to produce hydrogen in Ventspils. Freeport of Ventspils has a vision of making the area into an energy production and export hub, in which hydrogen has a crucial role (Port of Ventspils, 2023).

La2 – Riga airport is testing hydrogen solutions in the aviation industry. The project has been approved within the framework of the Interreg Baltic Sea Programme funding category "green mobility". This facilitates the connection with other aviation hubs in the Baltic Sea region, with a joint focus on utilisation of hydrogen in small aircrafts (Riga Airport, 2023).

Lithuania
The information of the Lithuanian hydrogen situation is limited.

Li1 – Achema, which is Lithuania´s biggest fertiliser producer, is planning to build an electrolyser that will produce hydrogen that will be further derived to ammonia. The facility will be located near a 264 MW onshore windfarm that is planned to be built in 2026. The Nordic Investment Bank has participated with a loan of EUR 100 million to facilitate the realization of the project (Polly, 2024)

Appendix 5. Offshore wind parks data

Table 1. All offshore wind parks mapped in the desktop study.

Country	Developer	Wind Park Name	Capacity (MW)	Development Phase	Estimated COD	Latitude	Longitude
Finland	OX2	Ajos Repowering	26,4	Production	2023	65.66800000019992	24.545000000149912
Denmark	nan	Anholt	399,6	Production	2023	56.6002436587243	11.217641118249299
Germany	nan	Arkona-Becken Südost	384	Production	2023	54.78285622465518	14.121069312383304
Sweden	OX2 AB	Aurora	5500	Concept/ Early Planning	2030	nan	nan
Denmark	nan	Avedøre Holme	10,8	Production	2023	55.60222966955402	12.461203166148763
Germany	Iberdrola	Baltic Eagle	476	Under construction	2024	54.82834558791665	13.860219007233532
Sweden	Njordr Offshore Wind AB	Baltic Offshore Alpha	2100	Concept/ Early Planning	2031	58.28000000000003	18.350000000299815
Sweden	Njordr Offshore Wind AB	Baltic Offshore Beta	2460	Consent application submitted.	2030	55.610000000299806	16.16999999980021
Sweden	Stakraft	Baltic offshore Delta	5000	Concept/ Early Planning	2032	59.0800000001999	20.049999999600345
Sweden	Njordr Offshore Wind AB	Baltic Offshore Epsilon	3000	Concept/ Early Planning	2032	58.60999999970028	19.90999999970029
Poland	Orlen-Northland Power	Baltic Power	1140	Final Investment decision	2026	55.04999999980021	17.649999999900103
Poland	PGE Baltica	Baltica 1	896	Planned	2030	55.560000000399725	17.529999999600363
Poland	PGE Baltica-Årsted	Baltica 2	1500	Under construction	2027	55.07000000029984	17.100000000099953
Poland	PGE Baltica-Årsted	Baltica 3	1000	Under construction	2030	55.059999999600336	17.450000000299838
Poland	PGE Baltica-Tauron	Baltica 4	990	Concept	2030	55.03404	17.217975
Poland	PGE Baltica	Baltica 9	975	Feasibility study	2029	54.971072	16.416083
Sweden	Eolus Vind AB	Blekinge Offshore AB	1000	Concept/ Early Planning	2027	55.95999999960037	14.959999999700301
Sweden	nan	Bockstigen Offshore	2,75	Production	2023	57.03600000039978	18.149999999800173

Sweden	Svea Vind Offshore AB	Bores Krona	3400	Concept/ Early Planning	2030	65.12000000000006	22.31000000029985
Finland	Ilmatar Offshore Oy	Bothnia & Bothnia West	10000	Concept	2031	61.92033	4.21180555555556
Sweden	Stakraft	Bothnia Offshore Lambda	1600	Concept/ Early Planning	2034	61.600000000199884	18.32999999980018
Sweden	Njordr Offshore Wind AB	Bothnia Offshore Omega	1500	Concept/ Early Planning	2034	64.89000000009997	22.950000000099976
Sweden	Njordr Offshore Wind AB	Bothnia Offshore Sigma	3354	Concept/ Early Planning	2034	61.95000000039977	19.31999999980019
Sweden	Freja Offshore AB	Cirrus	2000	Consent application submitted.	2029	nan	nan
Sweden	Hexicon AB	Dyning	2500	Concept/ Early Planning	2029	58.22000000029982	17.860000000199875
Estonia	Latvian Investment and Development agency	ELWIND	1000	Planned	2030	58.04000000029981	23.81999999980019
Germany	nan	EnBW Windpark Baltic 1	48,3	Production	2023	54.60926532063462	12.650490461186735
Germany	nan	EnBW Windpark Baltic 2	288	Production	2023	54.982701108839265	13.162383780543564
Denmark	tbd.	Energy Island Bornholm	3000	Feasibility study	2033	nan	nan
Sweden	Deep Wind Offshore DWO Sverige AB	Erik Segersäll 1	2000	Concept/ Early Planning	2032	58.7899999997000285	19.599999999600357
Sweden	Deep Wind Offshore DWO Sverige AB	Erik Segersäll 2	2000	Concept/ Early Planning	2034	58.7899999997000285	19.599999999600357
Sweden	Deep Wind Offshore DWO Sverige AB	Erik Segersäll 3	2000	Concept/ Early Planning	2036	58.7899999997000285	19.599999999600357
Sweden	Skyborn Renewables Sweden	Eystrasalt Offshore	4000	Permit application handed in for approval.	2032	nan	nan
Poland	BTI-RWE	F.E.W. Baltic II	350	Feasibility study	2026	54.884191	16.236132
Denmark	Frederikshavn OWF ApS	Frederikshavn Havvindmoellepark	72	Final Investment decision	2028	nan	nan

Denmark	nan	Frederikshavn Offshore	7,6	Production	2023	57.44383242020566	10.562079010657149
Sweden	Skyborn Renewables Sweden	Fyrskeppet Offshore	2800	Permit application. Consent application submitted.	2030	nan	nan
Sweden	Ørsted Wind Power A/S	Gävle East	5500	Concept/ Early Planning	2034	60.87000000039973	17.889999999600377
Sweden	Ørsted Wind Power A/S	Gävle West	4000	Concept/ Early Planning	2032	61.089999999600366	18.230000000000075
Sweden	OX2	Galatea	1700	Consent application submitted.	2030	nan	nan
Sweden	OX2 AB	Galene	400	Consent Authorised.	2028	nan	nan
Sweden	Årsted Wind Power A/S	Gotland	1500	Concept/ Early Planning	2029	56.759999999800186	17.889999999600377
Sweden	Svea Vind Offshore AB	Gretas Klackar 1	1600	Consent application submitted.	2029	nan	nan
Sweden	Simply Blue Group	Herkules I	1000	Concept/ Early Planning	2029	56.40999999960036	19.179999999900133
Sweden	Simply Blue Group	Herkules II	1750	Concept/ Early Planning	2029	56.8300000001999	19.449999999900115
Denmark	tbd.	Hesselø	800	Feasibility study	2029	nan	nan
Denmark	European Energy	Jammerland Bugt	240	Feasibility study	2026	55.57109815489051	10.966825520106568
Denmark	Wind Estate	Kadet Banke	504	Concept	2027	nan	nan
Sweden	nan	Karehamn	48	Production	2023	56.979999999900144	17.019999999900108
Denmark	tbd.	Kattegat Havvindmøllepark	1000	Feasibility study	2030	nan	nan
Sweden	Vattenfall Vindkraft AB	Kattegatt South	1200	Consent Authorised.	2027	nan	nan
Finland	Vattenfall	Korsnäs, Korsnäsin merituulipuisto	1300	Feasibility study	2028	62.75157	20.24796
Finland	OX2	Korsnäs, Närpiö, Kaskinen, Tyrsky	1400	Feasibility study	2032	62.621818	20.401231
Denmark	nan	Kriegers Flak	605	Production	2023	55.025768810156976	12.932268040310868
Denmark	tbd.	Kriegers Flak 2	640	Feasibility study	2028	nan	nan
Finland	Metsähallitus	Kristiinankaupunki, Kristiinankaupungin merituulivoimahanke	1400	Concept	2030	61.57617	21.00474

Finland	Suomen Merituuli Oy	Kristiinankaupunki, Siipyy	900	Feasibility study	2030	62.10581	21.14868
Sweden	Hexicon AB	Kultje	2150	Concept/ Early Planning	2029	56.94999999960038	17.630000000299844
Sweden	Svea Vind Offshore AB	Långgrund 1	2000	Consent application submitted.	2028	58.64999999980023	17.67000000039974
Sweden	Svea Vind Offshore AB	Långgrund 2	2310	Consent application submitted.	2028	58.50999999990012	17.339999999800227
Estonia	Enefit Green	Liivi	1100	Concept	2029	nan	nan
Denmark	Soenderborg Forsyningsservice A/S and European Energy	Lillebaelt Syd	160	Feasibility study	2028	nan	nan
Denmark	nan	Lillebklt Syd	160	Planned	2028	55.11896563969386	9.83861141337348
Sweden	nan	Lillgrund	110	Production	2023	55.50900000024984	12.763000000349791
Sweden	nan	Lovstaviken	11,5	Production	2023	56.88748068633467	12.469769583349633
Poland	Polenergia-equinor	MFW BaÅ‚tyk 1	1560	Final Investment decision	2029	55.495301	17.013927
Poland	Polenergia-equinor	MFW BaÅ‚tyk 2	720	Final Investment decision	2027	54.96514	16.751372
Poland	Polenergia-equinor	MFW BaÅ‚tyk 3	720	Final Investment decision	2027	55.033353	17.079116
Denmark	nan	Middelgrunden	40	Production	2023	55.691443246511085	12.669864919303713
Finland	Metsähallitus	Närpiö, Närpiön merituulivoimahanke	1600	Concept	2030	62.20413	22.05237
Sweden	Eolus Vind AB	Najaderna	1000	Concept/ Early Planning	2032	60.819999999600384	18.27000000009997
Sweden	OX2 AB	Neptunus	3100	Concept/ Early Planning	2032	55.66000000019989	16.3999999997003
Denmark	HOFOR	Nordre Flint	160	Feasibility study	2027	55.655909411175784	12.861813634899974
Finland	Ilmatar Offshore Oy	Norsskär	1550	Concept	2031	62.679483	20.38069
Denmark	nan	Nysted	165,6	Production	2023	54.5493008145301	11.714846108630681
Lithuania	-	Offshorewind-LT-1	700	Final Investment decision	2027	nan	nan
Lithuania	-	Offshorewind-LT-2	700	Feasibility study	2030	nan	nan
Denmark	Wind Estate	Paludan Flak	220	Concept	2028	55.71664702737843	10.605473481935975

Finland	OX2	Pietarsaari ja Uusikaarlepyy, Laine	2300	Feasibility study	2030	63.7731	6,280555556
Sweden	Pleione Energipark AB	Pleione	1050	Concept/ Early Planning	2034	57.39999999960037	19.57000000019991
Sweden	Skyborn Renewables Sweden	Polargrund Offshore	3000	Concept/ Early Planning	2030	nan	nan
Finland	nan	Pori Offshore 1	2,3	Production	2023	61.6199999998002	21.349999999700287
Finland	nan	Pori-Tahkoluoto Pori 2	42	Production	2023	61.60800000039973	21.2599999999700256
Sweden	Zephyr Renewables AB	Poseidon Syd	200	Consent application submitted.	2031	57.7999999999700276	11.120000000000061
Finland	Metsähallitus	Pyhäjoki ja Raahe, Pyhäjoki-Raahen merituulivoimahanke	1300	Concept	2030	64.17024	24.38613
Finland	Rajakiiri Oy	Raahe ja Pyhäjoki, Maanahkiainen	500	Feasibility study	2032	64.54603	24.01577
Finland	OX2	Raahe, Siikajoki ja Hailuoto, Halla	2600	Feasibility study	2030	65.0232	6,59375
Denmark	nan	Rodsand II	207	Production	2023	54.55466898794333	11.549101194943479
Sweden	RWE Renewables Sweden AB	Södra Victoria	2000	Consent application submitted.	2030	55.63999999970031	17.11999999970027
Estonia	Utilitas	Saare Liivi	1200	Concept	2028	nan	nan
Estonia	Saare Wind Energy	Saaremaa offshore wind farm	1400	Concept	2028	nan	nan
Denmark	nan	Samsa	23	Production	2023	55.72318545779841	10.584731720760148
Denmark	nan	Samso	23	Production	2023	55.71999999990015	10.580000000000041
Finland	Metsähallitus	Siikajoki ja Hailuoto, Seljänsuunmatala Itäisen merituulivoimahanke	1000	Concept	2030	64.510853	25.898068
Finland	Metsähallitus	Siikajoki ja Raahe, Pyhäjoki-Raahen merituulivoimahanke	1800	Concept	2030	64.40823	25.6897055
Sweden	Eolus Vind AB	Sjollen	1300	Concept/ Early Planning	2028	nan	nan

Sweden	Skåne Offshore Windfarm AB	Skåne havsvindpark	1500	Concept/ Early Planning	2029	nan	nan
Denmark	nan	Sprogo	21	Production	2023	55.3436984314616	10.960340886828108
Sweden	Lhyfe and ABB and Skyborn Renewables Sweden	Storgrundet Offshore - SoutH2Port	1000	Environmental permit from Swedish Land and Environment Court approved. Consent Authorised. SoutH2Port : Early permitting.	2029	nan	nan
Finland	Ilmatar Offshore Oy	Stormskar	1725	Concept	2031	60.710000000000036	20.100000000399746
Sweden	Kustvind AB	Sydkustens Vind	500	Concept/ Early Planning	2028	55.29000000039974	13.580000000299833
Sweden	Svea Vind Offshore AB	Sylen	8675	Concept/ Early Planning	2033	61.38000000009998	18.519999999600373
Finland	Rajakiiri Oy	Tornio, Röyttä, Merituulivoimahanke Kiiri	160	Feasibility study	2030	65.73402	24.2276
Sweden	Tritonia Vindpark AB	Triton	1400	Consent application submitted.	2029	55.16000000029982	13.299999999600345
Denmark	nan	Tunm Knob	5	Production	2023	55.96888211256023	10.35527907559457
Denmark	nan	Tuno Knob	5	Production	2023	55.97000000029982	10.35999999990014
Sweden	Svea Vind Offshore AB	Utposten 2	500	Consent application submitted.	2030	nan	nan
Finland	Ilmatar Offshore Oy	Väderskär	375	Concept	2031	60.6025984028746	20.179738322905
Sweden	Eolus Vind AB	Västvind	1000	Consent application submitted.	2029	57.78000000009996	11.219999999800223
Finland	Ilmatar Offshore Oy	Vågskär	1200	Concept	2031	60.7309739085318	19.5630767421636
Germany	nan	Wikinger	366,1	Production	2023	54.83561691726732	14.068330163507895
Germany	Iberdrola	Windanker	300	Final Investment decision	2026	54.890000000299835	14.030000000299822

Table 2. Wind parks in the sub-basins with the highest capacity within 40 km of a 120 m isobath. Data for BY29. In the maps within the report, Erik Segersall 1,2 and 3 are considered together as 6 GW total capacity.

Country	Developer	Name	Capacity (MW)	Planning phase	Estimated COD
Finland	OX2 / Ålandsbanken Noatun South	Åland, Noatun South	3000	Concept	
Sweden	Stakraft	Baltic offshore Delta	5000	Concept/ Early Planning	2032
Sweden	Njordr Offshore Wind AB	Baltic Offshore Epsilon	3000	Concept/ Early Planning	2032
Sweden	Deep Wind Offshore DWO Sverige AB	Erik Segersäll 1	2000	Concept/ Early Planning	2032
Sweden	Deep Wind Offshore DWO Sverige AB	Erik Segersäll 2	2000	Concept/ Early Planning	2034
Sweden	Deep Wind Offshore DWO Sverige AB	Erik Segersäll 3	2000	Concept/ Early Planning	2036
Finland		Noatun	3000	Planned	
Finland		Noatun South	3000	Planned	
Sweden	Eolus wind	Skidbladner	2000	Concept/ Early Planning	
Estonia		Sunly SW2	114	Planned	
Estonia		Sunly SW3	144	Planned	
Estonia		Sunly SW4	132	Planned	

Table 3. Wind parks in the sub-basins with the highest capacity within 40 km of a 120 m isobath. Data for BY10. Green highlight indicates within 40 km of 120 m isobath.

Country	Developer	Name	Capacity (MW)	Planning phase	Estimated COD
Sweden	**LandInfra Energy AB**	**Åland-Hoburg III**	**750**	**Concept/ Early Planning**	
Latvia		E1		Planned	
Latvia		E2		Planned	
Sweden	**Eolus wind**	**Herkules I**	**1000**	**Concept/ Early Planning**	**2029**
Sweden	**Eolus wind**	**Herkules II**	**1750**	**Concept/ Early Planning**	**2029**
Latvia		JK Energy	900	Planned	
Lithuania		Lithuanian Tender 1	700	Planned	
Lithuania		Lithuanian Tender 2	700	Planned	
Lithuania	-	Offshorewind-LT-1	700	Final Investment decision	2027
Lithuania	-	Offshorewind-LT-2	700	Feasibility study	2030

Table 4. Wind parks in the sub-basins with the highest capacity within 40 km of a 120 m isobath. Data for BY32.

Country	Developer	Name	Capacity (MW)	Planning phase	Estimated COD
Sweden		Anemone		Planned	
Sweden	Hexicon AB	Dyning	2500	Concept/ Early Planning	2029
Sweden	Zephyr Renewable AB	Kapheira	2000	Concept/ Early Planning	
Sweden		Neptune	2000	Planned	

Table 5. Wind parks in the sub-basins with the highest capacity within 40 km of a 120 m isobath. Data for BY31. Green highlight indicates within 40 km of 120 m isobath.

Country	Developer	Name	Capacity (MW)	Planning phase	Estimated COD
Sweden	**Njordr Offshore Wind AB**	**Baltic Offshore Alpha**	**2100**	**Concept/ Early Planning**	**2031**
Sweden	**Svea Vind Offshore AB**	**Långgrund 1**	**2000**	**Consent application submitted.**	**2028**
Sweden	Svea Vind Offshore AB	Långgrund 2	2310	Consent application submitted.	2028
Sweden	Cloudberry Develop AS (formerly Scanergy AS)	Norra Klasgrunden	600	Concept/ Early Planning	
Sweden	**LandInfra Energy AB**	**Oxelösund**	**600**	**Concept/ Early Planning**	
Sweden		Södra Klasgrunden		Planned	

Appendix 6. Offshore electrolyser platform data

Table 1. Data for theoretical offshore electrolyser platforms in the Baltic Sea.

Electrolyser	Latitude	Longitude	Sub-basin	Country	Relevant Economic Zone	Nearest port	Distance to nearest port (km)	Nearest wind farm	Estimated wind farm capacity (GW)	Distance to nearest wind farm (km)	Approximate distance to BHC (km)
E1	59.304619	20.593147	BY29	Sweden	nan / Sveriges ekonomiska zon - Stockholm	Mariehamn	75	Erik Segerställ	6	30	70
E2	59.209688	19.610596	BY29	Sweden	nan / Sveriges ekonomiska zon - Stockholm	Kapellskär	65	Baltic Offshore Delta North	5	15	50
E3	58.763485	19.169060	BY29	Sweden	Sveriges ekonomiska zon - Stockholm	Nynäshamn	70	Erik Segerställ	6	10	50
E4	58.504814	17.548535	BY31	Sweden	Sveriges ekonomiska zon - Stockholm	Visby	75	Baltic Offshore Alpha	2,1	40	55
E5	58.297582	18.674634	BY31	Sweden	Sveriges ekonomiska zon - Stockholm	Visby	80	Baltic Offshore Alpha	2,1	40	75
E6	57.940733	18.548291	BY32	Sweden	Sveriges ekonomiska zon - Stockholm	Visby	40	Baltic Offshore Alpha	2,1	40	80
E7	56.920745	19.017119	BY10	Sweden	nan	Ronehamn (Gotland)	50	Öland-Hoburg III	0,75	15	30
E8	56.749211	19.755292	BY10	Sweden	Sveriges ekonomiska zon - Stockholm	Liepäja	70	Herkules		15	15
E9	56.907055	20.127222	BY10	Sweden/ Latvia	nan	Liepäja	65	Herkules		20	40
E10	56.746206	18.533289	BY10	Sweden	nan	Ronehamn (Gotland)	55	Öland-Hoburg III	0,75	10	30

Appendix 7.
Basis of Design for WP3

Project: **BOxHy**

Title: **WP3 - Basis of Design**

Confidentiality Level: NC

Abstract: The purpose of this document is to present the basic requirements and boundary conditions for the concept design of an H2 production platform integrated with a Pure Oxygen Injection (WP3 of BOxHy project). This Basis of Design shall be used as a synthesize summarizing both technical and economic aspects foreseen by the implementation of a POI on a large-scale H2 production platform located offshore in the Baltic Sea.

(BOxHy)

Project	Document Number	Current revision
BOxHy	SE-001-000-SU-LHY-BOD-0001	A

Revision history

Date	Rev	Status	Written	Verified	Approved
23/07/2024	A	PRE	FLO	PHA	BME

Table of contents

1 INTRODUCTION

1.1 Purpose

The purpose of this document is to present the basic requirements and boundary conditions for the concept design of an H2 production platform integrated with a Pure Oxygen Injection (WP3 of BOxHy project). This Basis of Design shall be used as a synthesize summarizing both technical and economic aspects foreseen by the implementation of a POI on a large-scale H2 production platform located offshore in the Baltic Sea.

1.2 Abbreviations

Abbr.	Description
CEP	Conceptual Engineering Package
POI	Deep Oxygen Injection
DSO	Distribution System Operator
EIA	Electricity, Instrumentation and Automation
EPC	Engineering Procurement Construction
FEED	Front End Engineering Design
HSE	Health, Safety, Environment
HRS	Heat Recovery System
HAT	Highest Astronomic Tide
HV	High voltage
JUB	Jack-up Barge
LAT	Lowest Astronomic Tode
MSL	Mean Sea Level
NSS	Negative Storm Surge
PCU	Power Conversion Unit
PSS	Positive Storm Surge
PGS	Project General Specification
PSU	Power Supply Unit (same as PCU)
UPS	Uninterruptible Power Supply

1.3 Referenced documents

The documents listed in below shall be considered as part of the BOD.

Title	Document Name and Link	Revision
Civil & Structure		
Situation drawing	SE-001-070-CS-LHY-DRW-0001	A
General Elevation View	SE-001-070-CS-LHY-DRW-0002Q	A
Main Process Systems		
Block Flow Diagram	SE-001-020-PR-LHY-BLD-0001	A
Main Equipment List	SE-001-020-PR-LHY-LST-0001	A
General Documents		
Equipment, material, and signal numbering procedure C1	LH-001-00-QA-LHY-PRO-003	E
Basic Process Design Requirements and Criteria (BPDRC) C1	LH-001-000-PR-LHY-PHI-001	A
Lhyfe piping class complete set C1	LH-001-20-PV-LHY-SPE-001	D
Safety Layout design and rules C1	LH-001-60-HE-LHY-SPE-001	E
Lhyfe ATEX design specifications Corporate C1	LH-001-60-HE-LHY-SPE-015	A
Design specification of Fire and Gas detection systems C1	LH-001-60-HE-LHY-SPE-005	A

2 BASIS OF DESIGN

2.1 SITE AND ENVIRONMENT

2.1.1 Location

Location Information	Value	Unit	Value
Sub-basin	BY29		
Country	Sweden		
City	Sweden's economic region - Stockholm		
Offshore Site location	Lat	deg	59°12'25"N
	Long	deg	19°36'32"E

2.1.2 Ambient conditions

This section defines the environmental and ambient conditions at the site to be considered for the design.

The following conditions listed in below shall be considered for the design:

Table 1 Ambient Design conditions

Site environmental conditions		Unit	Value
Minimum Air design temperature	T_{Dmin}	°C	-20
Maximum Air design temperature	T_{Dmax}	°C	+ 30
Maximum Relative Humidity	RH_{max}	%	98%
Annual average Air Humidity	RH_{avg}	%	75%

2.1.3 Air quality and corrosivity

The ambient air quality on Baltic Sea is leading to a corrosion protection definition per

Table 2 Corrosion protection

Corrosion protection definition	Unit	Value
Corrosivity category[1]		CX for exposed equipment
Durability of paint system[2]		High

[1] Atmospheric corrosivity categories per ISO 12944-2 (2017): C1 (very low), C2 (low), C3 (medium), C4 (high), C5 (very high), CX (extreme)
[2] Durability ranges per ISO 12944-1 (2017): Low, L (up to 7 years); Medium, M (7 to 15 years); High, H (15 to 25 years), Very High, VH (more than 25 years)

2.1.4 Sea water temperature

The oceanographic parameters have been measured by the Swedish Meteorological and Hydrological Institute (SMHI) at Huvudskär East buoy, located at latitude: 58.9333, longitude: 19.1667 (SMHI, 2024), which is the closest measuring station to the E2BY29 electrolyser/ H_2 injection point, that has been chosen as the basis of design location.
The year 2020 was selected as reference year (except for the current data, which is further explained under its subheading), as it is the most recent year with complete seawater temperature data. For the 10-year period, the years 2010-2020 were used.

The seawater temperature is measured by SMHI once per hour at varying depths. The temperature in 2020 differed between 3,74 °C to 20,98 °C, see Table 1.

Table 1. Change in seawater temperature during 2020 and between 2020-2020 (SMHI, 2024).

Return period [years]	T average [°C]	T min [°C]	T max [°C]
1	9,11	3,74	20,98
10	7,56	1,04	24,67

From this it can be concluded that the mean temperature has increased during the last year, whereas the maximum temperature has decreased.

2.1.5 Waves

The significant wave height (Hs) is the mean value of the highest third of the wave under 30 minutes. The waves have been measured once per hour as a rule of thumb.
For this table, the 2020 values have been used to correlate with the other parameters. For the 10-year period, the period between 2010 and 2020 was used. The waves measured between minimum 0,07 m to maximum 4,88 m, see Table 1. However, no extreme spectral peak period (Tp) is given.

Table 2. Change in wave heights during 2020 and between 2010-2020Table 2

Return period [years]	Hs average [m]	Hs min [m]	Hs max [m]
1	1,02	0,07	4,88
10	0,91	0,05	5,66

2.1.6 Current

The year 2020 has not been used as reference for the current data, as the only existing data in the E2BY29 area is between March and May 2022, and end of May to July 2024. Both time periods have thus been evaluated for a broader perspective. However, it is important to consider the margin of error in the lack of data, and that no conclusions or rhythms can be determined. The direction is always presented in degrees and describes the direction of which the current is going to.
The speed is presented in centimetres per second, see values in Table 3.

Table 3. Change in current direction and speed between March and May 2022, and May and July 2024 (SMHI, 2024).

Return period [years]	Current direction average [°]	Current speed average [cm/s]	Current speed min [cm/s]	Current speed max [cm/s]
March-May 2022	174,09	32,09	0,10	65,00

May-July 2024	172,86	8,54	0,14	46,50

2.1.7 Water depth

The water depth at the E2BY29 electrolyser location/ O_2 injection point is approximately 62 meters deep, according to an interactive Swedish sea chart (Eniro, 2024).

2.1.8 Water quality

Bellow a typical seawater composition of Baltic Sea.

Total hardness	7 °dH
Manganese	0.005 mg/L
Conductance	8000 µS/cm
Sodium	3500 mg/L
Potassium	150 mg/L
Magnesium	250 mg/L
Calcium	70 mg/L
Strontium	0.5 mg/L
Barium	0.02 mg/L
Iron	0.005 mg/L
Aluminum	0.001 mg/L
Chloride	6500 mg/L
Sulphate	800 mg/L
Bicarbonate	120 mg/L
Carbonate	0.1 mg/L
Phosphate	0.05 mg/L
Nitrate	0.02 mg/L
Fluorides	0.8 mg/L
Silica	2 mg/L
Total Dissolved Solids	12000 mg/L
Total Suspended Solids	5 mg/L
Total Solid	12005 mg/L
Ammonia	0.2 mg/L
pH	8.2

These values are estimates based on available data and may vary slightly according to local conditions and seasons.

2.2 OPERATION

2.2.1 Site staffing

Operation	Unit	Value
Number of permanent workers on site offshore	people /day	6
Number of temporary workers on site Offshore	people /day	Up to 6

2.3 PERFORMANCE CRITERIA

This section states the performance requirements of the plant with regards to product delivery.

2.3.1 Design Life

The plant shall be designed for an operating lifetime as define below.

Plant Design Life	Unit	Value
Plant Design Operating Life	years	20

2.3.2 Global Plant Load

The plant shall be designed for a plant load as define below.

	Nominal conditions	Maximal conditions
Plant load factor	88%	100%
H2 Flowrate (Nm^3/h)	70000	80000
H2 Flowrate (t/d)	151	173
O_2 Flowrate (t/d)	1199	1370
Operating capacity (MW)	350	400
Installed capacity (MW)	400	400
LCOE (€/MWh)	65	65
Plant Design Availability[3]	94%	92%

Table 3 Global plant load

Mean downtime of the offshore H_2 plant will be minimized.

H2 subsea pipeline will be constantly pressurized.

O_2 riser will not be constantly pressurized but those downtime will few enough[4] to avoid any damage on the POI equipment's.

[3] Reliability, Availability and Maintainability Study (RAMS) performed on a basic level for this project.
[4] Less than five floodings per year expected.

2.3.3 Hydrogen quality

Use		Pipeline export
Hydrogen		
Delivery Pressure	bar(g)	28
Purity (dry basis)	%	4.5 – 99.995%

2.3.4 Oxygen quality

Use		Bubble plume diffuser
Oxygen		
Delivery Pressure	bar(g)	14-20
Dew point (1 atm)	°C	-40

2.3.5 Heat offtake

In nominal operations, part of the waste heat generated by electrolysers will be used to produce fresh water from seawater.

There are no other heat offtake requirements.

2.3.6 Grid service

No specific grid services to be considered in the design.

2.3.7 Storage

No specific H_2 or O_2 storage to be considered in the design.

2.4 HEALTH, SAFETY, ENVIRONMENT

2.4.1 Noise limitations

The noise limitations required and mandated by the local law shall be considered. Existing noise sources must be considered.

2.4.2 Effluent constraints

At sea, the temperature difference between the sea water inlet and the water outlet shall not exceed 10°C. Seawater intake will be used for:

-Producing demineralized water as raw material of electrolysis process.

-Cooling liquid to evacuate waste heat generated by the process.

2.4.3 Fire fighting

Sea water can be considered for firefighting purposes. Stored volume and pumping system need to be defined through specific studies.

2.5 INTERFACES

This section provides details on the external network interfaces required for the production plant.

2.5.1 Interfaces

2.5.1.1 Electrical

Parameter	Value
Voltage rating	HOLD
Short circuit power (3ph)	HOLD
R/X Ratio	HOLD

HOLD: Technical data will depend on the offshore wind farm interface.

2.5.1.2 Water

Water from the sea will be used.

For design water temperature please refer to section 2.1.4

Water Interfaces		Unit	Value
Raw Water Supply			
Water Source Type		-	From Sea
Connection location		-	At the platform
Wastewater			
Disposal Type		-	At Sea
Connection location		-	Pipe at the platform
Elevation at injection point		-	Platform elevation

2.5.1.3 Instrument Air and Nitrogen

Gaseous Utilities		Unit	Value
Instrument Air Supply			
On-site Instrument Air supply available		-	Yes

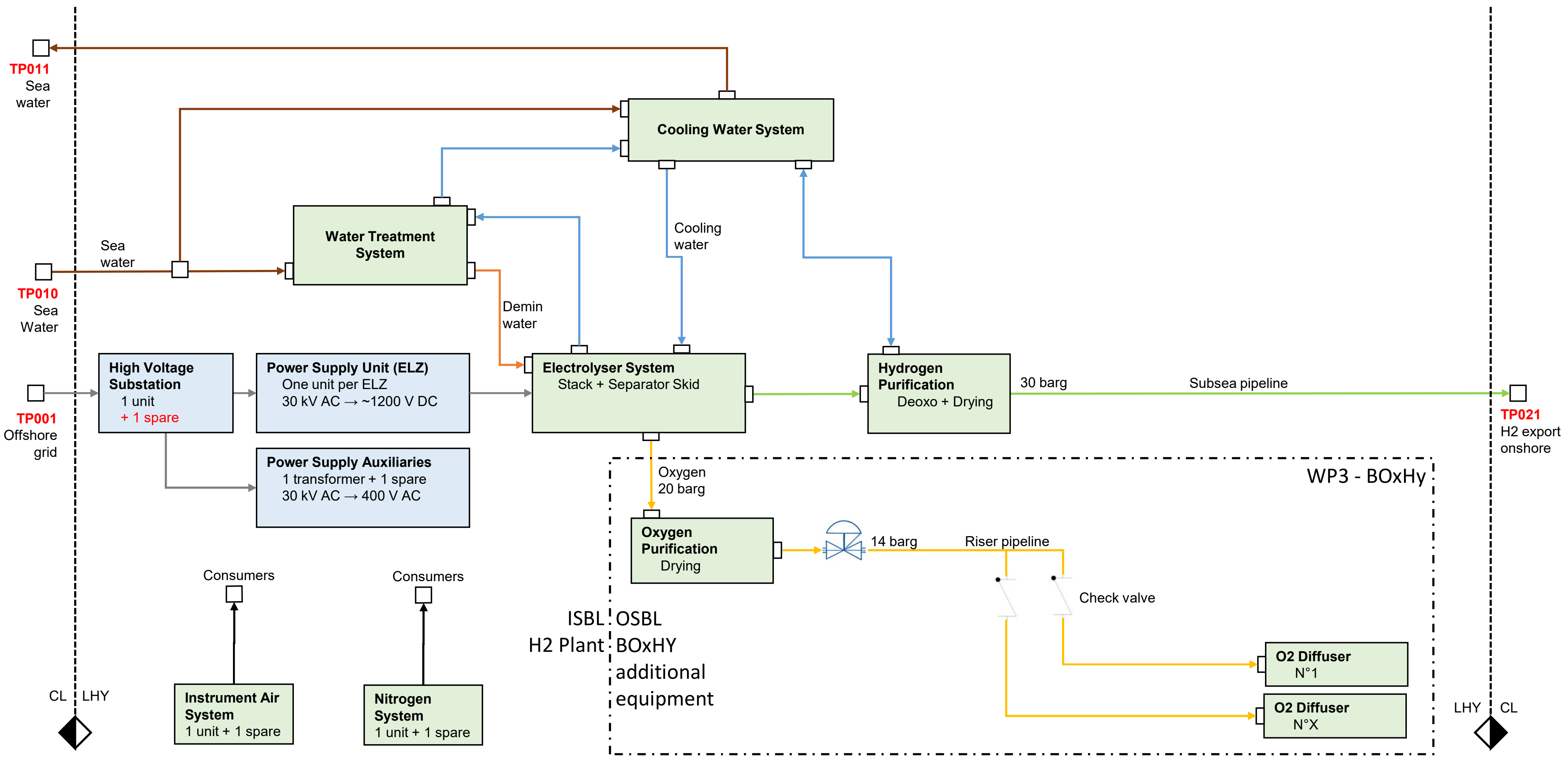
Nitrogen Supply			
On-site Nitrogen supply available		-	Yes

Appendix 8.
Block flow diagram

Lhyfe

Project:	BOxHy project 400 MW (offshore)
Title:	Block Flow Diagram
Site:	Baltic Sea, Gotland Basins
Document name:	SE-001-020-PR-LHY-BFD-0001

REV	DATE	BY	CHECK	APP
A	15/05/2024	FLS	BMT	BMT



General notes

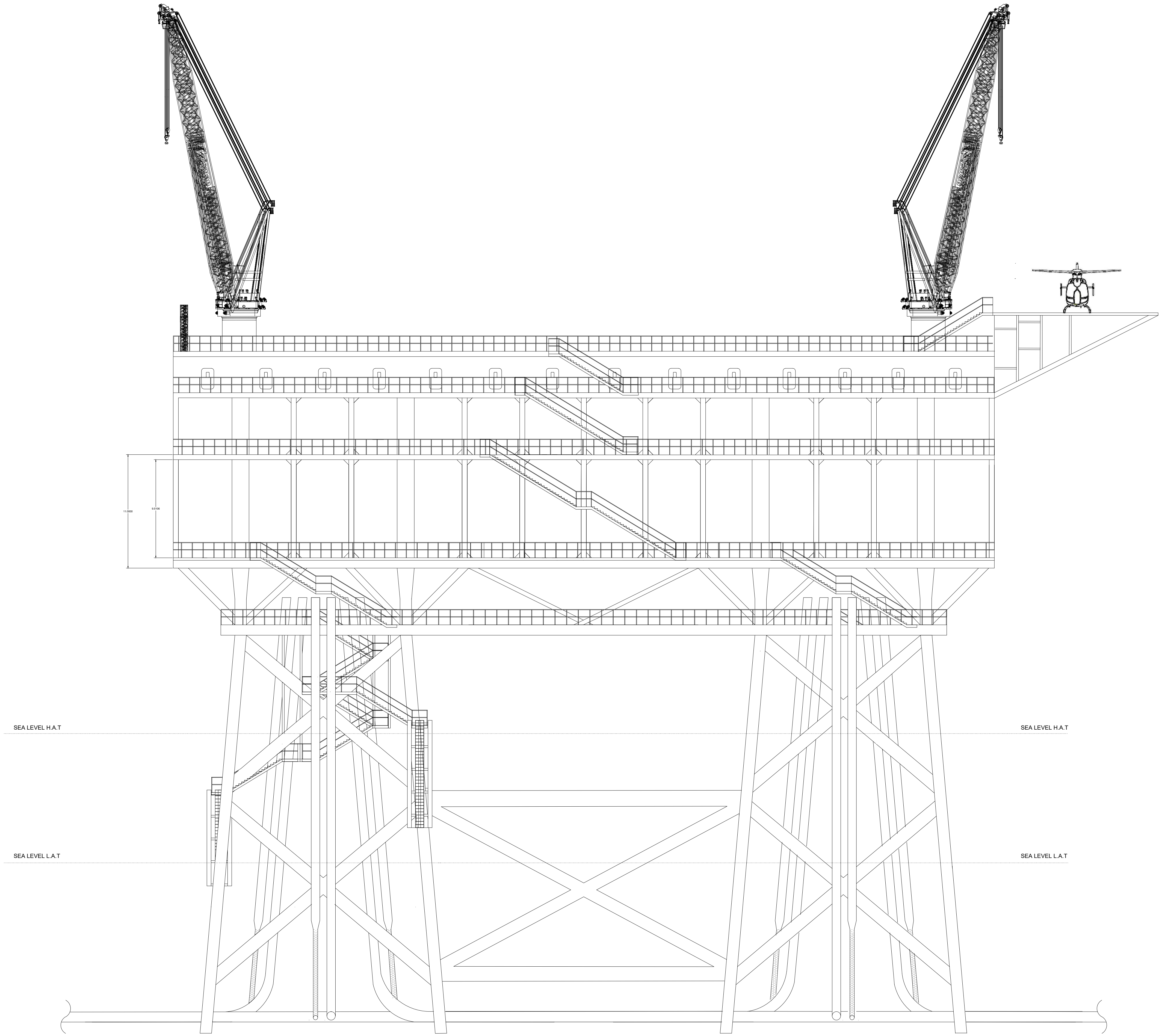
- Writing in red: Scope and setup to be confirmed.
- CL = Client, LHY = Lhyfe, DSO: Distributed System Operator
- ELZ = Electrolyser, BOP = Balance of Plant
- Flows and pressure are stated as nominal values. Design values and operating values may differ.
- ISBL / OSBL = Inside/Outside Battery Limit

Main Process Equipment Packages

Main Electrical Equipment Packages

Appendix 9.

General Elevation view



GENERAL

NOTES

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A	07/08/24	MNU	FLS	BMT	PRL	ORIGINAL ISSUE

AFFAIRE / PROJECT: BOxHy

TITRE DU DOCUMENT / TITLE OF DOCUMENT: GENERAL ELEVATION VIEW

PAGE / FOLIO: 1/1

NIVEAU CONFIDENTIALITE CONFIDENTIALITY LEVEL	FORMAT FORMAT	ECHELLE SCALE	CODE PAYS COUNTRY CODE	CODE PROJET PROJECT CODE	UNITE UNIT	DISCIPLINE DISCIPLINE	CREATEUR ORIGINATOR	TYPE DOC DOC TYPE	NUMERO SEQUENTIAL	LANGUE LANGUAGE
C2	A3	1/400	SE	001	070	CS	LHY	DRW	0001	EN

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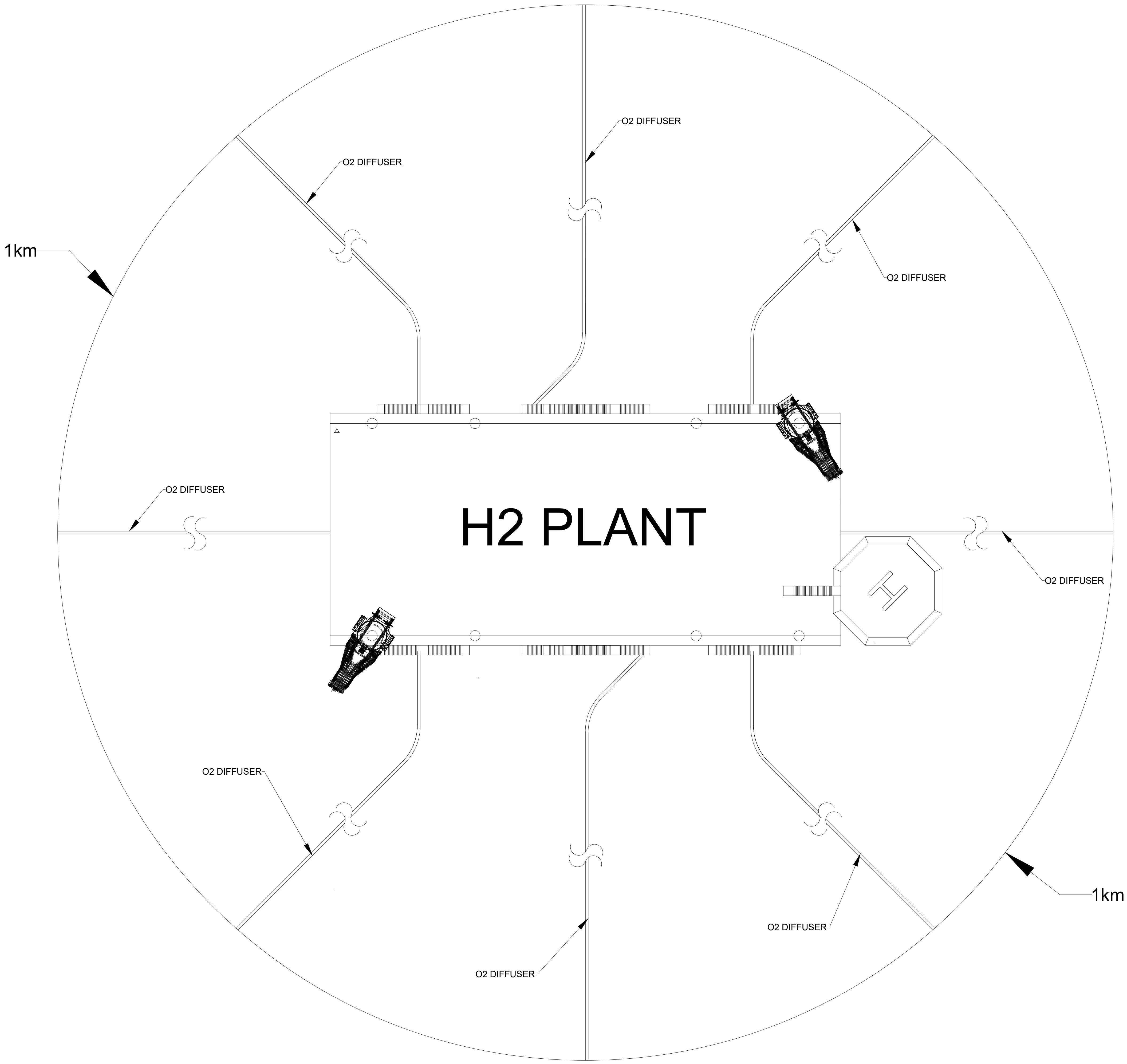
FRANCE

NUMERO DE PLAN DRAWING NUMBER	INDICE REVISION	STATUT STATUS
SE-001-070-CS-LHY-DRW-0001	A	PRL

Appendix 10.

Situation Layout



GENERAL

NOTES

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AFFAIRE / PROJECT: BOxHy

TITRE DU DOCUMENT / TITLE OF DOCUMENT: SITUATION LAYOUT

PAGE / FOLIO: 1/1

NIVEAU CONFIDENTIALITE CONFIDENTIALITY LEVEL	FORMAT FORMAT	ECHELLE SCALE	CODE PAYS COUNTRY CODE	CODE PROJET PROJECT CODE	UNITE UNIT	DISCIPLINE DISCIPLINE	CREATEUR ORIGINATOR	TYPE DOC DOC TYPE	NUMERO SEQUENTIAL	LANGUE LANGUAGE
C2	A3	NA	SE	001	070	CS	LHY	DRW	0002	EN

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NUMERO DE PLAN DRAWING NUMBER	INDICE REVISION	STATUT STATUS
SE-001-070-CS-LHY-DRW-0002	A	PRL

DRAWING FILE NAME : SE-001-070-CS-LHY-DRW-002-A.DWG

Appendix 11.

HSE Plan

Project: **BOxHy**

Title: **HSE Plan for BOxHy**

Confidentiality Level: C1

Abstract: The purpose of this document is to describe how Lhyfe manages Heath, Safety and Environment aspects for the BOxHY project.

A: First issue

	Project		**Document Number**			**Current revision**
(BOxHy)	BOxHy		SE-001-060-HE-LHY-GEN-PLA-0001			A
	Revision history					
	Date	**Rev**	**Status**	**Written**	**Verified**	**Approved**
	18/07/2024	A	FIN	FLO	ETE	BME

Table of contents

1 INTRODUCTION

1.1 Purpose

The purpose of this document is to describe how Lhyfe manages Heath, Safety and Environment aspects for the BOxHY project.

1.2 Abbreviations

Abbr.	Description
ATEX	Atmosphere Explosive
CEP	Conceptual Engineering Package
COD	Commercial Operational Date
EPC	Engineering Procurement Construction
FEED	Front End Engineering Design
FID	Final Investment Decision
HAZID	Hazards Identification
HAZOP	Hazards Operability
HSE	Health, Safety, Environment
HTTFS	Hydrogen Tube-Trailer Filling Station
HV	High voltage
JUB	Jack-up Barge
LOPA	Layers Of Protection Assessment
LOTO	Log-Out Tag-Out
PPE	Personal Protective Equipment
PSU	Power Supply Unit
QRA	Quantitative Risk Assessment
SIF	Safety Instrumented Function
SIL	Safety Integrity Level
SRS	Safety Requirements Specifications
SIMOPS	Simultaneous Operations

1.3 Related documents

Item	Name
LH-001-00-HE-LHY-GEN-003	Lhyfe HSE policy
LH-001-00-HS-LHY-SPE-003	Lhyfe onshore safety concept specification
LH-001-60-HE-LHY-SPE-001	Safety Layout design and rules
LH-001-60-HE-LHY-SPE-008	Lhyfe Corporate HAZID Procedure
LH-001-60-HE-LHY-SPE-003	Lhyfe Corporate HAZOP Procedure
LH-001-60-HE-LHY-SPE-004	Lhyfe Corporate LOPA Procedure
LH-001-60-HE-LHY-SPE-010	Safety Instrumented Systems life-cycle management within Lhyfe
LH-001-60-HE-LHY-SPE-005	Design specification of Fire and Gas detection systems
LH-001-00-HE-LHY-ANL-003 A	From process safety to major risk studies
LH-001-60-HE-LHY-SPE-006-A	Guidelines on hazardous effects assessment
LH-001-60-HE-LHY-SPE-015	Lhyfe ATEX design specifications Corporate
LH-001-00-QA-LHY-PRO-002	Management of Change
LH-001-60-HE-LHY-SPE-012	Permit to Work System
LH-001-00-OP-LHY-PRO-003	Log-Out Tag-Out Procedure
LH-001-60-HE-LHY-SPE-007	Personal Protective Equipment
LH-001-60-HE-LHY-SPE-019	Lhyfe Emergency Management specifications
LH-001-60-HE-LHY-SPE-009	HSE trainings and HSE inductions
LH-001-95-IT-LHY-SPE-001	Lhyfe Security specifications
LH-001-00-SC-LHY-SPE-018	Anti intrusion specification

2 BOxHy HSE Plan

2.1 Leadership and commitment for HSE

Leadership and commitment to HSE is key to ensure the good application of HSE at all levels and to all stakeholders. Commitment to rules and regulations is essential to ensure the legality of all actions.

2.1.1 Leadership

BOXHY Project will rely on Lhyfe HSE policy (LH-001-00-HE-LHY-GEN-003), sets objectives, communicates them at all levels of the organization and allocates resources necessary for their implementation.

Management at all levels demonstrates exemplary conduct, rigor, vigilance and professionalism regarding HSE in all their activities.

2.1.2 Commitments

In all activities, Lhyfe acts in compliance with applicable Belgian laws, regulations, relevant industry standards, and other specific rules and Lhyfe requirements.

2.2 Risk Management

For any activity the hazards to which people, the environment and assets are exposed are systematically identified, the associated risks assessed and the measures for reducing them defined and implemented. The risk level and risk reduction measures are periodically reassessed, at a minimum with each change of an activity or a process.

A complete and detailed Lhyfe internal specification (LH-001-00-HS-LHY-SPE-003) gives full safety design considerations for onshore plant site.

2.2.1 Safety Layout Assessment

The safety layout assessment is a preliminary assessment of the layout to ensure internal safety standards and layout design rules are applied (LH-001-60-HE-LHY-SPE-001), safe distances are respected between equipment to avoid escalation of events if not possible physical barriers are set up, material handling, maintenance access and storage areas are possible and safely located, emergency features and access to Fire Services are provided, well designed and practicable.

2.2.2 HAZID

HAZID Review is a systematic, keyword-based risk identification and analysis methodology that enables documented hazard identification on a project or an existing facility. It is moreover a guided group brainstorming activity that benefits from the broad experience of a multidisciplinary team.

The objective of the HAZID is to identify hazards for the people, the Environment, or the asset so that they can be assessed, controlled and/or mitigated.

At Lhyfe, HAZID Reviews are managed by an internal procedure (LH-001-60-HE-LHY-SPE-008) which sets the methodology and criteria to be applied during all HAZID performed. The risk ranking is performed using the Lhyfe Risk Ranking Matrix below.

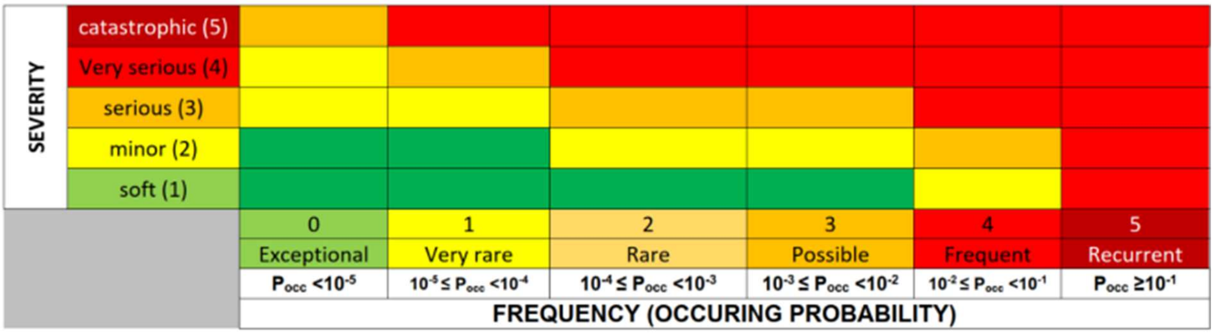

Figure 1 : Lhyfe Risk Ranking Matrix

The frequency or likelihood is assessed using the following Lhyfe criteria:

	0 Exceptional	1 Very rare	2 Rare	3 Possible	4 Frequent	5 Recurrent
Qualitative approach	"Extremely unlikely": Frequency such that it is not impossible for it to occur based on current knowledge, but not encountered globally over a very large number of installations / years.	"Very unlikely": Frequency as it has already occurred in this line of business but has been the subject of corrective actions significantly reducing its likelihood.	"Improbable": Frequency as it has already occurred in the industry worldwide, without any corrections since providing a guarantee of a significant reduction in its probability.	"Probable": Frequency as it has occurred and / or may occur at least once during the lifetime of the installation.	"Current": Frequency such that it may occur several times in a year of operation in any similar facility.	"Very common": Frequency such that it can occur several times in a year of operation in the same installation and on the same unit or equipment.
Quantitative approach (per unit and per year)	$P_{occ} < 10^{-5}$	$10^{-5} \leq P_{occ} < 10^{-4}$	$10^{-4} \leq P_{occ} < 10^{-3}$	$10^{-3} \leq P_{occ} < 10^{-2}$	$10^{-2} \leq P_{occ} < 10^{-1}$	$P_{occ} \geq 10^{-1}$
Semi-quantitative		"Very common": Frequency such that it can occur several times in a year of operation in the same installation and on the same unit or equipment.				

Figure 2 : Lhyfe likelihood scale

The severity is estimated in view of the potential impact on People, the Environment and asset damage using the following Lhyfe criteria:

	1	2	3	4	5
	Insignificant	Minor	Serious	Very Serious	Catastrophic
Human	Injury that can be take in charge on-site (FAC)	Injury requiring the intervention of a doctor, or resulting in temporary incapacity for work of less than 3 months	Minor impact on a third party without medical intervention Serious injury resulting in temporary incapacity for work of more than 3 months	Impact on a third party with medical intervention or impact on several third parties Injury resulting in permanent incapacity for work or death	Permanent incapacity for work or death of a third party Permanent incapacity for work or death of two or more staff
Environment	Primary loss of containment Spill contained in fixed recovery devices	Loss of primary containment requiring the use of mobile or temporary equipment.	Spill requiring notification to the competent authority. Controlled release of material classified as dangerous for health and environment.	Loss of containment requiring the use of a third party. Spill off site, Uncontrolled release of material classified as dangerous to health and the environment. Reversible impact on the biotope	Loss of containment supported by a third party. Irreversible impact on the biotope, or a protected species.
Material & finance	Slight damage to equipment. Negligible operating loss. Stop of operation less than 24 hours.	Damage to one or more equipment. Restart of the installation in less than 96 hours.	Critical damage to equipment. Mobilization of skills and specialized equipment. Restart of the installation in less than 7 days.	Loss of critical equipment. Immobilization of the installation from 7 to 30 days.	Loss of installation or interruption of operation for more than 30 days.
	Less than 20k€	20 k€ to 200 k€	200 à 1 000 k€	1 à 10 M€	More than 10 M€

Figure 3 : Lhyfe Severity scale

As an industrial good practice, the HAZID Review is led by an external chairman.

2.2.3 Process Risk Assessment

Process safety risk assessment is crucial in industries handling hazardous materials. It involves systematically identifying, evaluating, and preventing potential hazards to ensure safety and compliance with regulations and industrial good practices throughout a series or reviews and assessments.

2.2.3.1 HAZOP

The HAZOP methodology is implemented since the early 70s across the process industry.

HAZOP Review is a systematic, keyword-based risk identification and analysis methodology that enables documented process hazard identification on a project or an existing facility.

It is moreover a guided group brainstorming activity that benefits from the broad experience of a multidisciplinary team.

In line with the IEC 61882, The Lhyfe procedure LH-001-60-HE-LHY-SPE-003 sets the methodology and criteria to be applied during all HAZOP performed across LHYFE. The risk ranking matrix used for HAZOP reviews is the Lhyfe risk ranking matrix presented above in Figure *1* : Lhyfe Risk Ranking Matrix

As an industrial good practice, the HAZOP Review is led by an external chairman.

2.2.3.2 LOPA

The objective of the LOPA review is to assess whether adequate protections against specific HAZOP scenarios are put in place to reduce the associated risk to a tolerable level as per LHYFE requirement.

In line with the IEC 61511 [3], the Lhyfe procedure LH-001-60-HE-LHY-SPE-004 sets the methodology and criteria to allocate Safety Integrity Levels (SIL) to the Safety Instrumented Functions (SIF) by the Layer Of Protection Analysis (LOPA) method across LHYFE.

2.2.3.3 Safety Integrity Level

Safety instrumented systems (SISs) have been used for many years to perform safety instrumented functions (SIFs) in the process industries. If instrumentation is to be effectively used for SIFs, it is essential that this instrumentation achieves certain minimum standards and performance levels.

From a general perspective, the process safety design of Lhyfe renewable hydrogen production process is achieved by an inherently safe process design. However, in some instances this is not possible or not reasonably practical.

Therefore, it might happen that for given Lhyfe production sites and facilities, SISs are to be implemented.

The methodology which has been established by Lhyfe to manage Safety Instrumented Systems life-cycle activities is covered by Lhyfe procedure LH-001-60-HE-LHY-SPE-010.

It is considered that it reflects the best practices currently available. Its application will achieve the primary objective of maintaining and enhancing the safety of Lhyfe hydrogen production sites and facilities.

2.2.3.4 Safety Requirements Specifications

A Safety Requirements Specification (SRS) for Safety Integrity Functions (SIF) is a document that outlines the specific safety-related requirements for systems or components designed to achieve and maintain a specified level of safety integrity.

Safety Integrity Functions are typically associated with safety instrumented systems (SIS) used to mitigate or prevent the impact of hazardous events in various industries, such as chemical, petrochemical, oil and gas, and others. The purpose of an SRS for SIF is to provide a detailed and structured set of requirements to ensure the effective and reliable performance of safety functions.

2.2.4 Quantitative Risk Assessment

Quantitative Risk Assessments (QRA) are performed to systematically analyse and quantify potential risks associated with various hazardous scenarios. This involves assessing in the likelihood and consequences of incidents.

2.2.5 Major Risk Management

Major risks such as Fire, gas leaks are subjects to specific additional assessments to ensure these hazards are addressed properly.

2.2.5.1 Fire and Gas Risk Assessment

This assessment is performed to evaluate and mitigate potential risks associated with fires and gas releases. This assessment identifies potential sources of ignition, flammable materials, and gas hazards onsite, analyses likelihood and consequences of fire and gas-related incidents.

Furthermore, it provides guidelines for the selection, procurement, installation and operation of fire and gas detection systems.

This assessment is driven by the following Lhyfe procedures LH-001-60-HE-LHY-SPE-005, LH-001-60-HE-LHY-SPE-006 and LH-001-00-HE-LHY-ANL-003.

2.2.5.2 ATEX classification

Specifications of ATEX are managed by an internal procedure (LH-001-60-HE-LHY-SPE-015) which establish the different ATEX specifications to be considered for all Lhyfe onshore projects.

It covers among other topics the classification of hazardous areas, the selection of appropriate equipment, the rules for conception of Ex equipment, the mandatory documents as EPD (Explosion Protection Document) or DSEAR (Dangerous Substances and Explosive Atmospheres Regulations: UK), and relevant trainings.

2.2.6 Lightning Risk Assessment

Lightning risk assessments are performed to evaluate and mitigate the potential dangers posed by lightning strikes to people, structures, process and equipment. This assessment is performed by a specialized company and checked by Lhyfe.

2.2.7 Management of Change

Any change is managed by an internal Lhyfe procedure LH-001-00-QA-LHY-PRO-002.

2.3 Operational Safety

During our operations, we manage safety throughout risks assessments performed prior to any task for regular activities and uncommon/risky works by Permit To Work system. Whenever a work requires the Log-Out of some part of the process (electrical or fluids), we refer to our LOTO procedure. To operate safely for our operators, we prioritize collective protection barriers, however when it is impossible to set up and as an additional measure, Lhyfe requires to use of appropriate PPEs. Marine spread requirements and the management of potential simultaneous operations at sea will be covered by a dedicated Marine coordination procedure.

2.3.1 Permit To Work

The Permit to Work a systematic process used in industrial and hazardous environments to control and manage high-risk and uncommon activities The primary purpose of a Permit to Work is to ensure the safety of personnel, protect the environment, and prevent accidents by carefully planning, authorizing, and controlling potentially hazardous tasks.
It is managed by the Lhyfe procedure LH-001-60-HE-LHY-SPE-012-A. It covers the following types of work:

- Hot works
- Pressure tests
- Radiographic testing
- Confined space entry
- Chemical treatment/handling
- Electrical work
- Work at height / work on roofs/rope access
- Excavation
- Work on pressurized system / opening production systems
- Heavy lift / critical lift
- Any work requiring inhibition of safety devices/systems
- Any particular task, uncommon work in the industry, or work in safety downrated plant

2.3.2 Log-Out Tag-Out

In order to work safely or inspect some equipment, we might need to isolate a part of the process electrically or for fluids. Thus this log-out is managed onsite by our LOTO procedure (LH-001-00-OP-LHY-PRO-003) defining the specific methodology, its related risk assessment, the necessary material and trainings.

2.3.3 Personal Protective Equipment

Personal Protective Equipment are managed by Lhyfe procedure LH-001-60-HE-LHY-SPE-007.

In all cases, and when required, Lhyfe employees shall comply with Lhyfe rules indicated within this standard and must wear appropriate PPE which are given to them by Lhyfe.

Lhyfe shall ensure that all visitors on Lhyfe production plant sites and facilities are equipped with sufficient PPE in compliance with this procedure. If not equipped with proper PPE, Lhyfe shall equipped such visitors with appropriate PPE.

Subcontractors working for Lhyfe shall provide their staff with sufficient PPE and must comply with Lhyfe PPE requirements.

2.3.4 SIMOPS

Simultaneous Operations (SIMOPS) procedure is designed to safely manage and coordinate multiple activities or operations that are carried out concurrently in the same workspace or facility. The primary purpose of the SIMOPS procedure is to ensure the safety of personnel, protect assets, and prevent incidents or accidents that may arise from the simultaneous execution of various activities.

2.3.5 Offshore Operating Procedure

Offshore Operating Procedures are comprehensive documents that outline the steps, protocols, and safety measures to be followed during various offshore activities. Their purpose is to ensure the safe and efficient execution of operations on offshore facility due to the specific working environment.

The further set of procedures are including the following:

- Marine coordination plan
- Access and transfer procedure
- Man Overboard procedure
- Crane operation procedure
- Navigation safety procedure
- Radio communication procedure

2.4 Environment Management

The Environmental Management integrates environment impact assessment, environmental considerations into daily operations, promotes sustainable practices, and ensures compliance with environmental regulations. It aligns with broader environmental management systems such as ISO 14001 and contributes to the organization's commitment to environmental stewardship.

2.4.1 Environmental Impact Assessment

An Environmental Impact assessment is performed prior to any project to assess its impact on the neighbouring fauna, flora, biodiversity, sea views and cultural heritage, human activities, etc as defined by Belgian regulation Article 3 RD 01/09/2004 – EIA.

This specific study is performed by a independent and specialised company in order to get the best assessment possible on the environmental impact this project would have.

2.4.2 Chemical Management

Lhyfe manages chemical used onsite to ensure they are safely and responsibly registered, handled, stored, used and disposed. Their hazard is assessed throughout their SDS. Mitigation measures such as Spill Kits and eyewashers are available onsite.

Any new chemical material to be introduced on our site is checked.

2.5 Emergency Management

The emergency situations potentially critical for people, the environment and assets are identified based on a risk assessment.

Lhyfe will ensure that emergency plans, appropriately trained personnel and suitable equipment necessary for dealing with such situations are constantly on hand. Emergency and associated external assistance plans are drawn up, tested during periodic exercises and updated on a regular basis.

Where appropriate, these emergency plans take into account local communities, mutual aid organizations and authorities. All employees, contractors, suppliers and visitors are informed about what to do in case of emergency. Personnel that may be involved in the response or management of an emergency/crisis situation will be aware of their roles and accountabilities and have taken the required theoretical and practical training.

Emergency management is driven at Lhyfe by the procedure LH-001-60-HE-LHY-SPE-019 and is completed by Oil Spill Contingency Plan, and a Medical Evacuation Procedure.

Periodic drills are systematically performed to test and improve emergency measures and procedures. Lessons learned are identified and addressed.

2.6 Lessons Learnt

All incidents are reported and analysed in depth to determine their root causes. All corrective actions and preventive measures are defined and appropriately prioritized. The results of the analyses are reported to all interested parties that may benefit from the lessons learned.

All employees have a duty to report without delay, any dangerous situation or any deviation from HSE rules.

2.7 Competencies and training

For all activities, the competencies required are defined, taking into account HSE aspects.

Competencies of personnel are regularly assessed, and training and development plans are implemented to ensure that competencies are appropriate for the tasks to be performed.

The implementation of a training program in line with operations performed during BOXHY project will be done and monitored by the HSE Manager in consultation with the Operations Manager. A training is set up by Lhyfe and each Department Managers and Contractors are to ensure compliance to the training matrix for their respective department. The detailed information is included within the Lhyfe internal specification LH-001-60-HE-LHY-SPE-009.

2.8 Audit and Inspections

In every field of activity, HSE audits and inspections can be performed to control the compliance of Contractors, Subcontractors, Partners against the HSE requirements and HSE policy of the project.

Moreover, Lhyfe HSE and Quality departments conduct internal audits to ensure that all rules and procedure are applied.

Any shortfalls regarding the set objectives are analyzed and corrective actions and/or an improvement plan are subsequently defined, implemented and monitored through to closure.

2.9 Security

All Lhyfe activities are guided with the absolute priority being the protection of people.
Security risks and threats will be covered through specific assessment.
Sites are fitted with anti-intrusion systems, driven by Lhyfe procedures LH-001-95-IT-LHY-SPE-001 and LH-001-00-SC-LHY-SPE-018.