SEA-O2

Ensuring safe fishing around carbon storage sites

CONTENT

Executive Summary

In the future, a growing number of abandoned oil rigs will be converted into carbon storage facilities, injecting captured CO_2 to mitigate emissions. This approach is viewed as a transitional tool within a broader climate strategy rather than a permanent solution. These rigs, repurposed as carbon storage sites, also serve as artificial reefs that enhance marine biodiversity and attract fish, thereby supporting local fisheries.

To address fishermen's concerns regarding data transparency, technological and long term monitoring uncertainties, the SEA-O_2 program was introduced. This initiative unites fishermen, carbon storage operators, and other stakeholders in a collaborative effort to monitor and manage carbon storage. Fishermen use sensors mounted on their own vessels to detect potential leaks, and they share co-ownership of the collected data, empowering them to track storage status and maintain confidence in the system. In return, they receive targeted incentives, including financial rewards and "Blue Certifications" for CCS-compliant catches, which command premium market prices.

At the technical level, the system employs refined algorithms and advanced leak mitigation measures to ensure security and efficiency. A bespoke detection interface has been designed for fishermen's boats, providing seamless access to real-time data and insights that integrate effortlessly with their daily fishing routines.

Overall, the SEA-O_2 program demonstrates how repurposing oil rigs for carbon storage can serve as an effective transitional strategy. By combining sustainable carbon management with active community engagement and robust monitoring, the program not only mitigates uncertainty of leakage in large area and long term but also supports the long-term economic and environmental interests of coastal communities.

Meet the Team

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Acknowledgements

With Thanks to Pietro Ferraro, Chai Rukuan, Ryan McClure, Martin Blunt, Davis Bigestans, and Paco

PROBLEM

Key trends of 2055:

Political

- Governments worldwide proposing commitment to Net Zero by 2050 to tackle climate change[1]
- Governments are expanding CCS site licences on North Sea, repurposing a growing number of depleted rigs offshore

Economic

- Industries are scaling up investments in CCS as carbon pricing and tax incentives make it a cost-effective solution[2]

Environmental

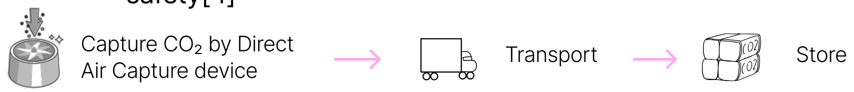
- CCS is becoming a key tool in global Net Zero strategies, significantly cutting emissions from heavy industries[1]

Social

- There has been much discussion worldwide about the crisis of trust, with evidence of declining trust in social, economic, political and media institutions[4]

Technological

- Companies are prioritising funding for advanced CCS technologies, focusing on injection techniques and reservoir simulation[4]
- IoT and automation are being adopted to enhance monitoring and safety[4]



Carbon Capturing and Storing (CCS) with Oil Rigs

CSS is a technology that captures CO_2 from industrial sources, transports them, and stores them underground to prevent atmospheric release. It helps reduce greenhouse gases by using geological formations like depleted oil reservoirs.

CCS using abandoned oil rigs involves injecting captured CO_2 into depleted offshore oil reservoirs for long-term containment. It offers high storage capacity, is much safer than onshore storage due to stable geological conditions, and has low costs by repurposing existing infrastructure.

625 km^2

Average size of an oil reservoir in the North Sea [5]

£26 million

Cost of repurposing the oil rig platform for CO_2 storage over a thirty-year period[6]

VS.

Decommissioning offshore platforms is approximately £14.8 million to £147.2 million per platform[10]

> 7500

Offshore oil and gas platforms across 53 countries are expected to become obsolete in the coming decades[9]

> 1000

Wells are scheduled for plugging and abandonment between now and 2027[9]

Fishermen Struggles

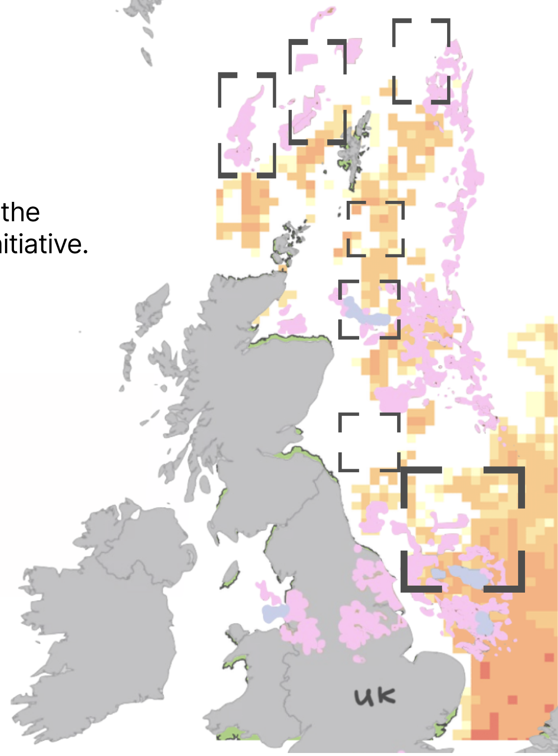
Offshore CCS expansion could disrupt fishing communities, restricting access and raising safety concerns over CO_2 leaks harming marine ecosystems. Uncertainty about long-term impacts may erode trust, demanding transparency and collaboration to protect fisheries.

"The risks of CO_2 leaks from underwater pipelines and storage sites pose environmental, health, and safety threats, and could have a significant impact on the marine environment."[4]

Potential CCS area (oil and gas rigs)
Current carbon storage site

USER

One key challenge in offshore carbon storage development is balancing co-location with fishery operations. If projects fail to address the needs and concerns of fishing communities, conflicts can arise, eroding trust and threatening both livelihoods and the broader CCS initiative. Effective stakeholder engagement is crucial[1].



Betty Veyron

"One of my favourite fishing spots is near the abandoned oil rig, where the waters are rich with marine life."

Fisherwoman who do gillnetting
Location: North Sea

"We deeply value the health of the ocean because our livelihood depends on it. We strongly oppose any project that might harm marine ecosystems"

"I am unsure about the technology—could it leak CO_2, explode, or put me at risk?"

0:00	4:00	5:00	9:00	10:00	11:00	12:00
I steer the boat while the rest of the crew rests	We arrive at an abandoned oil rig with abundant fish stocks.	We set the nets and begin fishing.	We continue setting nets, checking gear.	We wait, allowing time to rest as fish gather.	We haul in the catch, assessing fish quality and size.	We sort fish, returning undersized ones to the sea.

Currently, the fishing resource map largely overlaps with the oil reservoir map[3][5].

They Support

Economic Opportunities
Repurposing oil rigs as artificial reefs can sustain fish populations, generating long-term benefits for local fisheries.

Environmental Responsibility
Many fishermen recognise the importance of reducing carbon emissions and some are willing to participate in CCS activities if ecosystem safety is guaranteed.

[4]

They Oppose

Safety Concerns
Potential CO_2 leaks could harm marine life and pose direct risks to their operations and well-being.

Ocean Acidification

Lack of Trust
Distrust of government and corporations remains high. Fishermen want transparent oversight and active community engagement.

[2]

+ Rigs act like artificial reefs, improving local fish stocks and offering potential economic gains for fishermen

− Fears about leaks and accidents persist, fueling scepticism and highlighting the need for clear, consistent communication

+ Preserve and maintain the rig as a productive marine habitat, while enabling fishermen to safely engage in carbon storage efforts.

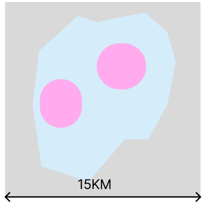
− Mitigate apprehensions through data sharing, open communication, and shared decision-making

RISK

CCS Site Transformation

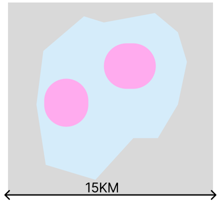
An estimated 7.5% of wells may leak CO_2, with active wells releasing 150 metric tons annually and abandoned wells 300 metric tons, due to limited monitoring and delayed detection.

5 Years — Preparation



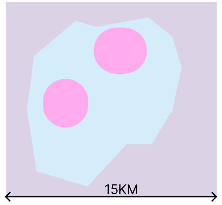
The licensee explores, **assesses risks, and characterises the site.** If qualified, the operator may apply for a Carbon Storage Permit [2].

10-20 Years — Operation



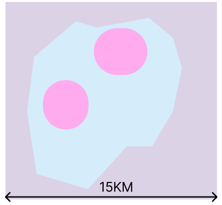
With the permit granted, CO_2 **injection begins** under the Monitoring Plan (MP) and Corrective Measures Plan (CMP), ending with site closure.

20+ Years — Post-Closure



After CO_2 injection stops, the site is closed, **monitored for at least 20** years, and then eligible for a Transfer of Responsibility.

30+ Years — Post-Handover



Site responsibility **shifts to the government,** with the operator funding 30 years of monitoring.

Unmonitored area · Around the injection point: highest possibility of leakage · Maximum expected spatial extent of CO2 storage · Geological context (which may be impacted by the CCS operation)

	Preparation	Operation	Post-Closure	Post-Handover
LEAKAGE	No leakage	Potential Burst (pipeline/well)	Slow seepage through geological faults or fractures	Slow seepage through geological faults or fractures
RISK [1]	-	High Risk	Mid-Low	Mid-Low
MONITORING	-	Easy	Difficult	Difficult
LEAKAGE TYPE	-	Severe	Severe if Unattended	Severe if Unattended
FINANCIAL [3]	High cost	High Cost	Uncertainty of Fund	Uncertainty of Fund
MITIGATION	-	Well and Pipeline Repairs	Pressure Management	Seal Enhancement

Type of leakage

Burst Pipeline or Well Blowout
- Extreme Case: Up to 578 kg/s [4].

Slow Seepage through Geological faults or Fractures
- Typically below 0.006 kg/s but could up to 0.1207 kg/s [4].

Impact

- Leaks below 0.012 kg/s (≈1 t/day) would have a minimal impact in terms of affected area [4].
- Larger leaks (for example, in excess of 0.12 kg/s (≈10 t/day) would have the capacity to impact large areas if left un attended [4].

DESIGN OPPORTUNITY

Current Needs and Roles of Stakeholders

Stakeholder	Government	Carbon Storage Operator	Fisherman	Fishing Coop	Research institution
Role	• Issues permits • Publishes incentives to operators • Sets regulations • Oversees long-term liability	• Site exploration • Injection • Initial and Post-closure monitoring • Initial handover funding	*No current participation in CCS*	• Protects fishers' rights • Advises on policy	• Environmental Impact Assessment • Analyses data for improved CCS performance
Need	• Meet Net Zero targets • Balance stakeholders' interests • Establish and maintain public trust	• Earn carbon credit from the government • Minimise the carbon storing cost • Comply with regulations for seamless operations	• Safe and profitable fishing • Be familiar with the area around the CCS site • Avoid disruptions to normal operations	• Leave fishing unaffected by the environmental changes in the long term • Sustainable fishing	• Acquire reliable data for advanced research • More detailed monitoring to improve leakage research

Design Opportunities

TRUST & BENEFIT

Create platforms for communication between policymakers, and fishing communities, meeting the needs of all stakeholders.

SAFETY

Implement IoT-based tracking for CO_2 leakage and marine biodiversity changes.

USABILITY & EFFECTIVENESS

Provide an efficient & easy to navigate software of carbon monitoring systems.

Design Requirements

Stakeholder Transparency – **clear & trustworthy communication with fishing** communities and regulatory bodies.
Attract the Stakeholders - to sustain the system long-term the mutual benefit of the stakeholders should be met.

Evaluated by: System design expert, Fishermen

Environmental Compliance – Sustainable monitoring and tracking CO_2 leaks for a long period of time.

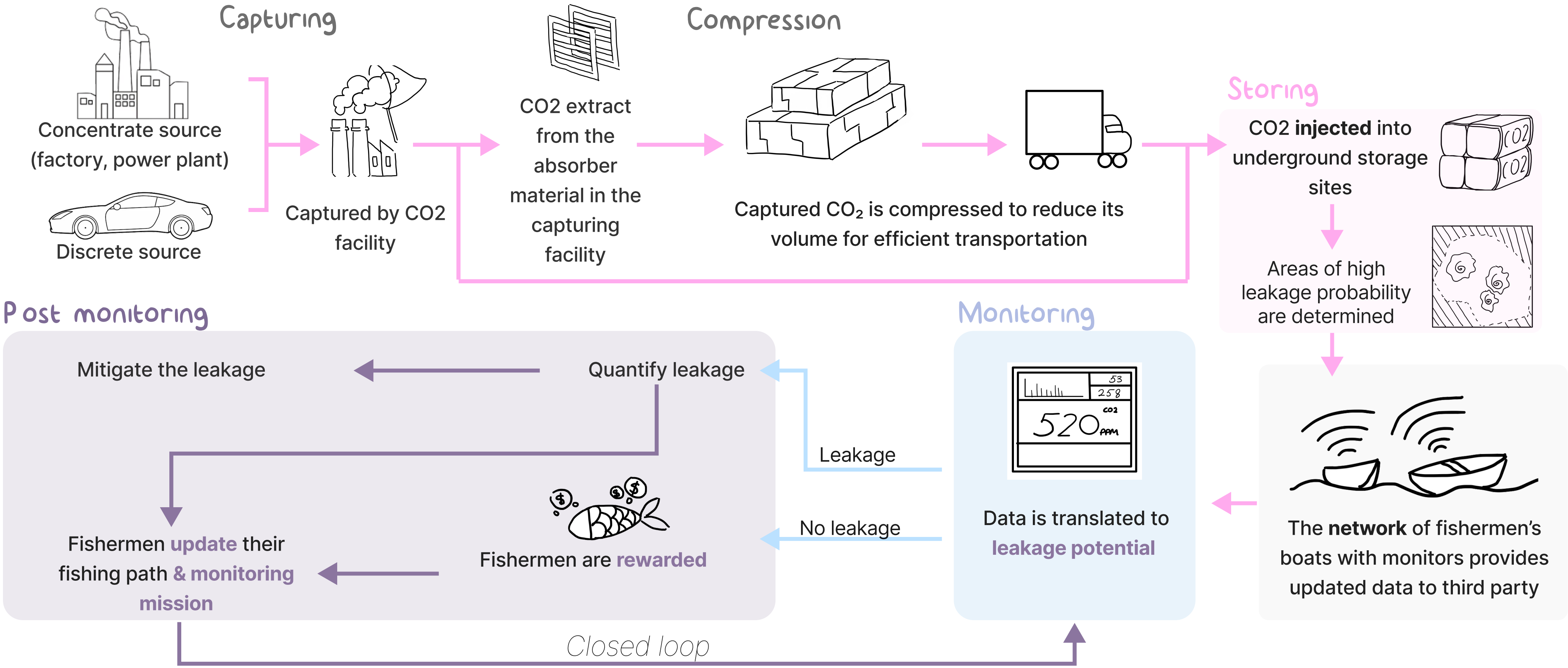
Evaluated by: System/Economical design expert, Calculations

Simple Interface - Accessible on boat, data is engaging & interpreted visually.
Effective Algorithm - Should be able to plan a route for monitoring and fishing, according to the data analysis.

Evaluated by: Design expert, Fishermen, UX design guidelines.

SYSTEM DIAGRAM

Validated by *Ryan McClure*



Key Roles

- **Capturing** – energy companies, industrial emitters, technology providers, government agencies.
- **Compression** – pipeline operators, engineering firms, regulatory bodies.
- **Storing** – geologists, storage site operators, environmental agencies.
- **Monitoring** – research institutions, fishermen community.
- **Post Storing**– policymakers, fishermen, operator, fishermen coop

Incentives

- **Financial** (tax credits, subsidies) and **investment** in carbon capture technologies, fostering innovation and job creation.
- Efficient compression reduces **transportation costs**, attracting investment in infrastructure and energy-efficient technologies.
- Underground storage is **cost-effective.**
- Advanced monitoring ensures regulatory compliance and builds **public trust, as well as helps with the research in the CO2 field.**
- **Ecosystem restoration,** additional financial support, as well as safe fishing for fishermen.

STAKEHOLDERS

Operator

Funds the Fishermen NGO for monitoring, provides devices and algorithms, and mitigates leakage.
Duties: Mitigate leakage and share the mitigation process.
Benefit: Outsourcing monitoring reduces management and operational pressure. Not owning the data builds trust among stakeholders and reduces public pressure.

Government

Duties: Regulate operators and incentivise fishermen.
Benefit: Reliable fishermen data, increased trust.

Research Institution

Fund fishermen for the data.
Duties: research on the carbon storage
Benefit: Reliable fishermen data to produce more accurate result.

Fisherman Coop (NGO)

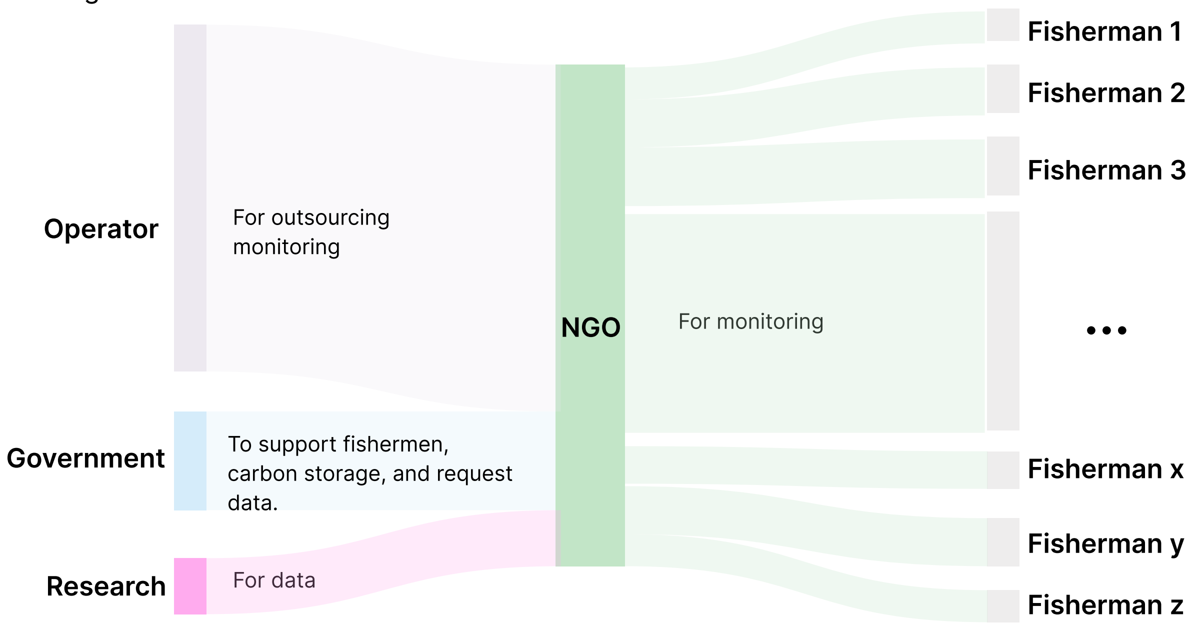
Owned and managed by fishermen, it represents their interests. It owns the monitored data.
Duties: Manage funds, allocate incentives, manage data, and share with fishermen and others, report any leakage.
Benefit: Information is managed here (by those affected by the leakage), making it more secure. Fishermen, when united, have a stronger voice.

Fisherman

Involved in the system by monitoring while earning incentives. Indirectly own data to ensure transparency.
Duties: Help to monitor while fishing.
Benefit: Ensure their safety by managing the system themselves, earn incentives, and boost sales through certification labelling.

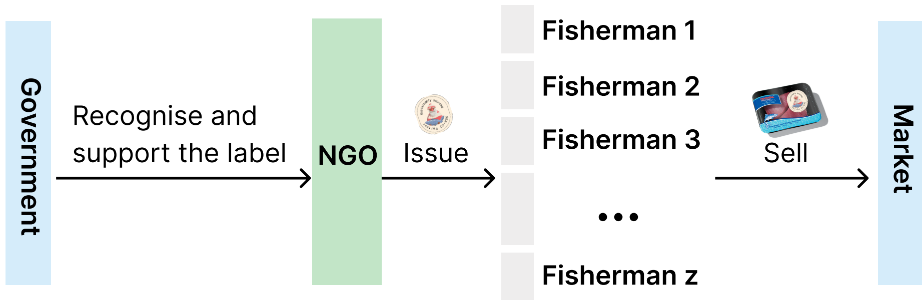
Economical benefit flow

The Sankey diagram illustrates the financial support and service exchange among all stakeholders, ensuring a collaborative framework for monitoring and maintaining carbon storage sites.



Social benefits

A key advantage for fishermen is a certification that validates their responsible participation. This certification can be displayed on their products, potentially increasing consumer trust and sales. Currently, sustainability-labelled products see an 18% higher consumer acceptance than unlabelled ones[1].



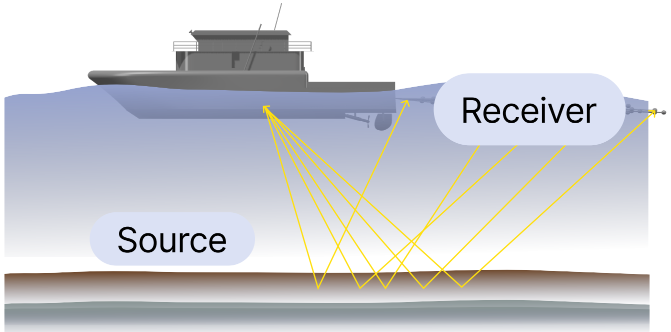
TECH ENABLERS

Tech Selection- Seismic Sensor

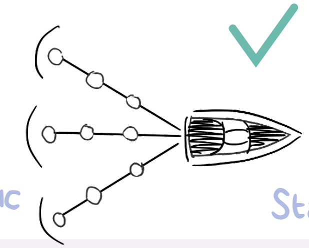
To enable CO_2 monitoring for fishermen, a range of sensors must be selected. Among the three common types, **seismic sensing is the most suitable**. It allows fishermen to monitor **on the go, covering a large area** and effectively observing regions with limited or delayed monitoring.

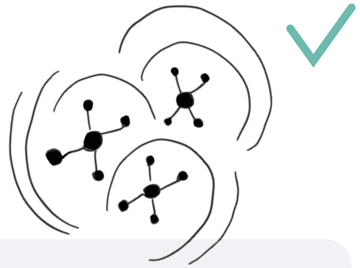
Static Sensor for Detail Inspection

A drawback of seismic sensing is that it only provides data on **underground activity**, helping predict CO_2 flow and identify potential leakage, but it **cannot quantify the severity**. Therefore, we propose **to additionally deploy static sensors**, such as cameras and chemical sensors, to better understand CO_2 flux once leakage is detected, in order to quantify the leakage.



CO2 storage

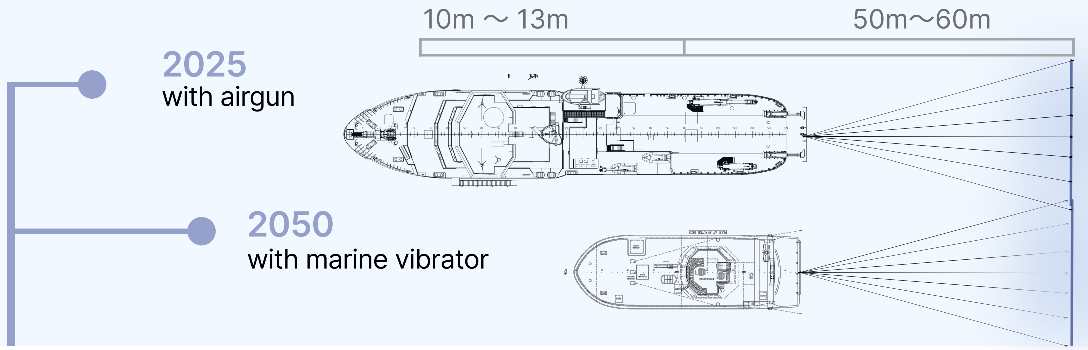




	Satellite	Seismic Sensor	Static Sensor
Resolution [1]	**1KM range**	**100M range**	**10M range**
Sensitivity	●	● ●	● ● ●
Cost	● ● ●	● ●	● ●
Scenario[1]	• providing sign of leakage • **global-scale** data	• monitors over **different fishing areas**	• high **precision** • installation around high risk (oil rig)
Usability	●	● ● ●	●

Future of the Seismic Sensor

By 2055, seismic source marine vibrators are expected to **replace the traditional airgun.** Compared to traditional source, marine vibrator system has the capability to emit the same energy as an airgun source, but it distributes over time and over a chosen frequency range. The use of seismic source marine vibrator is beneficial for our user, since it will allow **adapting monitoring to smaller vessels like fishermen's boat**, as emit less harm to the marine environment [2].



MONITORING

Assigning monitoring tasks to fishermen both ensures community engagement and reinforces trust by community involvement. However, the system must ensure complete coverage so that the entire area is assessed within a defined timeframe.

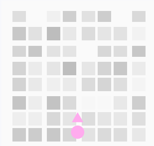
Define monitoring goal

Define area needed to be monitored and its frequency.

Determine the range

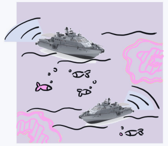
Monitoring stage

Update urgency



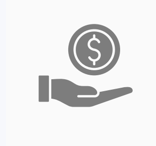
Represent urgency by pixel based map.

Give reference



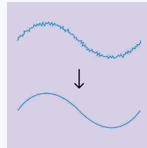
Fishermen monitor while fishing and travelling within or between fishing zones.

OR



Fishermen Cover Unmonitored Zones for Incentives(Usually beyond fishing area)

Data Processing stage

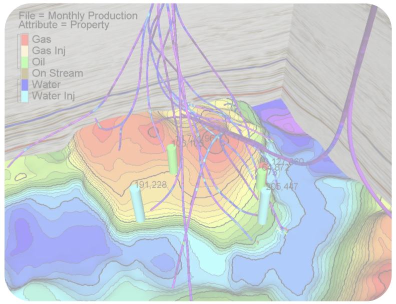


Signal processing to identify leakage.

Define the area of monitoring

The monitoring area is defined by CO_2 diffusion beneath the seabed. Repurposing oil rigs provides valuable initial geological and reservoir data, minimising effort since this analysis was already conducted during initial drilling. However, the geological conditions may change as CO_2 is injected, making fishermen's involvement in monitoring valuable. This data can be simulated using TOUGH3 software [1], which is currently being developed in the lab. The simulation provides a 4D output, allowing us to identify critical areas that require the most attention and determine the optimal timing for result evaluation.

1. Model of the reservoir (Already known+ Fisherman)

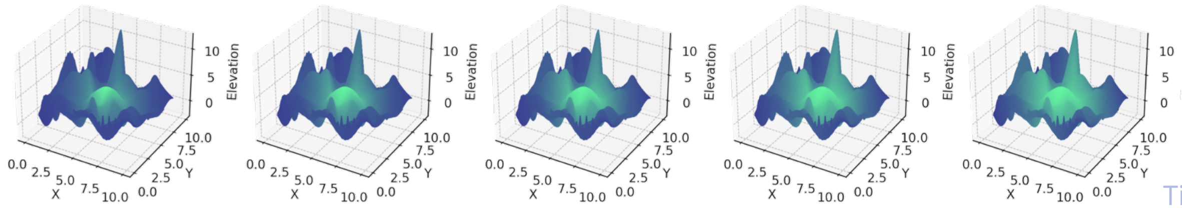


Oil and gas storage capacity, cavity volume, geological map, rock structure, input pipeline location, ...

Simulation

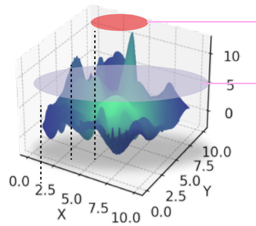
2. 4D simulation Result

The presence of CO_2 No risk of CO2 leakage



Time

frequency



Area need some attention, every 2 weeks

Area need less attention, every month

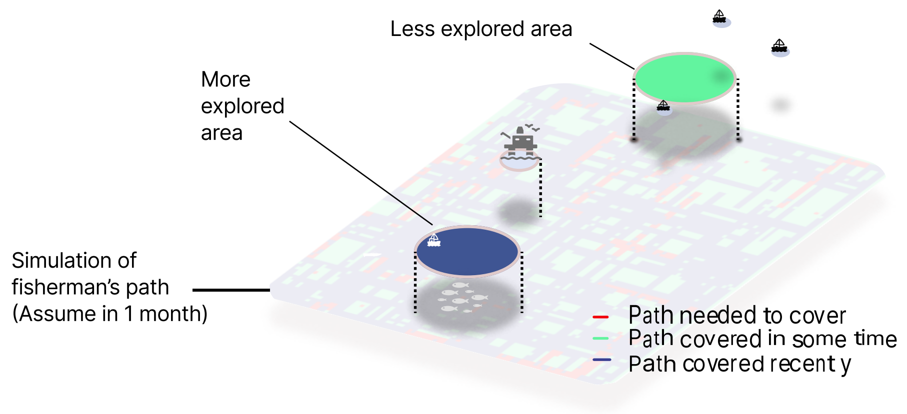
3. Determine the monitor frequency

There is no clear standard for monitoring duration, so we estimate it based on impact. We assume typical leakage rate is 0.006 kg/s as mentioned before. We calculate how long CO_2 leakage lowers seawater pH from 8.1 to 6.0 within a 10m radius[2], posing risks to certain species. Assuming full dissolution, even spread in a spherical volume, and a seawater buffer capacity of 0.1 mol/kg/pH, the required CO_2 is divided by the leakage rate. Without considering diffusion, currents, or real-world mixing, this worst-case estimate suggests 36.5 days. Under normal conditions, monthly monitoring is reasonable, with frequency adjusted based on risk.

MONITORING

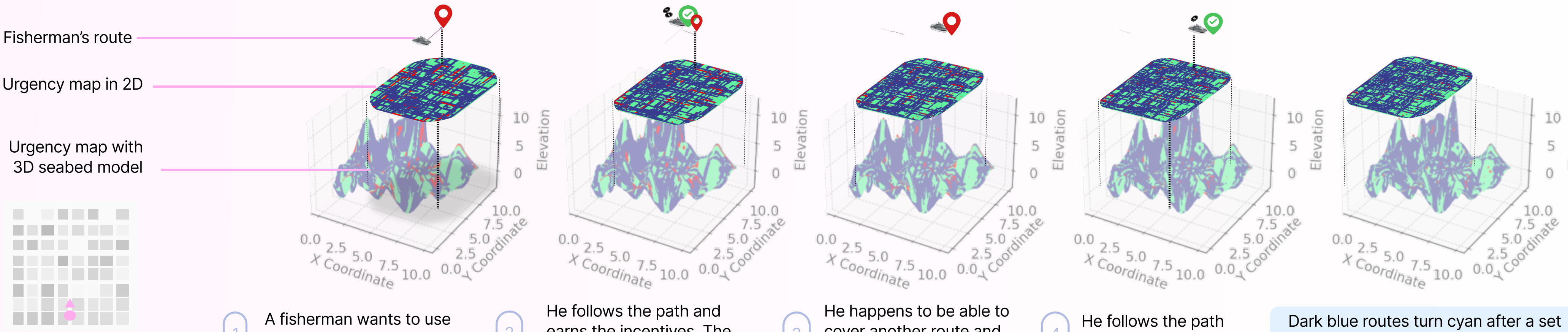
The fishing boat will go wherever the fisherman wants to fish. Simulations indicate that about 80% of the target region can be covered in a month (blue and cyan paths), but certain sections remain unvisited.

To address this gap, an urgency map guides fishermen toward high-priority sites, supplemented by incentives to encourage exploration of under-monitored zones.



Fisherman operates with urgency map

Fishermen can independently decide whether to cover high-priority sites. If they opt in, the system suggests nearby destinations, enabling them to follow a designated path and earn incentives. As shown below, the raw simulation outputs were initially difficult to interpret, so a pixel-based interface was developed to simplify navigation and enhance usability.



Pixel-based map in final UI

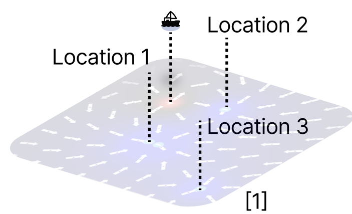
1. A fisherman wants to use its free time to explore uncharted areas and earn incentives.
2. He follows the path and earns the incentives. The system turns the red area into blue.
3. He happens to be able to cover another route and reach the next unexplored area.
4. He follows the path and earns another incentive.

Dark blue routes turn cyan after a set time and later turn red, indicating attention is needed.

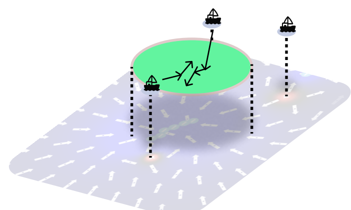
Increase efficiency

Efficiency challenges include providing destination options based on urgency and preventing multiple boats from overlapping.

A potential field algorithm can be applied, treating boats as positive charges and unexplored routes as negative charges. The higher the urgency of the destination, the greater the assigned charge. Since positive charges are attracted to negative charges, relating them with potential field law can effectively provide the most efficient options for fishermen. Additionally, boats share the same charge, causing their paths not to overlap, which enhances efficiency in path planning.



Location 1 is more urgent and carries a higher charge. The boat is influenced by locations 1 and 2, which are offered to fishermen for incentives.



The algorithm determines the monitoring route and prevents overlap.

MONITORING

Incentive

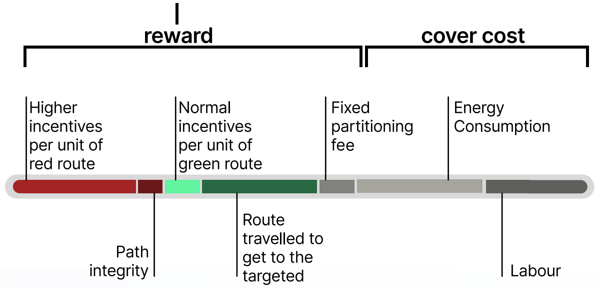
The carbon storage operator and government jointly offer incentives to fishermen, reducing the need to invest in new monitoring vessels. Since the operator relies on fishermen for leak detection, they are willing to allocate a budget specifically for exploring these areas.

The incentive will include a fixed base payment to encourage fishermen to explore the area when they are free, as well as effort-based incentives covering their operating costs and labor. This ensures that every additional distance they cover for us is well rewarded and all costs are covered. The incentive structure is shown on the right.

The incentives are set slightly below average fishing income to ensure monitoring remains supplementary.

Incentive structure

Should be less than £57 per person per day, based on current fishing income[1].



Why is the operator willing to pay?

We analyse the cost-effectiveness of purchasing a boat for the operator versus hiring fishermen, evaluating whether they can complete the required tasks within an acceptable budget.

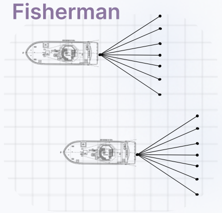
Assumptions

We assume an average size of 15 km laterally. Thus the size is 625km^2.

Assume that all area should be covered within one month.

Operators may prefer fishermen as they complete the task at a similar cost.

Fisherman



Work length: Although work durations vary, we assume an average total of 3 -6 free hours in total across all boats for a oil rig.
Daily scanned area: 37.5 -75 km²/day.
Days required: 8-16 days.

Completion in 1 month: Yes

Fixed Cost: Sensor (we assume it at 2000 pounds based on the current seismic sensor) /boat. Assume 10-50 boats.

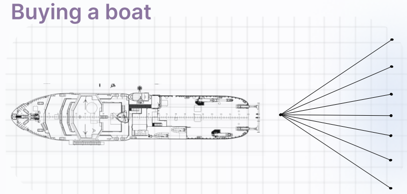
Operating per boat:
Estimation of £50/h-£80/h including fishing boat, labor, fuel consumption(based on today's renting fee)

Estimation of £30-80/h other incentives.

The cost over 15 years(Worst Scenario)
£98,826 per oil reservoir per year

The cost over 15 years (Best Scenario)
£47,413 per oil reservoir per year

Buying a boat



Work length: Assume able to work 12h
Daily scanned area: 150 km²/day.
Days required: 4.5 days

Completion in 1 month: Yes

Fixed Cost: Boat: £356,300
Sensor (we assume it at 2000 pounds based on the current seismic sensor) /boat £2000

Operating per boat:

Operating: Labor 500/day(assume working 20 days per month)

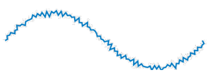
The cost over 15 years(Worst Scenario: only 1 oil rig)
£143,886 per oil reservoir per year

The cost over 15 years (Best Scenario: 4 oil rigs can be covered by 1 boat)
£35,971 per oil reservoir per year

Data Processing

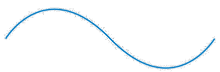
The data is then processed through machine learning to detect leakage.

Step 1: Data filtering



Data Gathered from Boats

Filter eg. Moving Average Filter to reduce noise by the sensor.



Processed Data

Machine learning to identify leakage automatically

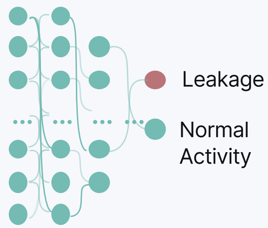
Machine learning algorithm

It is trained as shown below

Experiment data
+
Data from real world incidences
+
Simulated data

Training data

Test -ing



Leakage

MITIGATION

Current Approaches to Manage Leakage

When a leak is confirmed, operators resort to:

Well and Pipeline Repairs

- Isolating and repairing breached pipelines, and, in wells, replacing or supplementing leaking completion strings or adding extra cement in the annuli
- Plugging and abandoning wells using thick cement plugs if repair is not viable

Seal Enhancement

- Injection of sealants (for example, foams, gels, and polymers) is used to reduce permeability in fractures or weak spots in the caprock
- More recently, biomineralisation sealing technologies have been proposed which lead to the precipitation of carbonate

Pressure Management

Several methods allow for depressurisation of the reservoir, including:

- pressure release via new or existing wells
- injection of solid reactants, nanoparticles or water to immobilise CO2 either by dissolution of gaseous CO2 or precipitation of carbonates
- In more complex situations, reservoir pressure can be released by transferring fluids into neighbouring reservoirs.

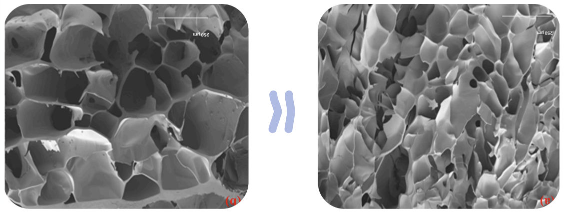
Recent Developments

CO_2-responsive particle gel

- In their fluid phase, gels can penetrate fine leakage pathways more effectively than conventional cements
- Controlled polymerisation: Once inside the fracture or annulus, gels can polymerise or set into a solid or viscoelastic matrix, plugging the pathway even under moderate to high pressures

- New Dual-network CO_2-responsive particle gel (DN-CRPPG) designed to mitigate CO_2 channelling and leakage [1]
- Gel is engineered to swell upon exposure to supercritical CO_2, thereby self-reinforcing its plugging capacity within fractures

Although large-scale field tests remain relatively few, pilot projects suggest gel solutions can seal micro-annuli and hairline fractures in depleted fields and saline aquifers.

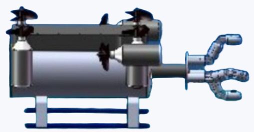


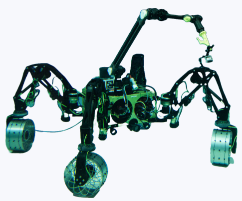
The DN-CRPPG gel absorbs CO_2, swells with larger pores, stays structurally intact, and enhances its sealing ability.

Although our proposed system focuses primarily on monitoring and sensing, we anticipate that emerging mitigation techniques will eventually be integrated.

Subsea Gel Injection Robots

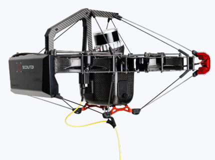
- Carry onboard canisters of sealant (gels, bio-cementation starters, polymer resins).
- Sonar-based mapping to locate fractures or conduits.
- Robotic arms inject or pressure-squeeze sealants directly into identified leaks.
- Operate autonomously or via tether, crucial for deepwater sites where diver-based interventions are impractical.





Wellbore-Inspection Drones

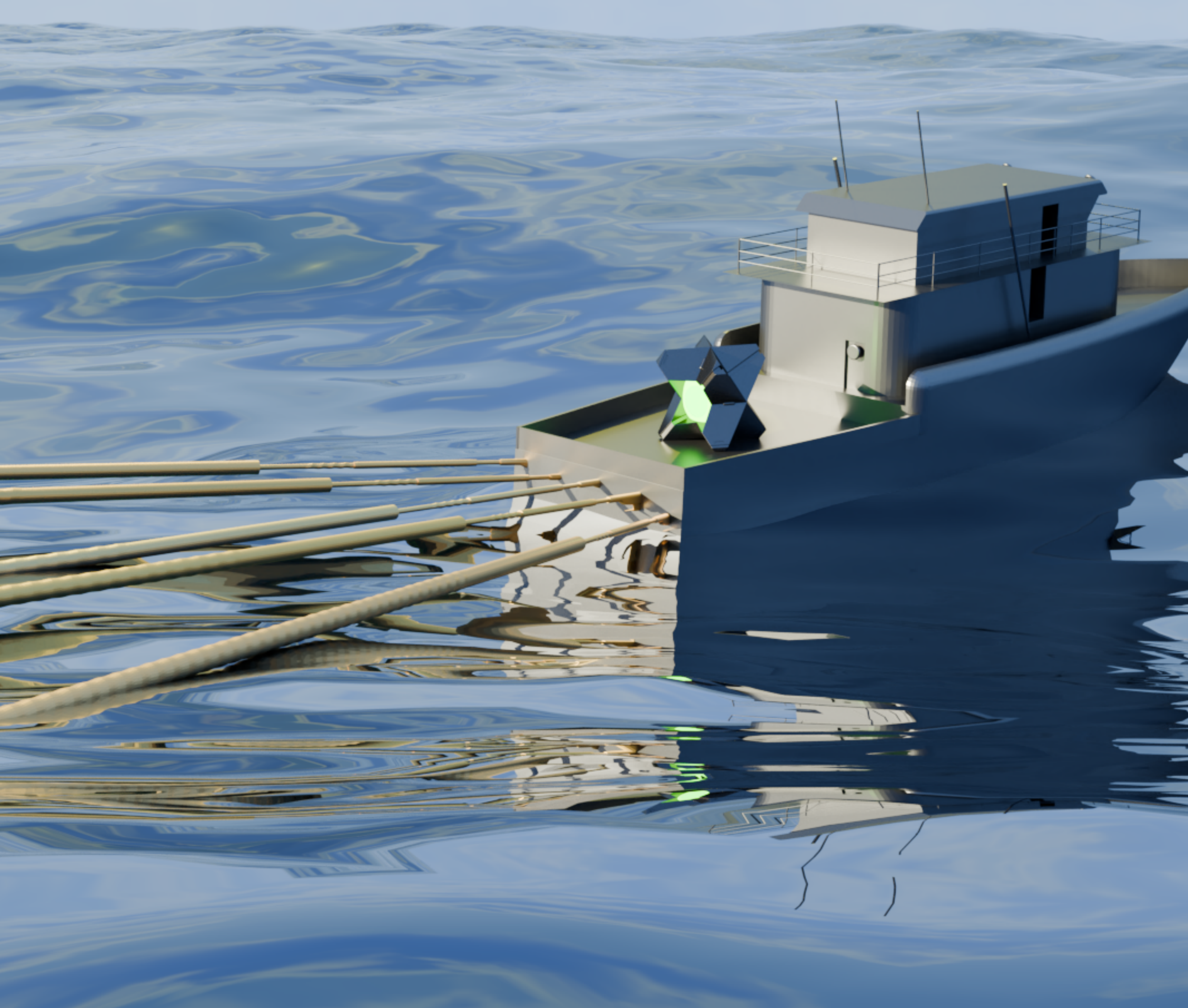
- Drone platforms are inserted through the wellbore to conduct high-resolution imaging of casing-cement interfaces.
- Live data analytics highlight micro-channels, delaminated cement zones, or corrosion hotspots.
- Deploy small volumes of self-healing cement slurries, polymer resins, or microbially active solutions to seal emergent leakage pathways.

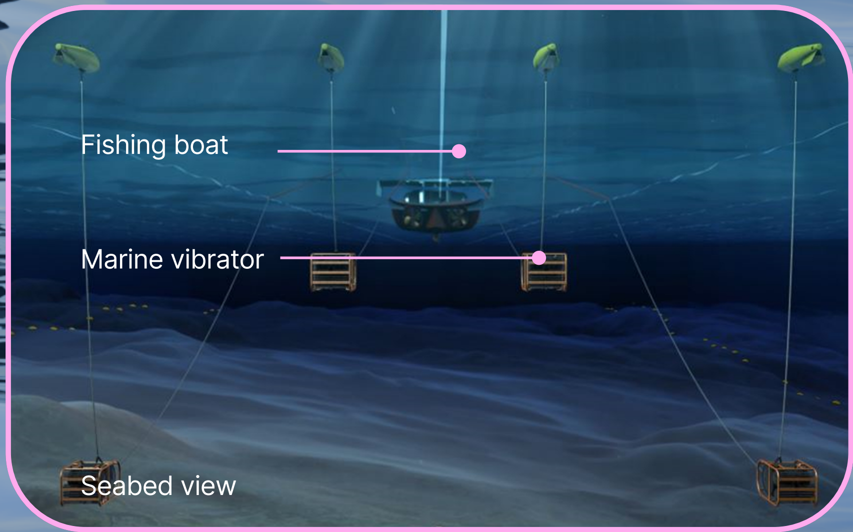


FINAL DESIGN

SEA-O_2 is a streamlined CO_2 leak monitoring solution that seamlessly integrates with routine fishing activities. Compact sensors on fishing boats capture real-time seismic data, which is processed by a simulation algorithm to pinpoint high-risk or under-monitored areas.

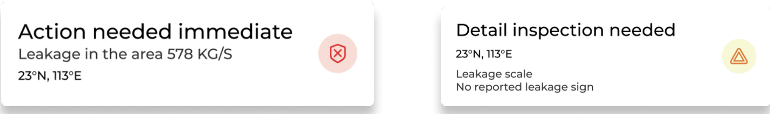
Fishermen benefit from eco-labels, financial rewards, and an onboard app that displays incentive zones, leak alerts, and optimised routes. This approach ensures broad coverage without disrupting their livelihoods.



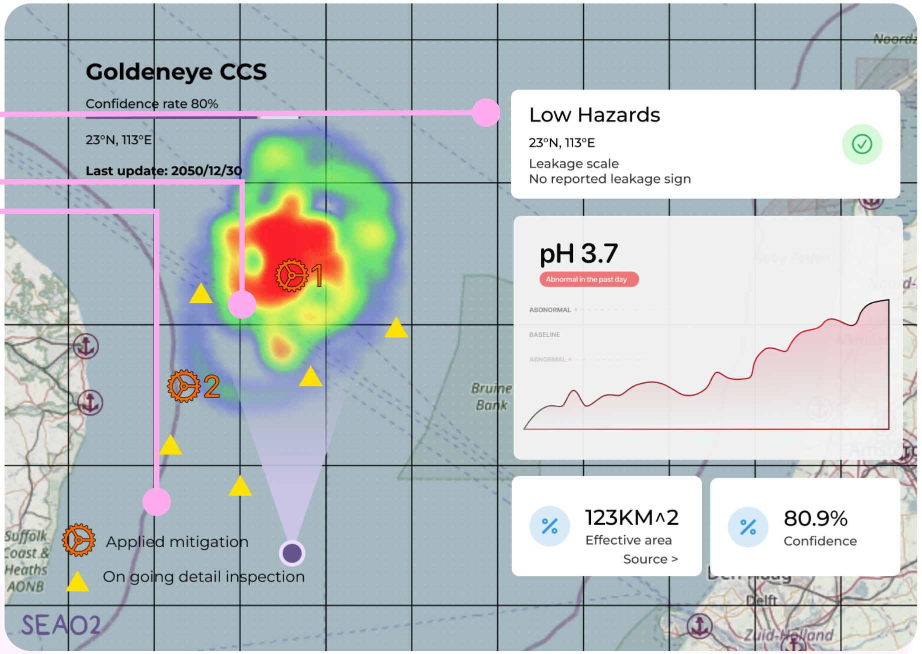


INTERFACE

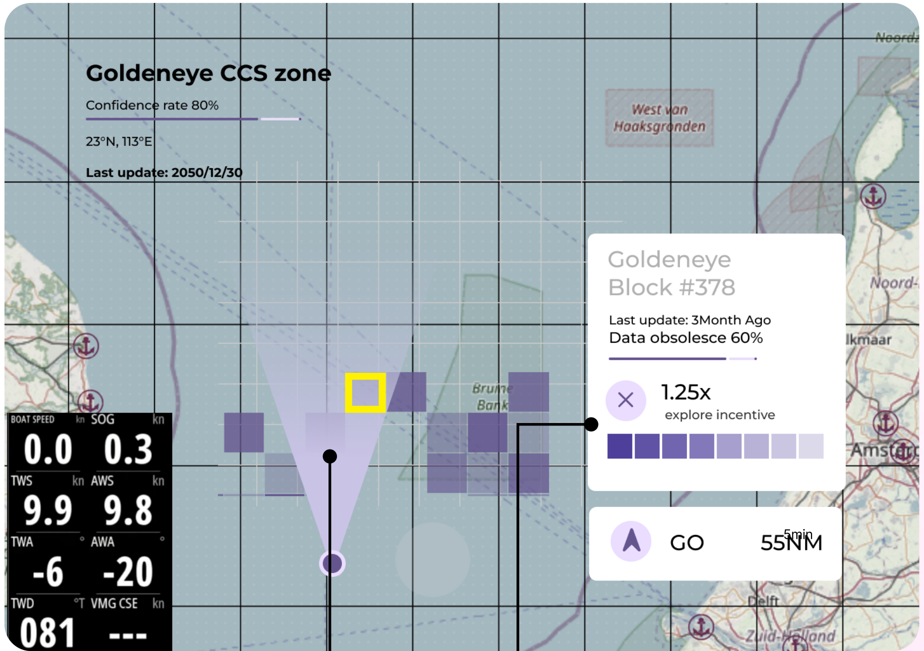
Other leakage states



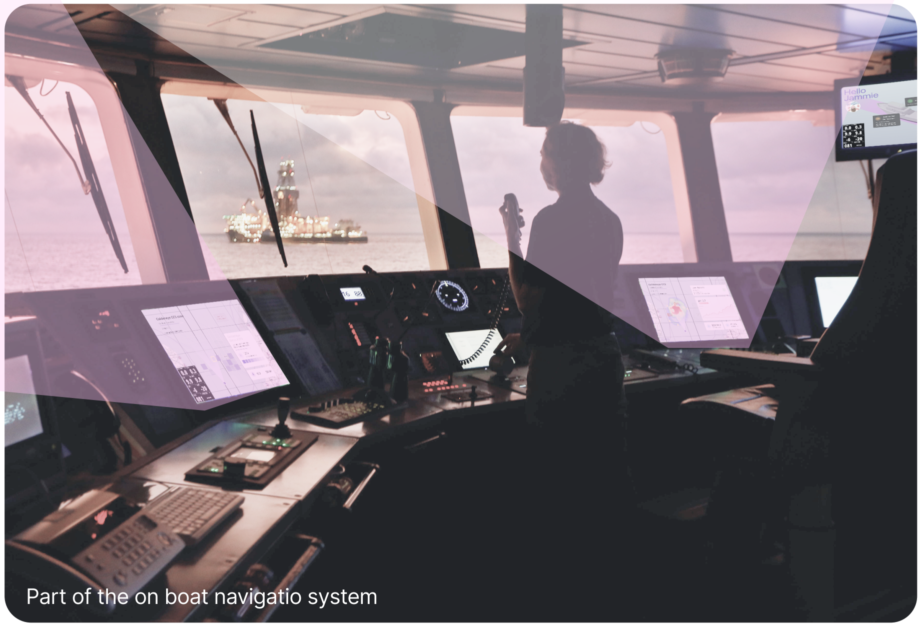
The heat map displays the intensity and size of any detected leak. Once a leak is detected, inspections and mitigation measures are set in motion. Clicking on a specific area reveals further details. This design enhances operational transparency[1] and increases fishermen's involvement in initial monitoring.



Public leakage information



Required monitored zone



Part of the on boat navigatio system

A colour-coded urgency map shows both monitored and unmonitored zones, guiding fishermen to areas that require attention. The urgency map can be used alongside their existing fishing maps for different methods such as trawling, gillnetting, and purse seining. This integration allows fishermen to adjust their routes based on real-time data, ensuring efficient planning and timely response.

USER JOURNEY

Onset

1. A fishery cooperative shares **official notices about CCS monitoring** for both CO_2 injection and post-closure phases. Fishermen learn that "Blue Certification" is now offered for CCS-compliant catches, commanding premium prices.

2. At a workshop, experienced fishers share success stories about **increased income** from earlier pilots. Organisers conduct **live sensor demonstrations**

3. The cooperative conducts sessions on sensor use, data upload, and reporting anomalies. Attendees learn to read colour-coded maps and address GPS alerts.

4. Motivated by clear economic benefits and reassured by safety, the fisherman formally joins the program.

Routine Fishing Setup

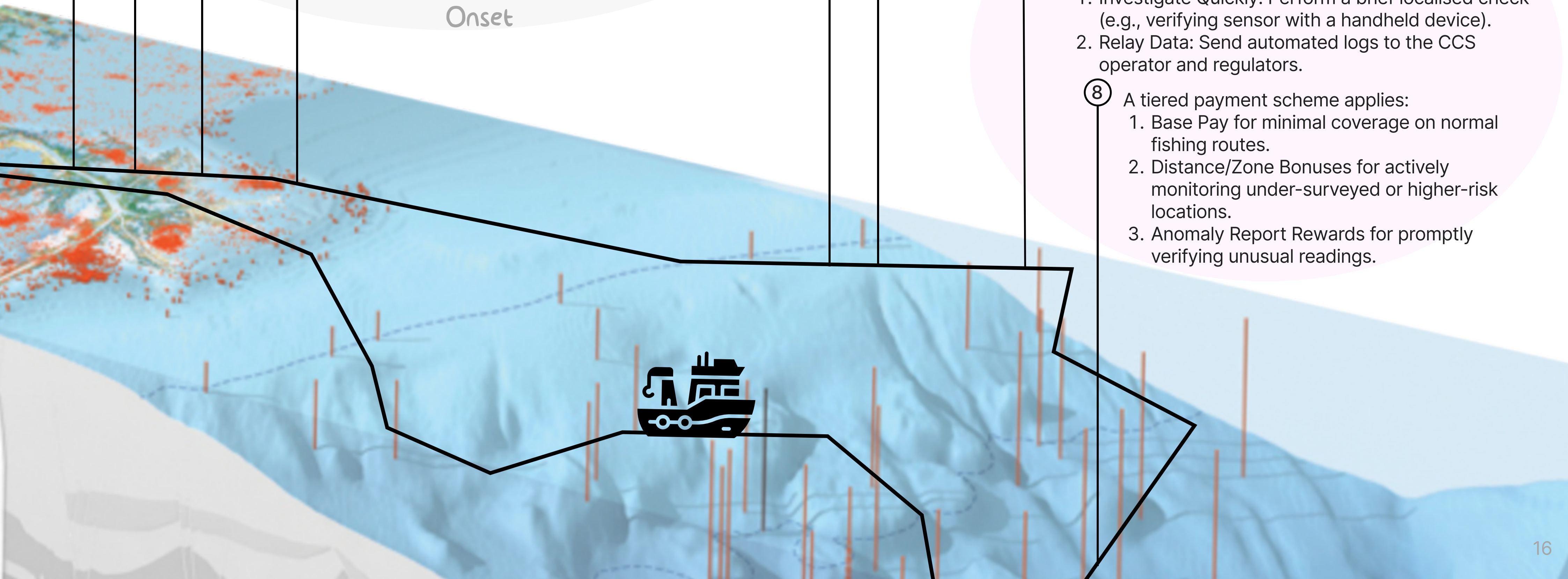
5. Each morning, the fisherman consults a colour-coded "urgency map" highlighting key zones of potential leaks. The cooperative sets **higher incentives** in regions lacking data or suspected of possible CO_2 anomalies.

6. Balancing fish abundance forecasts with higher incentive offers, the fisherman may deviate from the standard course. A quick **cost–benefit comparison** (fuel costs vs. bonus earnings) guides each decision. The fishing path is updated according to the monitoring plan.

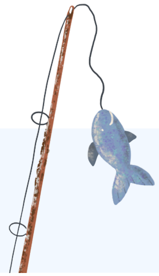
Monitoring Alerts

7. When sensor data is analysed and predict a leakage area or there is proving readings exceed safe CO_2 or pH deviation thresholds, the GPS interface issues an alert. The fisherman may:
   1. Investigate Quickly: Perform a brief localised check (e.g., verifying sensor with a handheld device).
   2. Relay Data: Send automated logs to the CCS operator and regulators.

8. A tiered payment scheme applies:
   1. Base Pay for minimal coverage on normal fishing routes.
   2. Distance/Zone Bonuses for actively monitoring under-surveyed or higher-risk locations.
   3. Anomaly Report Rewards for promptly verifying unusual readings.



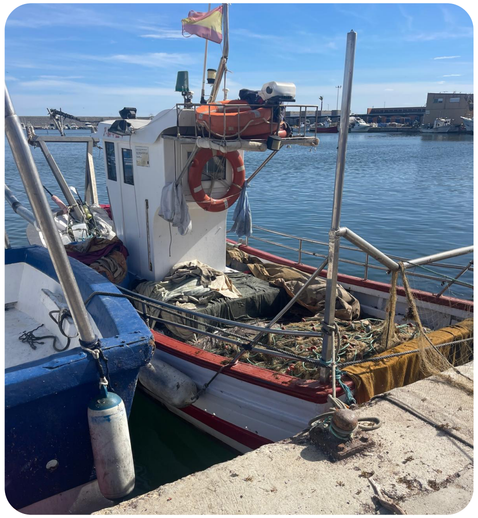
USER VALIDATION



Paco
Nationality: Spanish
Experience: 9 years in the fishing industry
Daily Catch: around 90 kg
Age: 28

SAFETY TRUST INCENTIVE **USABILITY**

- Trust in Data: Paco confirms that sensor data collected from his own boat minimises the risk of deception, ensuring that CO_2 leak information is reliable and verifiable.
- Automated Monitoring Integration: Since Paco follows natural fish migration rather than fixed routes, automatic sensor data collection during regular fishing operations provides extensive spatial coverage without disrupting activities.
- Economic Incentives: Subsidies for fuel, boat maintenance, and advanced GPS devices directly reduce his operational costs, making the system more appealing than straightforward hourly pay.
- Interface: The integration of sensor data into the boat's GPS system, using clear and intuitive visual cues, allows for fast understanding of environmental conditions without the need for specialised training.
- Operational Confidence: Real-time monitoring and immediate leak alerts increase confidence in the safety of operating near CCS sites, thereby reducing perceived risks and supporting sustainable fishing practices.



Paco states that his boat, sized and equipped for mid-range offshore fishing, can accommodate the proposed monitoring system without major retrofitting.

Post-Concept Validation

- Validate sensor performance in extreme marine conditions
- Validate government adoption of "Blue Certifications" for CCS-compliant catches, enabling premium sale prices for fishermen like Paco
- Cross-verify sensor data with buoys and satellite monitoring
- Simulate emergencies to evaluate system responsiveness and clarity of emergency protocols
- Measure ROI (e.g., fuel savings, catch increases vs. time spent on system upkeep).