# ACT2 DigiMon cost-effective monitoring

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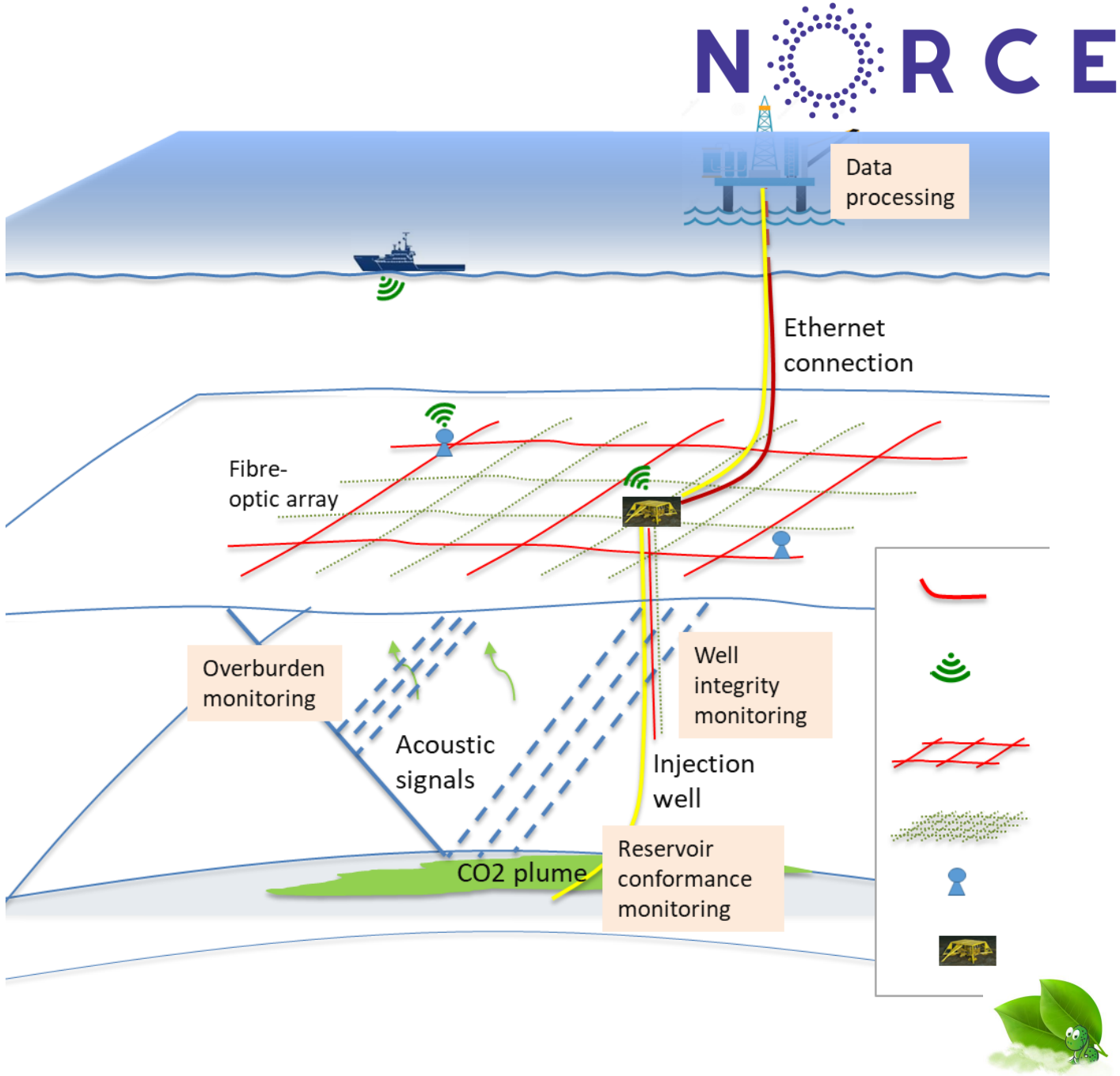
| | | | |
|---|---|---|---|
| NORCE (project manager) | | TNO | |
| OCTIO Environmental Monitoring | | GEOTOMOGRAPHIE GmbH | |
| CRES Centre for renewable energy sources and saving | | LLC Lawrence Livermore National Security | |
| UNIVERSITY OF BRISTOL | | SILIXA ltd | |
| NTNU | | EQUINOR Energy AS | |
| HELMHOLZ – Centre for Environmental Research (UFZ) | | REPSOL – Norge AS | |
| SEDONA Development srl | | UNIVERSITY OF OXFORD | |

# DigiMon (Digital Monitoring of CO2 Storage Projects) – the concept

| CO2 plume | Well integrity | Overburden |
|---|---|---|
| Monitoring the plume movement in the reservoir mainly using remote passive geophysical measurements of changes in saturation and pressure (Conformance monitoring). | Monitoring well integrity, mainly with downhole sensing (Containment and Contingency monitoring). | Monitoring the overburden, including monitoring of above-zone CO2 migration and early detection of CO2 leakage anomalies (Containment and Contingency monitoring). |



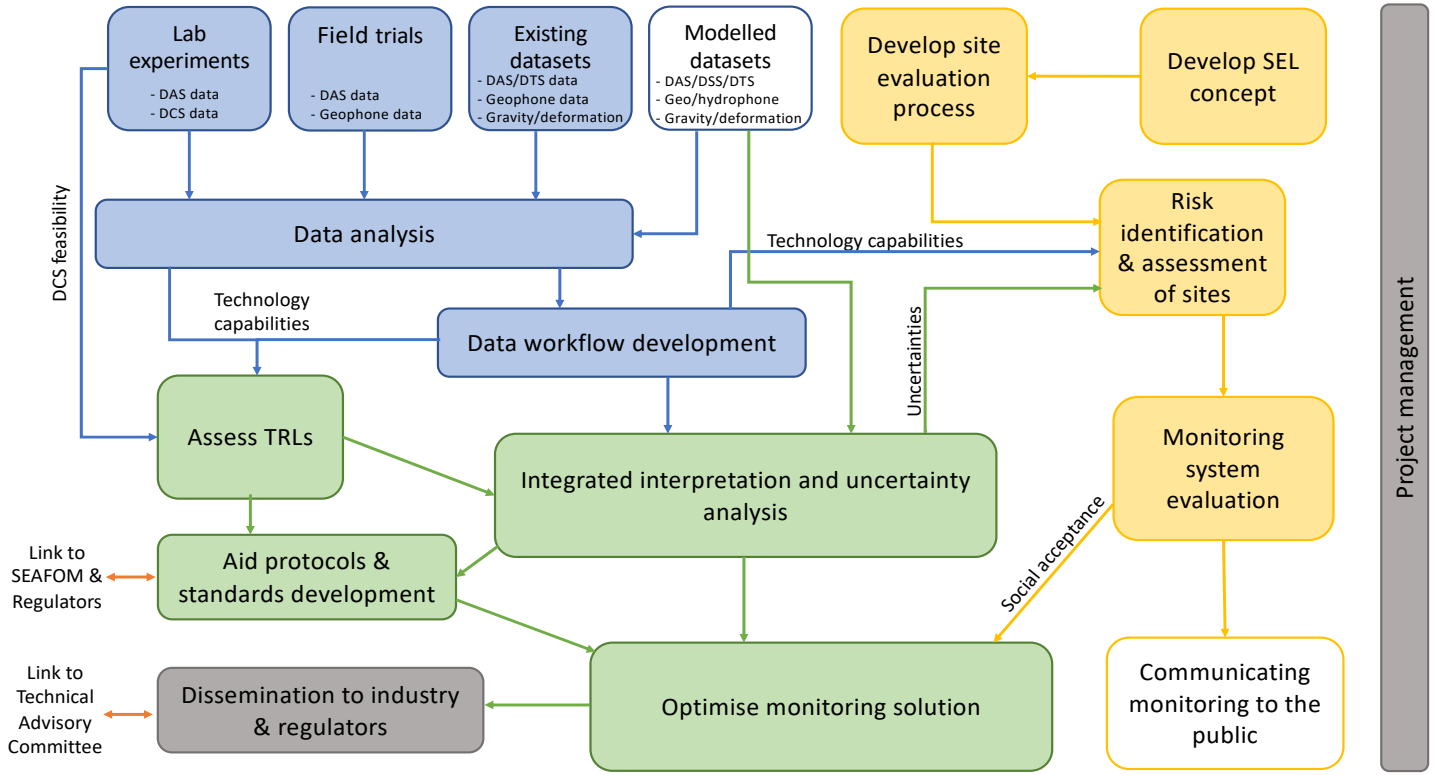
# DigiMon workflow

WP4 Project management (NORCE)

| WP1 | WP2 | WP3 |
|---|---|---|
| Critical technology elements (Silixa) | Integrating the components (Octio EM) | Designing a human centered monitoring system (TNO) |

Interdiciplinary package (IP) 1: Data collection (UoB)

Interdiciplinary package (IP) 2: Dissemination and exploitation (TNO)



# DigiMon key targets

- Improved knowledge of accuracy and sensitivity of technologies (DAS, DCS, gravimetry) for monitoring of CO2 storage (Targets 1,2,3)
- Improved understanding of workflows for addressing uncertainties related to integration of multiple data types at various resolution in a common monitoring system (Targets 4,5)
- Improved framework for evaluating and embedding CCS technology developments in a societal framework (Target 6)

| No | Key targets | WP |
|---|---|---|
| 1 | Develop individual components of the system to a common, high TRL. | 1 |
| 2 | Optimize and validate processing software for DigiMon system components. | 1 |
| 3 | Develop an effective DAS data interpretation workflow. | 1 |
| 4 | Develop a cost-efficient, integrated monitoring system. | 2 |
| 5 | Produce a flexible system compliant with prevailing and emerging open standard data and communication platform solutions. | 2 |
| 6 | Develop a societally relevant and acceptable monitoring system. | 3 |

# DigiMon WP1

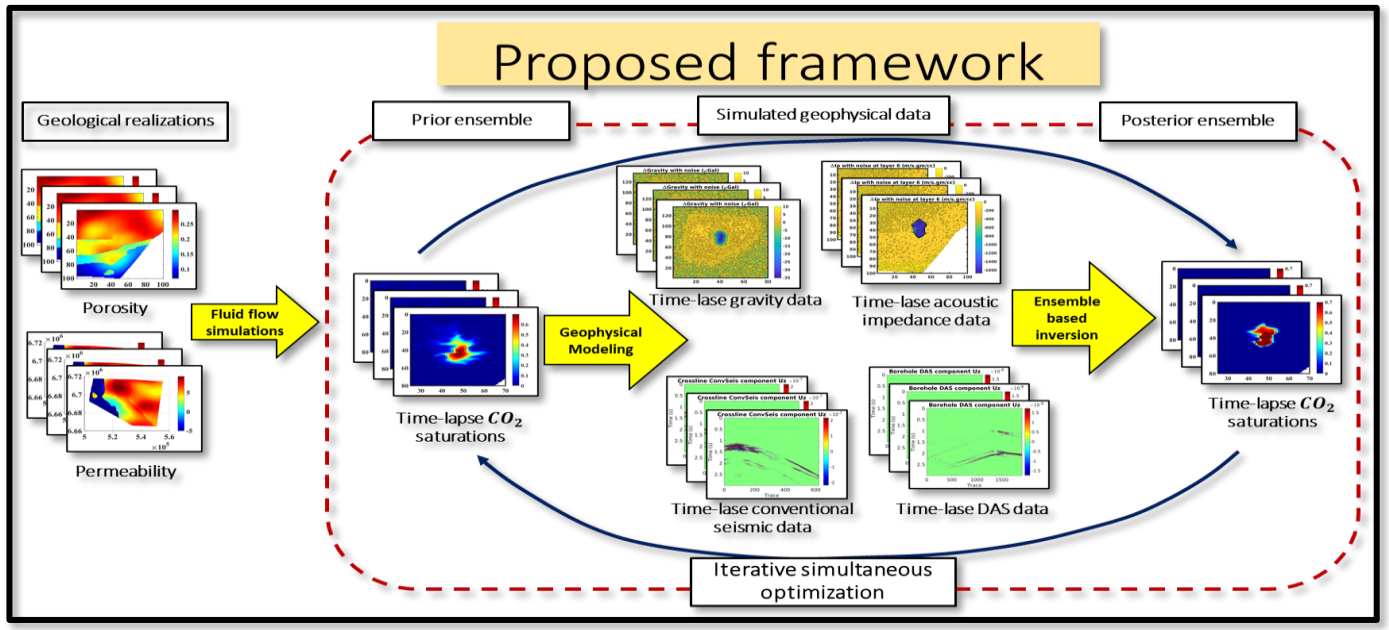
- FRS, Alberta, Canada  dataset - University of Oxford, TNO, Silixa & University of Bristol (2021)
  - Passive & active data, CCS research site (active $CO_2$ injection)
  - Surface and borehole data, straight & helical fibre, reference geophones
- Svelvik, Norway dataset - Geotomographie, NORCE & Silixa (2021)
  - Field test new SV source
  - Passive & active data, CCS research site (active $CO_2$ injection)
  - Surface and borehole DAS data - straight & helical fibre, hydrophones & geophones
- Determine DAS transfer function – Lead: TNO
  - Laboratory and field datasets
- Develop DAS data processing techniques and workflow
  - Microseismic dataset (Antarctica, FRS and FORGE)
  - Dataset for ambient noise interferometry (FRS)

**Key output**

- DAS Processing Algorithms
- Algorithms to aquire and process gravity and deformation data
- Methodology for ambient noise interferometry
- Feasibility of using distributed chemical sensing for $CO_2$ leakage monitoring

# DigiMon WP2

- Technology readiness assessment
  - Comprehensive analysis of critical technology components in DigiMon monitoring concept
- Inversion framework set up for selected case Smeaheia, including conventional seismic, DAS, 4D gravity, and seafloor deformation data
  - Investigating the preliminary results on estimation of plume movements using FWI
  - Aim to also invert for the pressure plume including seafloor deformation data
- Optimizing the monitoring solution
  - Accounting for technical, economic and societal requirements




(Bahkta et al; ACT II DigiMon, 2022)

| Application | Class | CTE |
|---|---|---|
| Surface and seabed reflection methods | Seismic reflection surveys | Conventional hydrophone or in case of OBN multi component sensors |
| | | Distributed acoustic sensors (DAS) |
| Borehole seismic methods | VSP | Conventional VSP |
| | | DAS-VSP |
| | Crosshole tomography | Conventional sensors |
| Passive seismic methods | Microseismics | Geophone/hydrophones |
| | | DAS |
| | Ambient Noise Interferometry | Geophone/hydrophones |
| | | DAS |
| Microgravity | Microgravity at the seafloor | Point-based, mobile, microgravity sensors |
| Seafloor deformation | Measurements at the seafloor | Conventional point pressure sensors |
| | | Tiltmeters |
| | | Distributed strain sensor (DSS) |
| Downhole Pressure sensing | Measurements in well | Conventional pressure sensors |
| | | Distributed Pressure Sensors (DPS) |
| Temperature sensing | | Distributed Temperature Sensor (DTS) |
| Chemical sensing | | Conventional Sensors |
| | | Distributed Chemical Sensor (DCS) |

**Key output**

- TRA assessment
- Forward modelling framework
- Inversion framework and methodology
- Optimization of monitoring solution

# DigiMon WP3

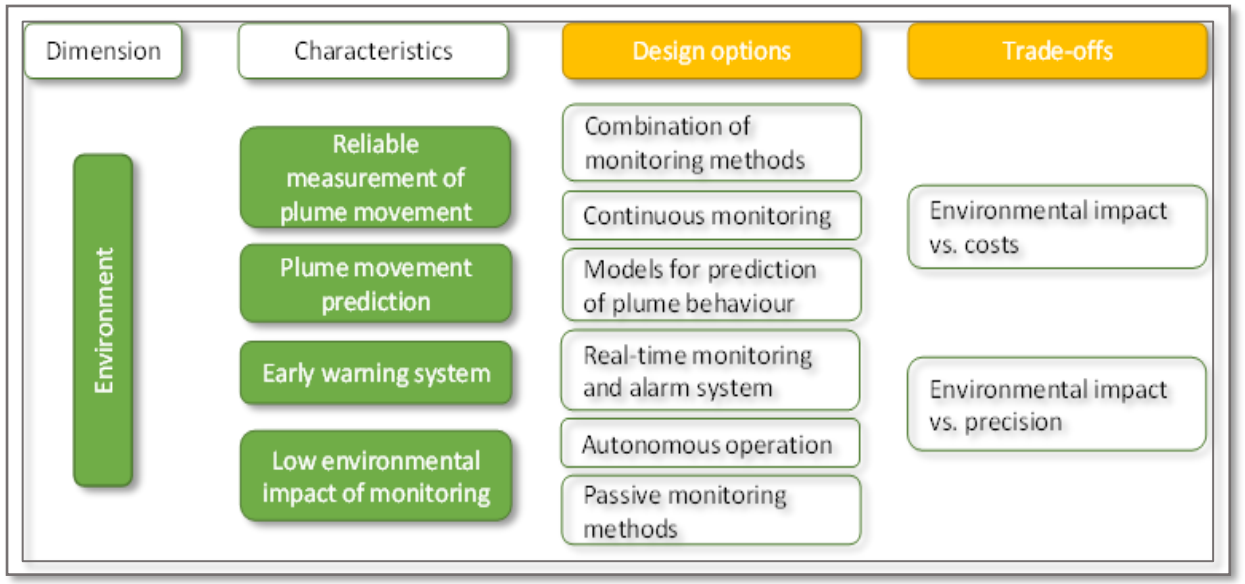
- Development of SEL methodology for CO2 monitoring purpose
  - Calibration with TRL scale
- 4 local assessments in 4 countries
  - Germany
  - Greece
  - Norway
  - Netherlands
- Survey among general public related to local developments
- In-depth interviews with CCS experts

**Key output**

- Insights in public perspective on CCS
- Insight in public perspective on CCS monitoring
- CCS experts' perspectives on societal requirements for CCS and CCS monitoring > link SEL dimensions
- Overarching narrative: comparison between countries: overall perspective on CCS and CCS monitoring.

| Basic Principles observed | Technology Concept formulated | Experimental proof of concept | Technological validated in a lab | Technology validated in relevant environment | Technology demonstrated in relevant environment | System prototype demonstration in an operational environment | System completed and qualified | Actual system proven in operational environment |
|---|---|---|---|---|---|---|---|---|
| TRL 1 | TRL 2 | TRL 3 | TRL 4 | TRL 5 | TRL 6 | TRL 7 | TRL 8 | TRL 9 |

| SEL 1 | SEL 2 | SEL 3 | SEL 4 |
|---|---|---|---|
| **Exploration** - An idea is studied from various perspectives, i.e. technological, environmental, , stakeholder, market, legal, political | **Development** - Further development of the idea by taking into account the societal conditions of relevant stakeholders, policy and regulations, financial resources, required knowledge on impact on society, etc. Actions taken to create financial, stakeholders, policy and regulatory – support. | **Demonstration** - Innovation is demonstrated with the support of relevant stakeholders, policy and regulations and financial commitment. Societal bottlenecks that arise in this phase are coped with. An improved societal innovation is the result. | **Small scale Implementation** – Innovation is embedded in society: support of relevant stakeholders, sound societal business case, supportive policy and regulations and continuous financial commitment. |




(Otto et al; ACT II DigiMon, 2022)

# Advancing State-of-the-art – the CETP RamonCO project

- The overall objective of the project is "*to develop multi-dimensional robust conformance assessment methodology and advance risk-based monitoring and societal implementation strategies*", and thereby contribute to acceleration of the CO2 storage project permitting phase and secure containment and conformance during the project execution phase.
- Research frontiers addressed by RamonCO
  - *Field scale application of multi-physics data modelling and inversion*
  - *Risk governance strategies for CCS*
  - *Multi-dimensional decision support*

Research partners: NORCE, LLNL, TNO, UFZ, CRES, CO2Club, GeoEcoMar
Industry partners: RiskTec, Reach Subsea, EBN, Equinor, Neptune, Wintershall

# Multiphysics inversion

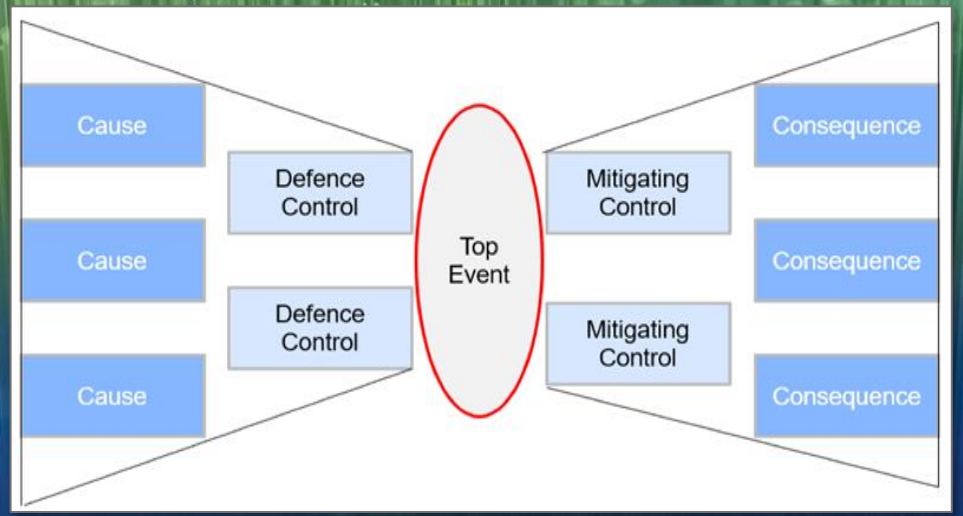
| Application | Class | CTE | TRL | Note |
|---|---|---|---|---|
| Surface and seabed reflection methods | Seismic reflection surveys | Conventional hydrophone of in case of OBN multi component sensors | 9 | Mature technology |
| | | DAS | 5-6 | Recent experiments show good potential |
| Borehole seismic methods | VSP | Conventional VSP | 9 | Mature technology |
| | | DAS-VSP | 8 | Good results only used onshore sofar |
| | Crosshole tomography | Conventional sensors (Novel SV source) | 5-6 | In testing phase at different environments |
| Passive seismic methods | Microseismics | Geophone/hydrophones | 9 | Mature technology |
| | | DAS | 7-8 | Operational but not applied |
| | Ambient Noise Interferometry | Geophone/hydrophones | 4-5 | |
| | | DAS | 4-5 | |
| Microgravity | Microgravity at the seafloor | Point-based, mobile, microgravity sensors | 9 | Mature technology |
| Seafloor deformation | Measurements at the seafloor | Pressure sensors | 9 | Mature technology |
| | | Tiltmeters | 4 | Good results, only used for other applications sofar |
| | | DSS | 4-5 | Good results, only used for other applications sofar |
| Downhole Pressure sensing | Measurements in well | Conventional pressure sensors | 8-9 | Commercially available but lack long term use in CCS |
| | | DPS | 5-6 | |
| Temperature sensing | | DTS | 9 | Mature technology |
| Chemical sensing | | Conventional sensors | 9 | Mature technology |
| | | DCS | 3 | |

- In order to mature the multiphysics inversion framework from a TRL 4-5 (ACT II DigiMon) to a TRL 6 (this project) on the DOE scale, RamonCO will work on and address some key challenges.
  - *Extend the inversion framework to include more monitoring data types collected by high TRL monitoring techniques (tools).* These include (downhole) pressure, ground/seafloor movement (subsidence and uplift), conventional seismicity monitoring and (distributed) strain, gravity and temperature monitoring.
  - *Accommodate field scale monitoring data in the inversion workflow for 3D subsurface structure and properties*. This will demand a combination of sophisticated modelling strategies with a significant increase of efficiency and computational resources.

# Societal risk assessment

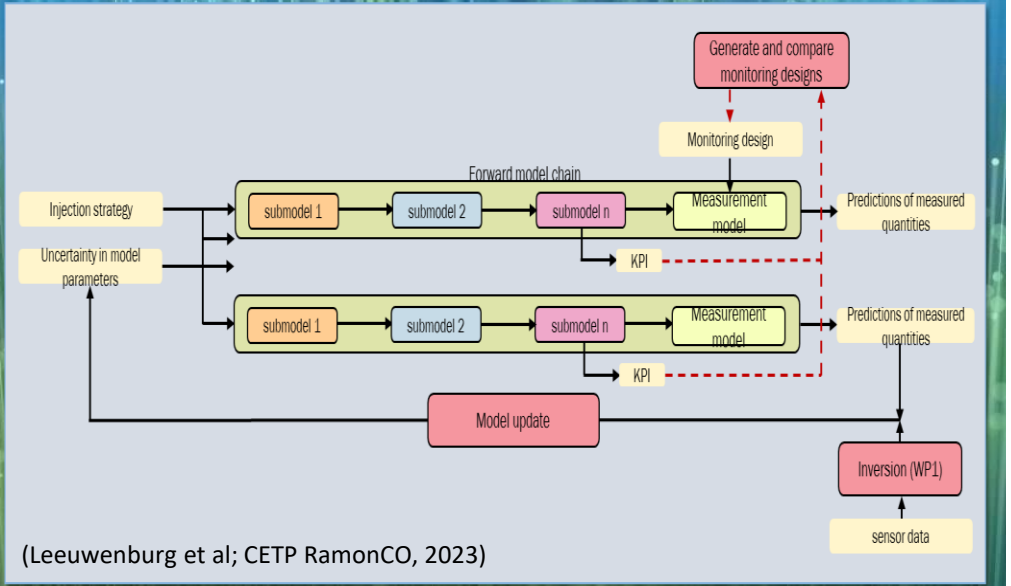
| | SEL 1 | SEL 2 | SEL 3 | SEL 4 |
|---|---|---|---|---|
| | **Exploration** | **Development** | **Demonstration** | **Small scale Implementation** |
| Knowledge and R&D | First idea on the impact of concept idea on the environment. | Substantiated researched impact of innovation on environment, risks, safety and uncertainty. | Tested and improved innovation in society. Taking into account societal factors. | Sufficient knowledge to embedded innovation in society. |
| Societal involvement | Basic idea on stakeholder field. | Designed stakeholder process and involved stakeholders in development innovation. | Stakeholder participation in testing innovation. Taking into account needs, concerns, values of stakeholders. | Stakeholder participation in small scale implementation, innovation supported by relevant stakeholders. |
| Policy and regulation | Explored policy and regulatory framework. | Designed policy and regulatory framework. | Clear policy and regulatory framework, solve regulatory barriers. | Supporting policy, law-and regulations for small scale implementation. |
| Financial resources | Start-up capital for basic idea exploration on costs and benefits and impact on environment innovation. | Budget for research, identification market need and a first business case. | Financing construction for demonstration, i.e. research, participation, societal business case, etc. | Solid business case, new market. |

(Puts et al; ACT II DigiMon, 2022)



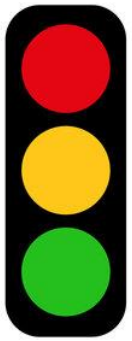

- Research on the societal embeddedness of CO2 storage projects has proved Societal Embeddedness Level (SEL) methodology as a powerful tool, however, how to incorporate societal concerns in risk assessment has yet to be developed.
  - *RamonCO will extend the field of application of the SEL Assessment Framework* to gain better insight in the societal challenges in earlier stages of the CCS chain, which might have impact on and cause risks to the business case and societal embeddedness of CO2 storage activities.
  - *Building on the SEL methodology, the bow-tie methodology (developed by RiskTec) will be used* to deepen insights in the causes of the identified societal risks, as well as in their potential consequences and possible preventative or mitigative measures.

# Multi-dimensional decision support




(Leeuwenburg et al; CETP RamonCO, 2023)

- No overarching performance targets exist, for either the storage project, or the monitoring system. This creates a problem in deciding whether a proposed monitoring plan is effective enough to manage site-specific risks.
  - *RamonCO will design a probabilistic methodology to enable regulators and operators to assess the expected performance of monitoring strategies* in the context of specific identified risks. This methodology can be used to assess proposed monitoring plans *prior to the start of injection*, and to assess site conformance *during and after the operational phase*. Furthermore, methodologies will be developed to determine the right triggers for actions given differences between modelled and measured data.



# Thank you for your attention!

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