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Abstract

An Autonomous Offshore Power System (AOPS) provides in-situ power, energy storage, real-time data and communications support, asset management, and other capabilities at sea. It has applications for all offshore industries: energy, defense and security, aquaculture, science and research, and communications. This paper highlights how an AOPS can reduce cost, complexity, and carbon-intensity for existing offshore operations and enable new capabilities for offshore industry leaders.

This new AOPS technology has two primary advantages. First, it unlocks the autonomous, electric future of the ocean economy via 'local' power generation and energy storage, in addition to real-time connection to the data cloud. Second, it helps enable a material change in the global energy mix through cost-effective, reliable generation and storage technology for use cases including mobile/static data-gathering and reporting systems, operating equipment, and charging networks for uncrewed surface vessels. AOPS technology will help transform the ocean economy, and thus has implications for offshore industry leaders as they push to reduce costs today and make an autonomous and decarbonized future possible.

A SeaRAY AOPS, which is the focus of this paper, consists of three primary components:

- C-Power's SeaRAY surface wave power system
- A non-complex, combined mooring, data communications, and power system
- Verlume's Halo seafloor energy storage and intelligent energy management system

The following paper highlights both a real-world and hypothetical deployment of a SeaRAY AOPS, demonstrating its ability to benefit a diverse array of activity in the ocean economy. First, the paper details the work of C-Power and Verlume, in partnership with the U.S. Navy, U.S. Department of Energy, Saab, R2Sonic, Hibbard Inshore, and other industry leaders, to deploy an AOPS at the Wave Energy Test Site in Hawaii for six months, beginning in the first half of 2023. The Hawaii AOPS will power multiple mobile and static assets capable of delivering persistent, self-contained, and self-powered intelligence, surveillance, and reconnaissance (ISR) and reporting capabilities for 24x7x52 maritime defense and border security. The ability to support this use case demonstrates AOPS applicability across a wide variety

of offshore applications. Second, the paper explores a theoretical use case to deploy AOPS technology to reduce capital and operational costs and carbon emissions, as well as reduce operational complexity, at the Northern Lights carbon sequestration facility located off the Norwegian coast. While the case study examines the Northern Lights greenfield opportunity using an AOPS in lieu of a power and data umbilical, brownfield upgrades or replacements of failed/failing umbilicals are equally applicable scenarios.

Introduction

Within the ocean economy, increasing amounts of effort and resources are being devoted to upgrading existing hardware and creating new systems that will be able to:

- Be more autonomous and persistent, while performing increasingly complex tasks
- Collect, process, and transmit richer datasets more often
- Enable the drive toward electrification and net–zero operations
- Do any or all the above more cost-effectively, more safely, and with reduced shore dependencies and less environmental impact (C-Power News, 2020)

Unfortunately, efforts are hindered by the fact that the ocean is an energy and data desert, leaving the $2.5 trillion global ocean economy saddled with high costs, high carbon emissions, and high complexity operations that rely on liquid and gas fuels. The lack of low cost, low carbon, low complexity energy and data solutions means the ocean economy is leaving tremendous economic value on the table, as it is held back from deploying the digital, electrified, connected, clean, and autonomous technologies that have revolutionized the terrestrial economy over the past twenty years.

Renewable energy-powered AOPS' are a missing piece of the puzzle for the ocean economy. These systems deliver energy in the form of carbon-free electricity as well as near real-time/real-time, two-way data communications. Those power and data capabilities unlock the future of resident, autonomous, digital operations at sea that the ocean economy has been building toward for years.

The Northern Lights carbon transport and storage facility located in the North Sea off the Norway coast serves as a prime example of a major offshore operation that could reduce its cost, carbon, and complexity through AOPS deployment. While an AOPS can benefit the global ocean economy, this paper presents a case study of AOPS deployment at Northern Lights due to the clear economic value and the technology's ability to help the project meet its primary mission to prevent the release of carbon emissions into the atmosphere by minimizing the carbon intensity of operations.

Background

An AOPS provides in-situ power, energy storage, real-time data and communications, and asset management support at sea. It acts as a combination of a remote charging station, a data server, and a cell tower out in the ocean. These power and communications systems are easy to transport and deploy. AOPS platforms enable deployment of mobile and static assets for weeks, months or years in shallow- and deep-water locations (C-Power News, 2020).

An AOPS has applications for all offshore industries: energy, defense and security, aquaculture, science and research, and communications. They provide the local energy and real-time data and communications services needed to reliably support resident systems and ocean operations that aren't possible today. They also eliminate the need for persistent topside, carbon-fueled energy sources or lengthy, expensive umbilicals delivering power, data, and communications from faraway offshore installations or onshore locations.

The configurations of an AOPS are flexible and scalable, allowing them to meet the needs of a wide array of customer uses across industries. Some of the most common use cases across include: sensors, monitoring, and other data-gathering equipment; operating equipment; robotics including autonomous underwater vehicles (AUV); and electric surface vessel charging. Multiple assets can be supported simultaneously by an AOPS. Payloads can be supported on the surface, in the water column, on the seafloor, or any combination of these.

Generically, any power source can be used within an AOPS. For the SeaRAY AOPS, a single or array of SeaRAY wave power systems from C-Power can deliver power in the single to tens of kW range. Thanks to satellite imagery and a long history of ocean meteorological data, energy from ocean waves is highly predictable. Due to the consistency of waves, the energy source is less intermittent than solar or wind in a typical deployment. It is also a significantly more energy dense resource. However, given the critical need to provide sufficient electricity when required, multiple power generation resources may be employed (e.g., ocean wave and solar). The SeaRAY can be configured as a moored or free-floating system. In a moored configuration, the electricity-generating surface wave power system is connected via a single, combined mooring, data, communications, and power cable to a base energy storage unit.

Subsea battery energy storage mitigates the problems associated with matching energy demand to supply by ensuring a continuous supply of energy. Based on the wave energy resource available at the AOPS deployment site and the profile of the end-user's energy needs, both the wave power system and battery energy storage system are sized to ensure energy availability and reliability for the specific use case. Redundant stored energy, e.g., pre-charged hydrogen fuel cells, can offer ‘failsafe’ supply, regardless of prolonged unfavorable environmental conditions.

In addition to power generation and electricity storage, the system provides asset management capabilities. Integrated software provides intelligent energy management for offshore assets, and real-time data and communication capabilities allow operators to remotely upload mission instructions for autonomous robotics, such as AUVs, to complete and download data without costly trips to manually collect the equipment.

Verlume’s Halo energy storage system integrated with C-Power's SeaRAY renewable wave power system delivers a zero-emission power system at a fraction of the cost of traditional methods of power delivery. The result is ultra-reliable, autonomous offshore power, energy storage, and real-time data and communications for a wide range of payloads.

C-Power

C-Power harnesses the immense power of ocean waves to deliver groundbreaking solutions. The company’s kW-scale solutions change the ocean from a power desert into a power- and data-enriched environment, reducing operational costs, carbon, and complexity for offshore, island, and coastal applications. The systems are easy to transport and deployable anywhere in the world, unlocking innovation in critical industries such as offshore energy, defense and security, aquaculture, science and research, and communications. C-Power’s high-power solutions will power the next wave of zero-carbon energy for terrestrial electric grids and remote mini-grids (C-Power About, 2022).

C-Power technology allows customers to deliver new, innovative solutions that redefine what’s possible in ocean operations, reduce costs, increase human and environmental safety, and lower emissions. The company’s products include the SeaRAY AOPS for offshore kW-scale power needs and the StingRAY AOPS for offshore and onshore MW-scale power needs.

The SeaRAY (Figure 1) provides in-situ power, energy storage, and real-time data and communications support that will advance the ocean economy toward a future of autonomous, connected and resident technologies. It is designed to support uncrewed offshore activities and equipment, including subsea vehicles, sensor packages, and operating equipment. The SeaRAY is transportable anywhere in the world and deployable with smaller, lightly-crewed vessels (C-Power Products, 2022).

Figure 1: C-Power StingRAY wave power system

The StingRAY (Figure 2) delivers cost-effective, utility-scale renewable energy. Applications include providing "village" power for isolated island or coastal communities that currently rely on diesel-powered generators or other costly forms of fossil fuel-powered generation, connecting to utility electric grids that seek to replace coal- and natural gas-fueled generation, and powering private mini-grids for offshore and near-shore business operations (C-Power Products, 2022).

Figure 2: C-Power StingRAY wave power system

A more comprehensive view of both systems deployed is shown in Figure 3.

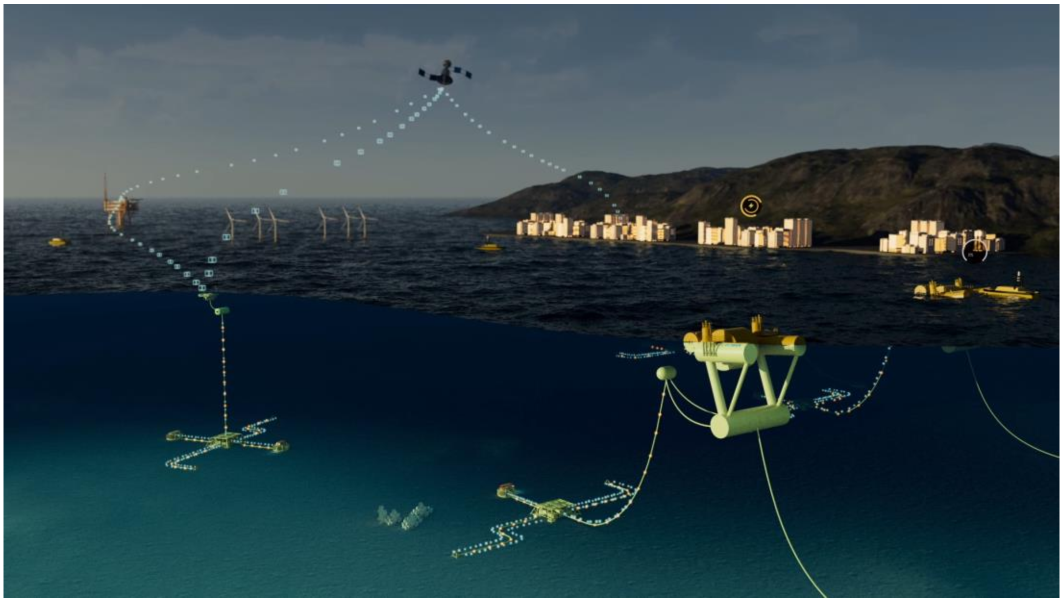

Figure 3: Overview of SeaRAY and StingRAY ecosystem of use cases

The AOPS concept of self-contained, offshore power and data mini-grids was born from market feedback gathered during the design phase of the second generation of the SeaRAY wave power system. Field trials of succeeding generations are now partially driven through C-Power's Partner Engagement and Co-Development (PEC) Program (C-Power Partner With Us, 2022). A goal for the PEC program is pilot demonstrations, such as the Hawaii pilot described below, to accelerate introduction of the equipment into the field. The hypothetical Northern Lights configuration described below is an example of an application that, without actual integration into the subsea assets, can be validated through a PEC pilot, validating the opportunity for lower capital and operating costs, reduced operational complexity, less shore dependency, decreased carbon intensity, and increased environmental and human safety. C-Power has three upcoming PEC-driven pilot demonstrations (Figure 4).

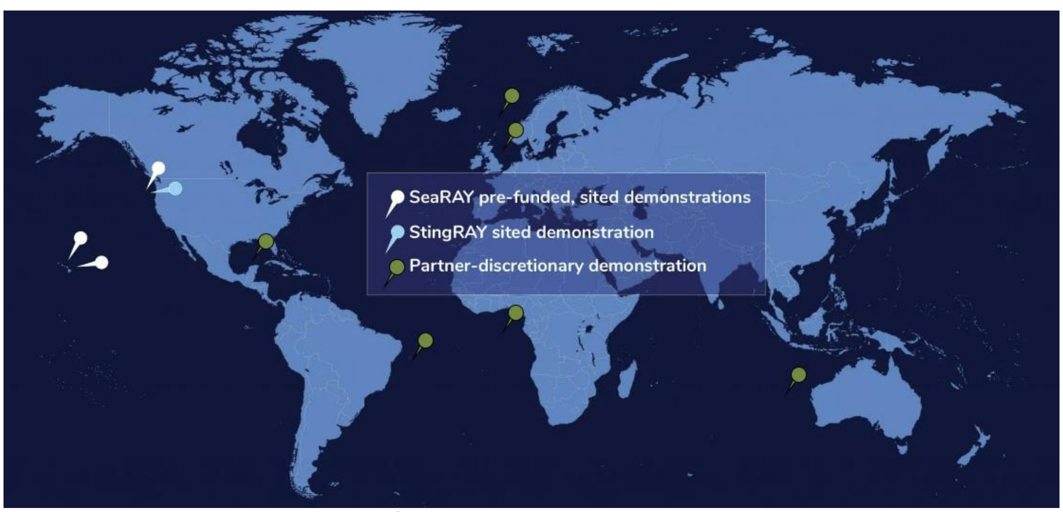

Figure 4: C-Power demonstration project site map

Verlume

Verlume is a specialist in intelligent energy management and energy storage, enabling renewable energy integration through the use of intelligent battery systems. Intelligent energy storage is used to provide energy security and overcome the intermittency challenges of integrating clean, renewable power generation to high value assets. Use cases include asset electrification, resident vehicle charging, long-distance tie-backs and field extensions in the subsea sector.

The company's Halo technology is a seabed energy storage system which has been designed and optimized for use in the harsh, deepwater environment. Halo acts as the gateway from renewable energy inputs to high value assets in the offshore environment, ensuring continuity of power supply.

To create a dependable energy storage system, Verlume focuses on the power needs of the consumer and its location, using a proprietary analysis tool to calculate the required storage capacity for any given application. The key to efficient energy storage is not only the selection of the most suitable storage medium, but also consideration of the environmental conditions, redundancy requirements, operational limitations and the safety needs of the client.

With a Lithium ion-based cell chemistry, the system is built to be modular and scalable, depending on the payload requirements. These battery cells offer superior energy density at low cost, which is particularly important for subsea applications where space can be at a premium and project economics can be impacted significantly by weight.

Within Halo, there is an integrated intelligent energy management system known as Axonn. The fully integrated system is capable of resource and yield analysis; assessment of energy resource at a project location to determine the optimum power generation system, as well as capacity analysis; optimized energy storage for overcoming generation intermittency and ensuring maximum energy availability. Through Axonn, performance management also takes place by modelling system operation in the harsh marine environment.

Figure 5: Verlume Halo subsea battery energy storage system

Within the AOPS configuration, this seabed battery energy storage system provides the base unit on the seafloor, including acting as the payload interface for power, data and communications to multiple subsea payloads. This project was the first commercial delivery of the Halo system as shown in Figure 6.

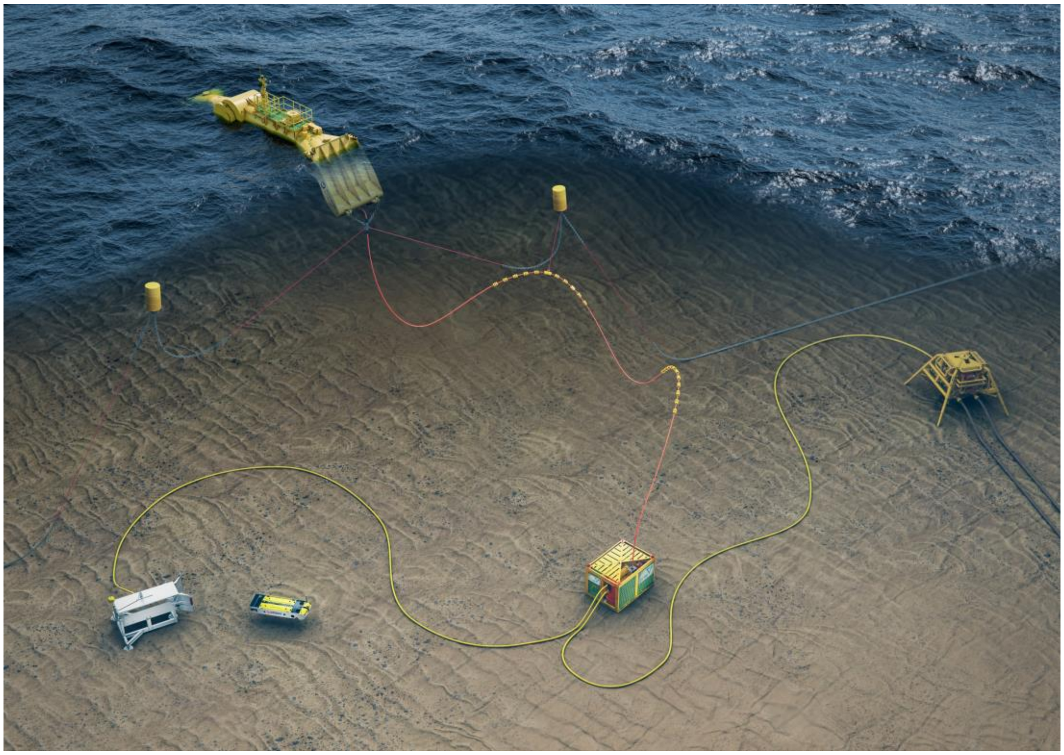

Figure 6: Renewables for Subsea Power AOPS deployment graphic rendering

A further project which builds on this renewable energy integration through intelligent energy management is the Renewables for Subsea Power (RSP) project in the UK North Sea, which integrates a Scottish wave energy developer's wave energy converter with Verlume's Halo to create an offshore mini grid and communications gateway, to provide reliable power and data access to a selection of high-value subsea assets and critical functions.

As noted in OTC-31887-MS, the RSP demonstration project adopts a phased approach, with the ultimate objective of demonstrating a wave energy converter and seabed energy storage system for subsea power delivery (Slorach, et al., 2022). A schematic of the project layout is shown in Figure 6.

Phase 1 of the RSP project comprised the completion of a detailed front end engineering design (FEED) study. Phase 2 consisted of system communication bench testing, assembly of the subsea systems, and onshore commissioning of both the wave energy device and the seabed energy storage system which was completed in Q4 2022. Phase 3 will be the final part of the project, including offshore deployment and underwater demonstration taking place in Q1 2023 off the Orkney islands, UK North Sea. The configuration will be tested across a range of sea state conditions over the harsh winter months.

Hawaii SeaRAY AOPS Demonstration

In partnership with the U.S. Navy, U.S. Department of Energy, Saab, R2Sonic, Hibbard Inshore, and other industry leaders, C-Power and Verlume developed a SeaRAY AOPS with a Halo subsea battery energy storage system to be deployed at the Navy's Wave Energy Test Site in Hawaii for six months, beginning in the first half of 2023.

The Hawaii AOPS is a moored configuration consisting of a SeaRAY ocean energy and data system that floats on the surface; a single, combined mooring, data, communications and power cable; and the Verlume Halo, a seafloor base unit that provides energy storage and communications management for seafloor asset operation and acts as the gravity anchor for the AOPS. It will demonstrate the use cases of resident subsea vehicles and data gathering systems receiving power and data services autonomously and remotely (Figure 7). With a 5 kW generating capacity and 55 kWh energy storage system, the AOPS delivers ample power for many of the types of operations that take place in the ocean economy.

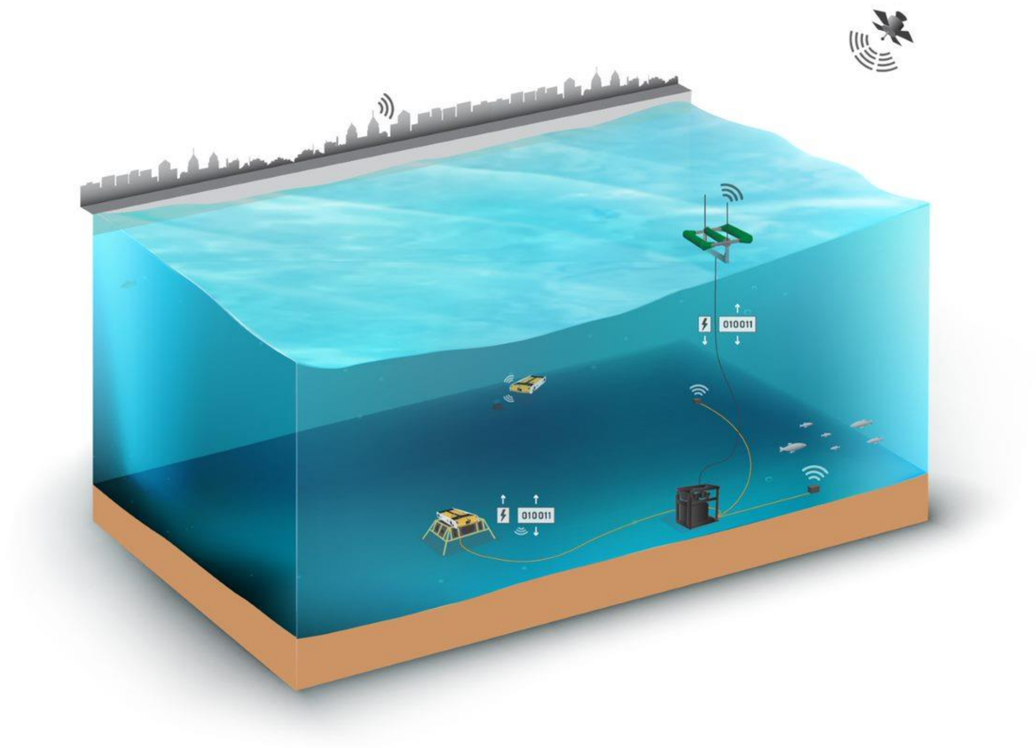

Figure 7: Hawaii AOPS deployment graphic rendering

It will be an on-site power station, data server, and internet connection supporting four assets — 3 static and 1 mobile:

- A SAAB Sabertooth AUV will operate in untethered mode, without a top side vessel. The Sabertooth docking cassette connects to the Halo via an umbilical. Missions will be downloaded from the cloud through the AOPS to the AUV, which will perform its mission, return to the dock, download its data for upload to the cloud, recharge, and then repeat the cycle until the demonstration is complete.
- A seafloor data-gathering system from Fugro will deploy for four months, transmitting data real-time to the cloud.
- A Franatech methane emissions sensor that is integrated into the Fugro system.
- A BioSonics long-range subsea environmental monitoring system will be deployed for the entire six months, sending data real time to the cloud. The BioSonics echosounder will also serve as an intrusion detection system during the trial.

Multiple assets will be supported with energy and data simultaneously (C-Power News, 2021).

Moving beyond this ISR-driven demonstration and in support of an offshore remote field, an example configuration is shown in Figure 8. Here, the SeaRAY AOPS is providing power and data communications capabilities to subsea equipment in addition to a resident tethered vehicle.

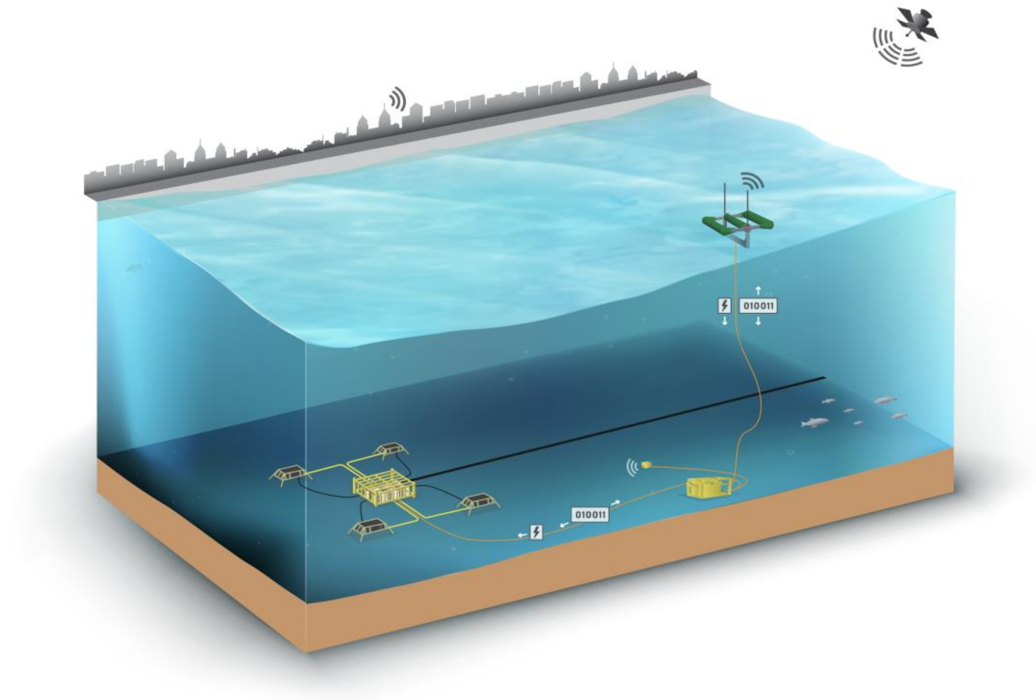

Figure 8: Offshore remote field AOPS configuration graphic rendering

Northern Lights Case Study

C-Power and Verlume have no affiliation with the project and used publicly available information to present this case study and produce the schematics below. The schematics are provided for illustrative purposes only.

Northern Lights is the transport and storage component of Norway's Longship project, which includes capture of CO2 from industrial point sources in the Oslo, Norway, region. When in operation, CO2 will be transported in liquefied state by ship to the Northern Lights onshore terminal on Norway's western coast and then by pipeline to a subsea storage location in the North Sea (Figure 9). The project's stated ambition is to reach a capacity to store 5 million tonnes of CO2 per year. The receiving terminal, offshore pipeline, and planned umbilical to the offshore template will be built to accommodate this potential volume. At that fully realized capacity, Northern Lights will be able to receive CO2 from European sources and 800,000 tonnes of CO2 per year from Longship (Northern Lights, 2023).

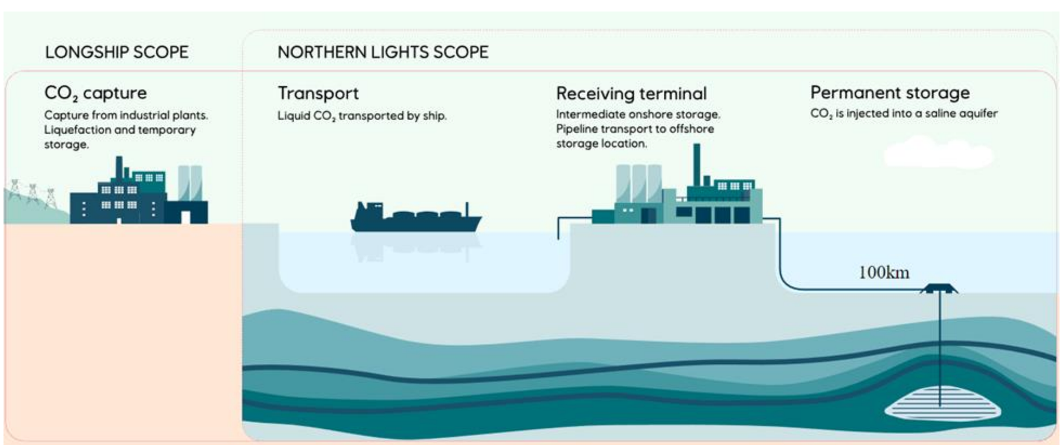

Figure 9: Northern Lights operations infographic (Equinor, 2023)

When Northern Lights starts operations, it will be the first cross-border, open-source CO2 transport and storage infrastructure network. Phase 1 of the project will be completed in 2024 with a capacity of up to 1.5 million tonnes of CO2 per year.

The onshore receiving terminal will be located at the Naturgassparken industrial area in Øygarden, Norway. Once the CO2 is delivered to Equinor facilities at the Sture terminal, it is transported to the subsea CO2 injection site via a 100 km pipeline, where it is injected and permanently stored 2,600 m below the seabed. The 100 km pipeline from has a 25-year design life. Phase 2 of the project includes plans for an additional four wells, with a max step-out of 25 km from the Phase 1 well site.

The CO2 storage complex has been named Aurora and is part of Exploitation License EL001. In March 2020, the Eos confirmation well was successfully drilled at a water depth of 300 m and completed, confirming the reservoir characteristics and storage capacity.

Power, communications, hydraulics, and mono-ethylene glycol (MEG) injection to the subsea facilities will be supplied from Oseberg A platform, with remote control of the field being possible from both the platform and an onshore operations center. The Phase 1 project plan calls for installation of a 36-km-long fluids umbilical and power and signal cable that will connect the injection well to the Oseberg A platform. Phase 2 would result in an additional 25 km (max.) of umbilical and power and signal cable between the Phase 1 and Phase 2 subsea locations.

Operations located at Oseberg A and well sites requiring power and data include a standard electro-hydraulic vertical tree in Phase 1 and the potential for all-electric trees in Phase 2. The topside injection system is estimated to emit 40–45 tons of CO2 per year during the first three years of operation. Leak detection should be installed as a best practice around the well sites, and inspection and maintenance for subsea assets will occur at regular intervals. Yearly, there will be a general visual inspection of the satellite well covering the structure, tree, control module, pipeline, and umbilical tie-in. Specifically, Northern Lights plans to use a remotely operated vehicle (ROV) or AUV to inspect the pipeline. Every fourth year, there will be an umbilical visual inspection and structure corrosion control and detailed visual inspection of the structure, tree, control module, pipeline, and umbilical tie-in (Equinor, 2020).

AOPS Configuration for Northern Lights

Figure 10 presents a schematic (for illustrative purposes only) of Phase 1 of the Northern Lights operation, as described in the case study. To recap, the offshore assets and operations include a pipeline from shore that delivers liquified CO2 for injection into the well located in the Aurora field. Power, communications, hydraulics, and MEG injection are provided from the Oseberg A platform via a fluids umbilical and power and signal cable.

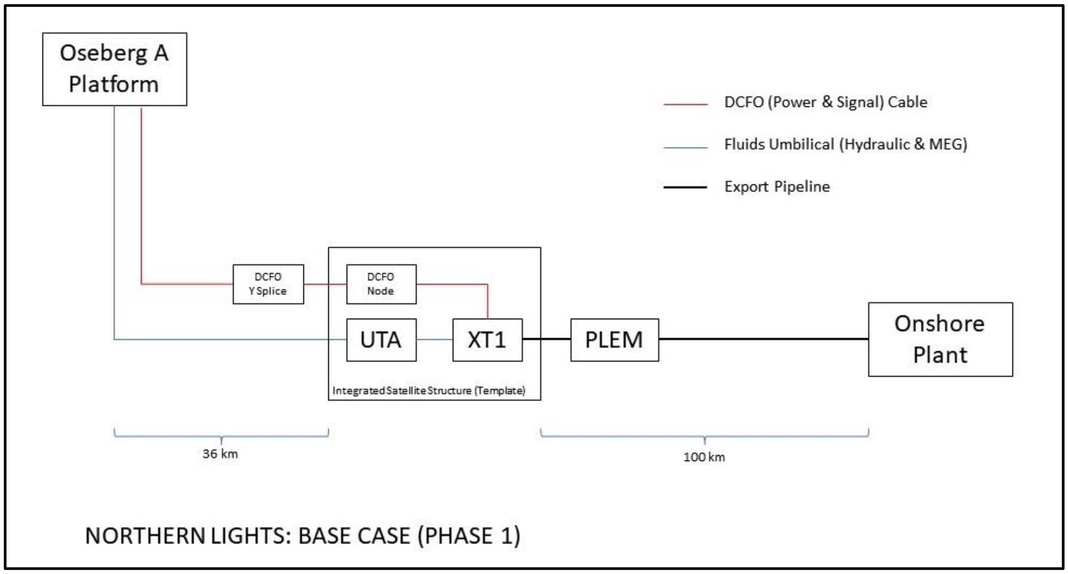

Figure 10: Northern Lights Phase 1 operations

Figure 11 envisions Northern Lights Phase 1 deploying AOPS technology to support offshore operations. The AOPS — which includes the topside SeaRAY wave power system, seafloor Halo battery energy storage system, and subsea chemical storage and injection (SCSI) — eliminates the need for the 36 km fluids umbilical and 36 km power and supply cable from the Oseberg A platform. In addition, the AOPS provides power, data, communications, and asset management capabilities for a resident, autonomous, IoT-enabled CO2 sniffer (leak detection) and Underwater Intervention Drones (UID™) docking station (domain awareness) (Transmark Subsea, 2019). The AOPS could be integrated with a resident docking system, such as Equinor's Blue Logic subsea docking system. Doing so would allow the AOPS to serve as the host for resident or campaign-based underwater vehicles to conduct remote, autonomous/semi-autonomous, subsea inspection of lengthy pipelines, umbilicals, and cables. (Not pictured are periodic inspection and maintenance operations the AOPS could also support via existing resident or campaign-based AUV or UID™, as needed.)

For Phase 1, estimated power demand for all-electric, fully subsea operations (in place of the electrohydraulic system with topside power and MEG injection currently proposed) is nearly 9,000 kWh per year. Operation of the tree accounts for roughly half of the annual power demand, at approximately 4,400 kWh. The continuous power need is below 1 kW, while peak power demand could top 9 kW.

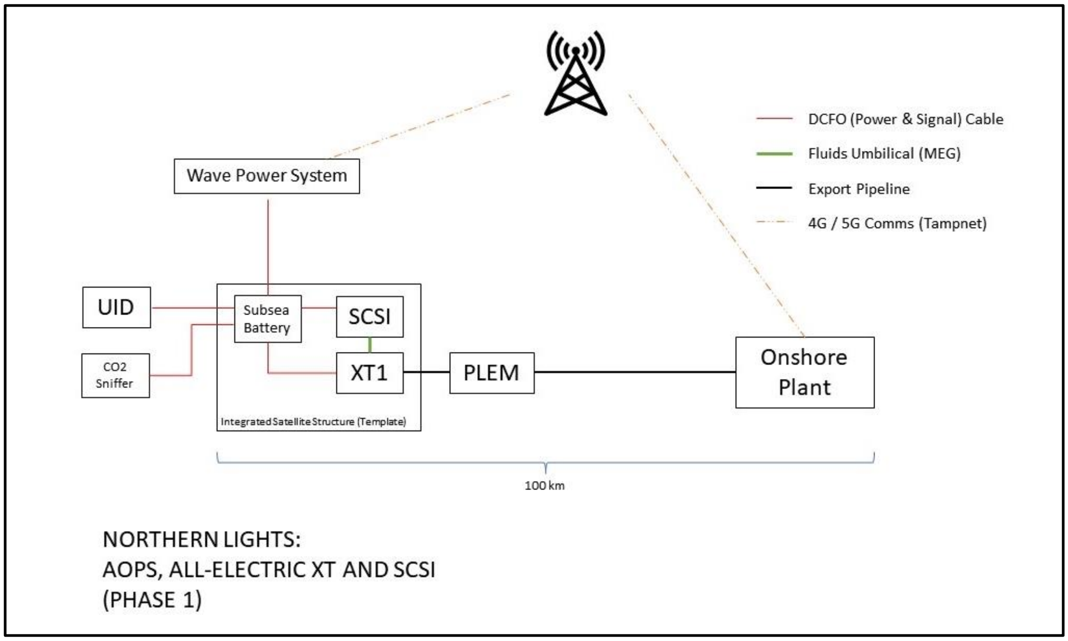

Figure 11: Northern Lights Phase 1 operations with AOPS deployment

Figure 12 presents a schematic of the Northern Lights operation after a complete Phase 2 expansion, as described above. The liquified CO2 transport pipeline has now been extended to connect to additional trees for well-site injection. Similarly, the fluids umbilical and power and signal cable have been extended an additional 25 km (max.) to provide power, communications, hydraulics, and MEG injection from the Oseberg A platform.

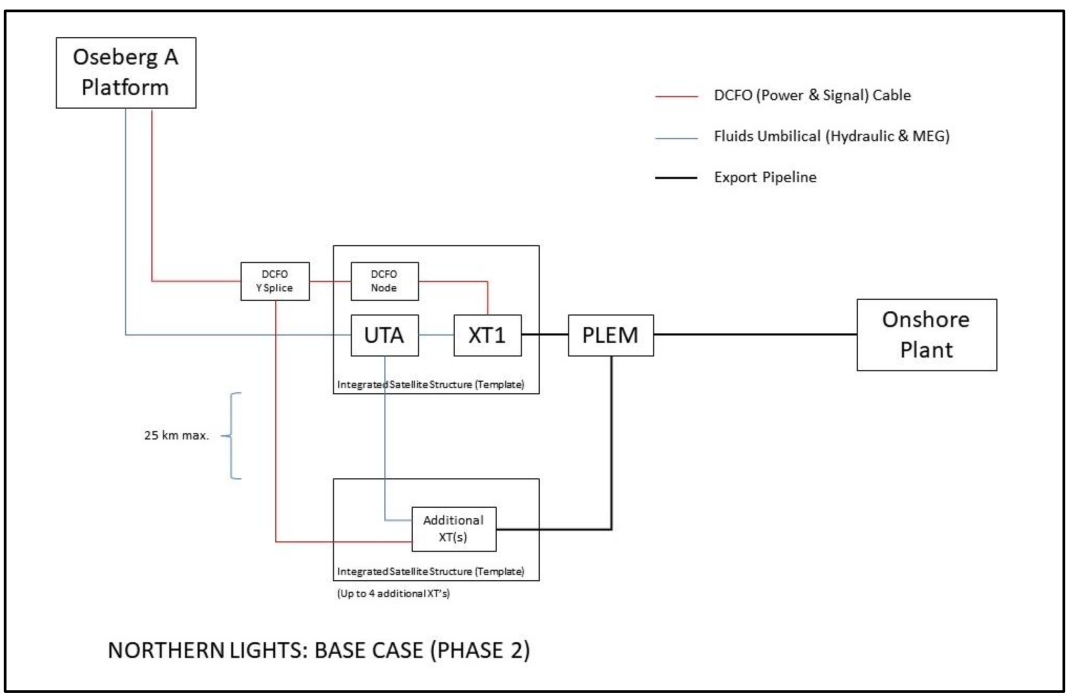

Figure 12: Northern Lights Phase 2 operations

Figure 13 envisions Northern Lights deploying a second AOPS system to support offshore operations after fully realizing Phase 2. The AOPS — which includes the topside SeaRAY wave power system, seafloor Halo battery energy storage system, and SCSI — eliminates the need for the additional 25 km fluids umbilical and 25 km power and supply cable added to serve Phase 2 well operations. In addition, the AOPS provides power, data, communications, and asset management capabilities for a resident, autonomous, IoT-enabled CO2 sniffer (leak detection) and UID docking station (domain awareness). (Not pictured are periodic inspection and maintenance operations the AOPS could also support via existing resident or campaign-based AUV or UID™, as needed.)

Upon completion of Phase 2, estimated power demand for the all-electric, fully subsea operations rises to approximately 28,000 kWh per year, driven largely by the addition of four additional trees. The continuous power need for the entire project rises to approximately 3 kW, and peak power demand would likely top 18 kW.

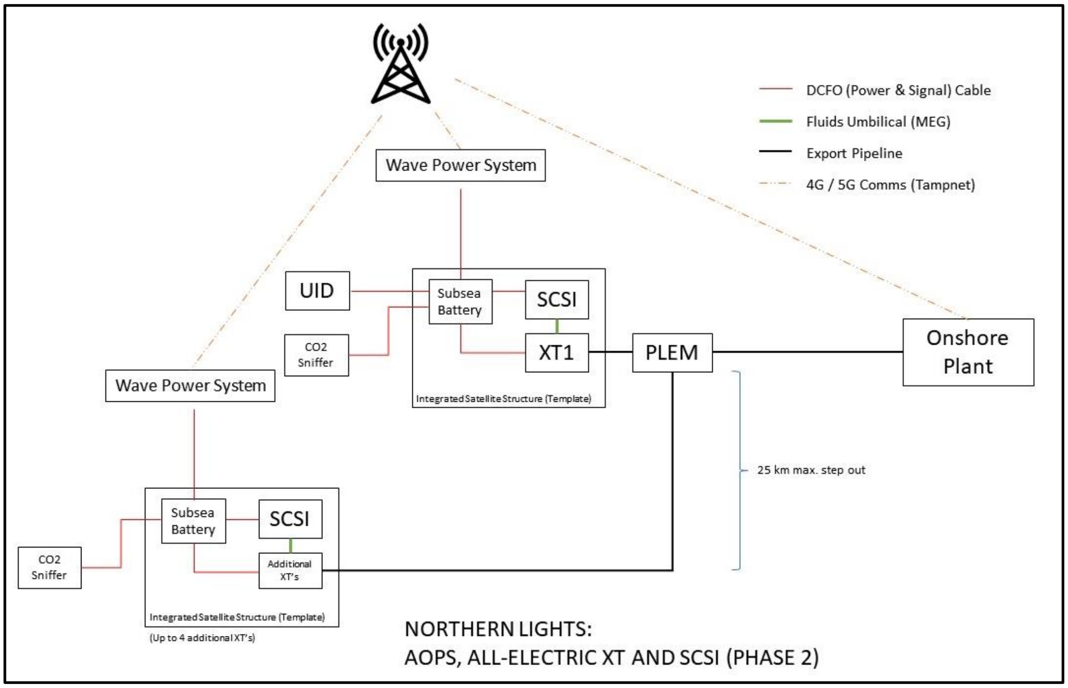

Figure 13: Northern Lights Phase 2 operations with AOPS deployment

Benefits

Compared to proposed plans to meet power, data, and offshore operational needs, AOPS deployment yields cost, carbon and efficiency benefits. An AOPS provides the power, data, and communications for:

- Subsea controls and injection systems
- Leak detection
- Domain awareness solutions, solving the need for overtrawl protection of seabed structures and providing a security alert system
- All named inspection activities

Specifically, an AOPS delivers enhanced value compared to the incumbent business plan for the following operations:

- An AOPS with SCSI would eliminate the need for all umbilicals and cables from the Oseberg A platform to the Phase 1 well and Phase 2 wells (approximately 60 km of umbilical at an estimated cost between $35-50 million). Eliminating this need delivers significant cost savings and reduced operating complexity and risk incumbent in inspecting and maintaining lengthy cables.
- An AOPS would eliminate the CO2 emissions currently projected from the proposed topside injection system, along with vessel-produced emissions for any monitoring or inspection activities.

- Should Northern Lights initiate plans for remote maintenance, an AOPS is also a solution for remote, autonomous, resident robotics and operating equipment.

In summary, estimated cost savings through deployment of AOPS solutions, compared to the incumbent proposed approach, are at least 50%. Given that the purpose of Northern Lights is to decarbonize the European economy, it is critical that the facilities also operate at a net-zero CO2 level. AOPS deployment would result in a significant reduction of CO2 emissions primarily from removing vessel operations. While the quantitative value is difficult to estimate, AOPS deployment would also reduce operational complexities and risk by enabling resident, autonomous, 24/7 leak detection, domain awareness, infrastructure security, and inspection capabilities via zero-emission power, real-time data and communications, and asset control.

Conclusion

Within the ocean economy, increasing amounts of effort and resources are being devoted to upgrading existing hardware and creating new systems. Unfortunately, efforts are hindered by the fact that the ocean is an energy and data desert, leaving the $2.5 trillion global ocean economy with only high cost, high carbon emissions, and high complexity options — or, in some cases, no viable alternative at all.

AOPS technology breaks new ground to solve these limitations with a wave-powered device, and thus will help transform the ocean economy. These systems deliver energy in the form of carbon-free electricity as well as near real-time, two-way data and communications. Those power and data capabilities unlock the future of resident, autonomous, digital operations at sea that the ocean economy has been building toward for years. It has applications for all offshore industries: energy, defense and security, aquaculture, science and research, and communications.

The technology will be demonstrated at the U.S. Navy's Wave Energy Test Site in Hawaii in a full-scale pilot. This AOPS will demonstrate the use cases of resident subsea vehicles and data gathering systems receiving power and data services autonomously and remotely. With scalable generation and energy storage capacities, the AOPS delivers ample power for many of the types of activities that take place in the ocean economy.

To demonstrate how AOPS technology could deliver benefits to a real-world offshore operation coming online in the near future, a hypothetical AOPS use case for the Northern Lights carbon transport and storage project was created. This case study determines that AOPS would reduce the cost, CO2 emissions, and operational complexity of Northern Lights' subsea operations. Notably, AOPS deployment would eliminate the need for 60 km of fluids umbilical and 60 km of power and supply cable, resulting in at least 50% cost savings net of the cost of the AOPS.

Given these demonstrations, the AOPS projects to serve a wide array of applications across all sectors of the ocean economy and can deliver at-scale decarbonisation of offshore operations globally.

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