Report D3.5

Best practices for developing a human centered monitoring system for CO_2 storage projects through a collaborative and interdisciplinary research approach

ACT II – DigiMon project

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With valuable contributions of all interviewees and survey respondents in Germany, Greece, The Netherlands and Norway as well as the Digimon research community.

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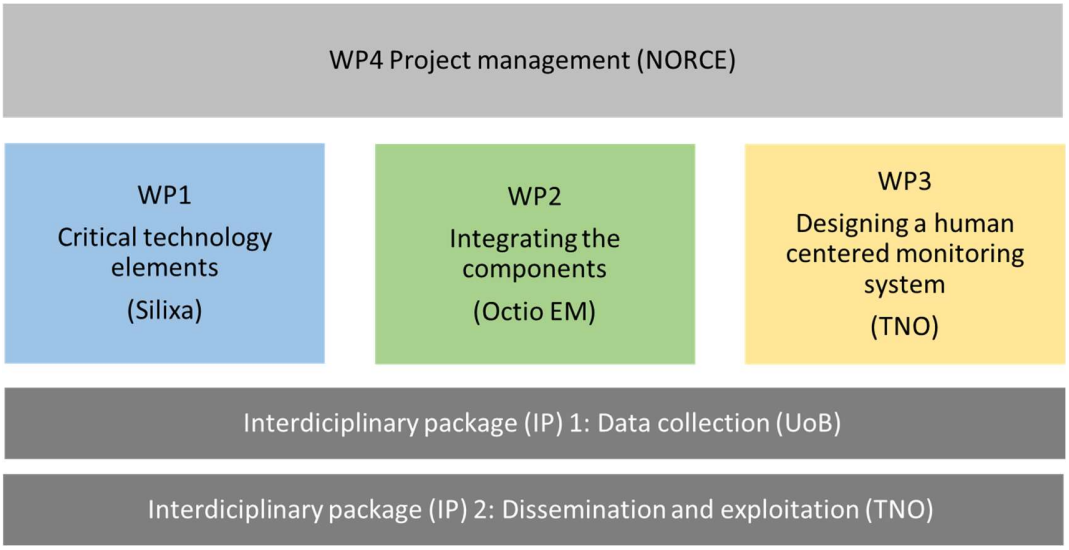
Scope of report

This deliverable was created in the context of the European ACT II project DigiMon and is part of work package 3 (designing a human-centered monitoring system), task 3.3 (evaluation of the research process and writing best practices report).

INTRODUCTION DIGIMON PROJECT

Carbon capture and storage (CCS) is a key wedge in any strategy for reducing greenhouse gases in the atmosphere and climate stabilization. Demonstration and commercial projects have shown that CCS is technically feasible. However, the technology requires upscaling, particularly with respect to storing large volumes of CO_2. Cost-effective and societally acceptable monitoring of CO_2 reservoirs is a major hurdle. As a regulatory requirement, measurement, monitoring and verification (MMV) strategies and plans must demonstrate Conformance (models are in alignment with monitoring data), verify Containment (be capable of ensuring there are no leaks) and provide Contingency plans (employment of corrective measures in the case of a leak).

The Digimon project aims to contribute to these monitoring requirements by developing an innovative, cost-effective, and human-centered monitoring system for CO_2 storage projects. The Digimon research is structured along several work packages (see figure below).



In this report, we present reflections and best practices of the process of developing a human centered monitoring system for CO_2 storage projects, from a perspective of the tasks and collaboration in work package 3.

Executive Summary

This deliverable was developed in the context of the European ACT II project 'DigiMon' and is part of work package 3 (designing a human-centered monitoring system), task 3.3 (evaluation of the research process and writing best practices report). The report presents best practices for developing a human-centered monitoring system through a collaborative and interdisciplinary research process. We derived the best practices through the following steps:

1. Descriptions of previous steps in the research process (see figure 1);
2. Reflections on the tasks and the interdisciplinary process within work package 3;
3. Interviews with six DigiMon participants to reflect on the interdisciplinary process in DigiMon and how this contributed to the project results and research objectives;
4. Analyzing input on open answers provided in questionnaires (handed out to participants of interdisciplinary events) to evaluate on the interdisciplinary process.

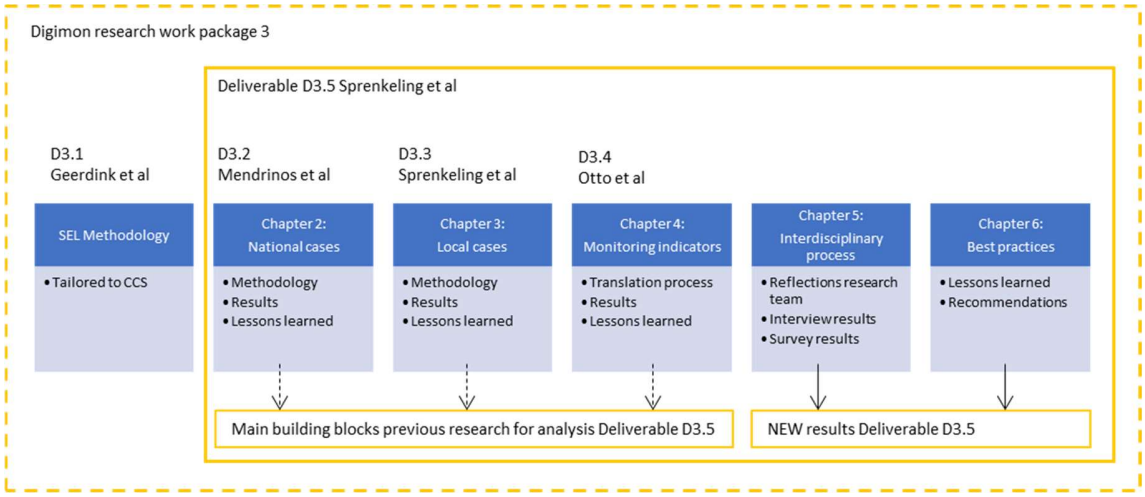


Figure 1 ***Relation research activities and deliverables within work package 3 Digimon project***

The research in WP3 has been structured as pictured in figure 2. Each research phase benefits from the collaborative and interdisciplinary research process. In the following three paragraphs we elaborate on how the interdisciplinary research process has been integrated into each research phase.

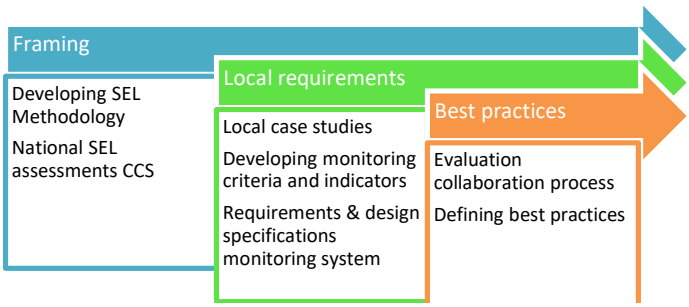


Figure 2 ***Schematic overview of the steps in the WP3 research process***

ADDED VALUE INTERDISCIPLINARY RESEARCH PROCESS 1ST RESEARCH PHASE – FRAMING

The collaborative and interdisciplinary research process in the phase of framing, in which the full DigiMon consortium was involved, is characterized by 2 key events: (1.) The interdisciplinary training event on the Societal Embeddedness Level methodology, in March 2020, and (2.) The interdisciplinary event on valuing the outcomes of the national case studies for improving current monitoring practices, in March 2021. Both events were open to attend for all DigiMon partners involved in the DigiMon project.

The interdisciplinary training event on the Societal Embeddedness Level methodology (March 2020) resulted in an improved assessment framework for assessing the societal embeddedness level of CCS initiatives on a national level as well as in the improved scoping of the SEL assessment guideline and its' application in Digimon. Main take aways from this interdisciplinary event and the exchange between all participants consisted of:

- A collective understanding of the SEL methodology within the DigiMon consortium;
- Insight in how the methodology should be applied to CCS as part of the DigiMon research;
- An improved definition of the four SEL levels as well as the four SEL dimensions;
- Additional explanation about setbacks: can an innovation fall back to a lower SEL level because of new developments and/or societal dynamics?
- New milestones which are integrated in the SEL assessment framework;
- Building blocks for a stepwise process for applying the SEL assessment framework within DigiMon;
- An improved description of the scope of the SEL assessment guideline.

For further information about the SEL methodology we refer to the previous deliverable (Geerdink et. al. 2020).

The added value of the interdisciplinary event on valuing the outcomes of the national case studies for improving current monitoring practices (March 2021) can be found in:

- Intensive interactions between DigiMon partners for better understanding of diverse backgrounds and perspectives;
- Suggestions for applying the SEL methodology in other policy domains;
- First ideas for setting up the four local case studies, building on the outcomes of the national assessments;
- New insights among DigiMon partners regarding interconnections between technical and societal requirements for CCS.

Furthermore, the development of the SEL guideline and the design of the research process for the national case studies have been experienced as intensive collaborative and interdisciplinary research processes within the work package 3 team. By making optimal use of the diverse backgrounds of the researchers, multiple perspectives, experiences, and conceptual frames could be integrated in the design of the societal

embeddedness level assessment framework as well as in the research approach for the national case studies.

ADDED VALUE INTERDISCIPLINARY RESEARCH PROCESS 2ND RESEARCH PHASE – LOCAL CASES

Translating the generic SEL assessment framework into a format for an informed questionnaire and an interview protocol required the combination of different social and technical disciplines. Mainly because the narrative for the informed questionnaire contained technical aspects of CO_2 storage and CO_2 storage monitoring. Technical knowledge was needed to inform the respondents about the technical aspects of CO_2 storage and CO_2 storage monitoring and social disciplines were needed for designing the questionnaire and interview protocols and for translating the technical information into understandable pieces of information for the survey respondents.

As social scientists, the WP3 team gained more (crucial) technical knowledge about CO_2 storage and CO_2 storage monitoring during the collaboration with the technical disciplines in DigiMon and during the interviews (especially those with technical experts on CCS). This strengthened the understanding of the DigiMon project as well as CCS and subsurface monitoring in general and made it easier to participate in technical discussions and set up a knowledge integration process to develop design options for a societally embedded monitoring system.

ADDED VALUE INTERDISCIPLINARY RESEARCH PROCESS 2ND RESEARCH PHASE – TOWARDS SOCIETAL MONITORING REQUIREMENTS

One of the interdisciplinary meetings with all DigiMon partners focused on the outcomes of the local case studies, using the perspectives and expertise of the full DigiMon consortium to identify building blocks for the translation process towards so-called societal monitoring requirements and indicators. The WP3 researchers introduced an approach to identify not only indicators for monitoring but also trade-offs that might occur with that monitoring indicator (Otto et al., 2022) based on the local case study outcomes. These results have been well-received by the DigiMon consortium and integrated social and technical sciences. Next, the idea of composing an interdisciplinary research team consisting of researchers from work packages 1, 2 and 3 was introduced for designing the research process towards societal monitoring indicators as well as reflecting on intermediate results and making optimal use of the WP3 outcomes for ongoing research activities in WP2. This interdisciplinary team initiated a so-called analytical hierarchy process for integrating WP3 outcomes into WP2 research steps. This connection was a direct result of the interdisciplinary research approach. A key success factor for this collaboration was that the participating researchers from all work packages were open-minded and tried to understand each other's disciplinary language and work.

TOWARDS BEST PRACTICES

For deriving best practices from the interdisciplinary research process, three steps have been taken:

1. We collected reflections on the interdisciplinary research process from the involved researchers in work package 3.
2. We analysed the outcomes of the evaluation forms (surveys) filled in by the participants after each interdisciplinary DigiMon event.
3. Interviews have been held with a group of DigiMon partners to capture their experiences and insights regarding the interdisciplinary workflow.

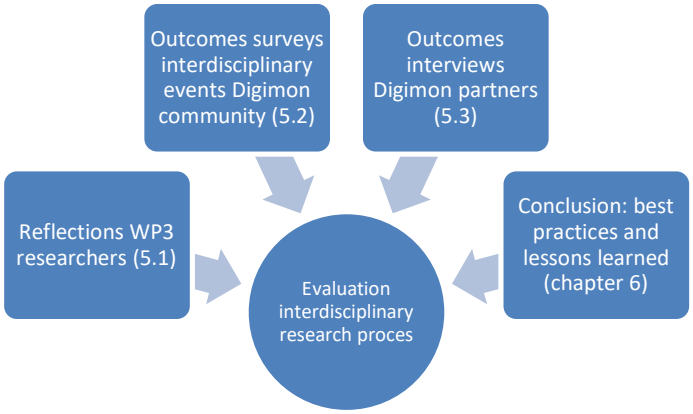


Figure 3 ***building blocks for evaluation of the interdisciplinary research process***

Based on these building blocks, we derived best practices, lessons learned and recommendations for future collaborative and interdisciplinary research processes (figure 3). These best practices, lessons learned, and recommendations are elaborated on in the following three paragraphs.

BEST PRACTICES

It was important for the DigiMon project that the interdisciplinary approach was adopted successfully. A varied audience was reached with interdisciplinary events and dissemination activities. In addition, DigiMon presentations are of interest to a broad audience. A varied audience was able to understand the content of the presentations, as presentations do not only refer to in-depth technical content. The DigiMon narrative is improved through interdisciplinarity. The interdisciplinary collaboration between scientists in DigiMon enhanced the awareness of how challenging it can be to comprehend each-other's disciplinary language and improved the clarity of presentations. Additionally, whilst very in-depth technical knowledge is hard to grasp for a wider audience, social sciences outcomes are often understood easier.

We derived the following best practices based on the experiences in the DigiMon project:

- **Interdisciplinary process embedded in the project:** It was a major strength of DigiMon that the interdisciplinary process was embedded in the project management as well as in the workflow of WP3.

- **Regular exchange between disciplines:** The regular exchange between the work packages supported multiple objectives: sharing (intermediate) scientific outcomes, keeping the conversation between researchers with diverse backgrounds going and securing awareness of the usefulness and necessity of interdisciplinary process for the DigiMon project. Furthermore, it has contributed to the alignment of and interaction between the tasks.
- **Task force for knowledge integration:** An interdisciplinary task force has been set up to engage in a knowledge integration process to translate social scientific outcomes to design options for a DigiMon system.
- **Working with the SEL methodology:** The SEL methodology has provided a vocabulary to bridge between technical and social sciences. It is stated to encourage interdisciplinarity. The SEL framework offers a structured approach, way of thinking and vocabulary that guides the conversation in the interdisciplinary process.
- **Scientific collaboration between disciplines and co-creation with non-scientific stakeholders:** Apart from integrating scientific knowledge from social and technical disciplines, the collaborative and interdisciplinary research approach also supported collaboration between industry, experts and (local) stakeholders and the public.
- **Fit for purpose:** As an international scientific community we operate in different (and changing) contexts. This relates to societal aspects (cultures, political situation, history with CCS) as well as technical characteristics of storage sites and industries. During the research process and in composing our scientific outcomes, we kept this in mind. Although local contexts were important in our research, we put a substantive effort into aligning the methodologies over the four countries as much as possible. In our results we introduced a fit-for-purpose monitoring system, with design options that can be adapted to multiple societal and technical contexts.

LESSONS LEARNED

The main lessons learned from the DigiMon project are:

In general

- **A common language – a common challenge:** Finding a common language has been a challenge that kept coming back during the entire project. However, it most certainly progressed. some of the participants experienced finding a common ground. However, even at the end of the project some participants state that there are issues with wording and really understanding each other's concepts.
- **Disciplines within disciplines:** Within DigiMon we focused on collaboration between social and technical sciences. However, there are multiple technical and social disciplines. Within work package three we succeeded in creating a shared understanding and language. We did so by very frequent interaction about the research design, process, and results. Avoiding jargon as well helps in being aware of differences between disciplines and understanding each other's language.
- **Bridging between scientific community and industry:** Within DigiMon we focused on bridging between social and technical sciences. However, the is a gap between scientific perspective and perspectives of the industry (like CO_2 storage site operators) as well.

Regarding digital collaboration:

- **More frequent interaction with increased accessibility:** We found that although we had to adapt a new way of working, the digital collaboration turned out very well. It is easier to engage multiple partners in one meeting and it takes less time and costs for travel. This was experienced in collaboration within and between work packages.
- **Less in-depth interaction and less commitment:** Although digital interaction is more accessible and less time consuming, we found that it is more challenging to engage in in-depth discussions while talking online, especially with participants who have not met each-other in person before. Creating a collective understanding about complex matters is more challenging online.
- **Getting used to a new way of working:** With Covid-19 we adapted to a completely new way of working. At first, with most countries being in strict lockdowns, this resulted in decreased availability for all teams. Then, we had to get used to digital collaboration, within as well as across teams and country boundaries. In the beginning this resulted in a search for a 'new normal', including technical problems. We have worked with multiple platforms and tools and eventually succeeded in stable interaction and a rich toolbox of instruments for online sessions. Finally, reflecting on this period, we can see the benefits of digital collaboration as valuable addition to the classical way of working.

RECOMMENDATIONS FOR FUTURE COLLABORATIVE AND INTERDISCIPLINARY RESEARCH PROCESSES

- **A kick-start for the interdisciplinary process:** Although the interdisciplinary process was strongly embedded in the process design of the DigiMon project, it took some time to get an understanding of each other's work and find each other to engage in knowledge integration processes. Additionally, we found that not everyone had the same sense of urgency of interdisciplinary exchange. It might be helpful if the interdisciplinary process is kick-started in an earlier stage of the project, for example by having an early-stage interdisciplinary workshop, or an interdisciplinary deliverable, to get to know each other and each other's way of thinking and working.
- **Do not forget about exchange within the work package:** Although within DigiMon we focused on the exchange between technical and social sciences, we acknowledge that within the technical and social sciences, there are multiple disciplines, and often multiple institutes with multiple nationalities working within these disciplines. A strong baseline of exchange between technical disciplines and social disciplines, which include a common disciplinary language and being aware of each other's perspectives, offers a stable common ground for collaboration between social and technical disciplines as well.
- **How to embed the interdisciplinary process even better in the project and teams:**
  - **Option 1:** Having a broad interdisciplinary task force responsible for scientific knowledge integration. Interdisciplinary exchange, like we did in the interdisciplinary events, is relevant and interesting for all participants. However, we found that it requires time, effort, willingness, and intellectual flexibility to engage in a scientific knowledge integration process. We also found that it is not necessary for every participant to be involved in this process. An interdisciplinary task-force that was set up for translating the social scientific outcomes to design requirements for a monitoring system. This task force managed to bring the disciplines together. Such a team, with a

minimum of one participant per work package, could engage in interdisciplinary processes during the entire project to broaden and deepen the interdisciplinary work. In this way, the initiative for the interdisciplinary exchange would not only be at one discipline and knowledge input in the interdisciplinary knowledge exchange events is broadened.

- **Option 2:** In DigiMon we have worked with work packages and tasks, which represented one discipline (either technical or social) and one institute responsible per task. Mixing this up would drive the exchange between disciplines as well as between institutes.

- **Excel in digital collaboration:** During the Covid-19 pandemic, digital collaboration has proven to be effective and led to increased exchange within and between disciplines. Although we find that real-life meetings and exchange are unabated valuable to engage in in-depth discussions, cross-boundary collaborations can be enriched with frequent digital exchange. We recommend to have frequent meetings, stick to one digital tool (like miro, whiteboard or padlet) and facilitate in-depth discussions by securing enough time and engagement in breakout groups.

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1 Introduction

TOWARDS BEST PRACTICES

In this report, we elaborate on developing a human-centered monitoring system for CO_2 storage projects, from a perspective of the tasks and collaboration in work package 3 of the DigiMon project. To develop best practices, we have reflected on the collaborative and interdisciplinary research process by:

(1.) Reflecting on the tasks and the interdisciplinary process within work package 3;
(2.) Doing interviews with six DigiMon participants to reflect on the interdisciplinary process in DigiMon and how this contributed to the project results and research objectives;
(3.) Analyzing inputs on open answers provided in questionnaires (handed out to participants of interdisciplinary events) to evaluate on the interdisciplinary process.

The outcomes of these reflections and evaluations are gathered and compared and form the basis of the conclusions in this report, consisting of best practices, lessons learned and recommendations. We paid attention to working in the context of the Covid-19 pandemic, which impacted the collaboration within the DigiMon community. To demonstrate how we build on previous tasks within the DigiMon project, the report gives an overview of the main research methodologies and corresponding results as part of work package 3. We do this to picture the lessons learned in the context of the activities within the project. For a complete report on the results of the various tasks of work package three we refer to previous deliverables.

HOW WE STRUCTURED THE WP3 RESEARCH

The research within work package 3 has been structured along 3 tasks with several subtasks (figure 4):

Task 3.1: Framing - Societal Embeddedness Level for CCS (**TNO**, Norce, UFZ)
- Subtask 3.1.1: Developing and tailoring the SEL concept for CCS (**TNO**, UFZ, CRES)
- Subtask 3.1.2: Identification SEL for CCS in four countries (**CRES**, TNO, Norce, UFZ)

Task 3.2: Researching the Societal Embeddedness Level at local level (**TNO**, NORCE, UFZ, CRES
- T3.2.1 State-of-the-art local case studies (TNO, NORCE, UFZ)
- T3.2.2 Develop monitoring criteria and indicators (UFZ, TNO, NORCE, CRES)
- T3.2.3 Requirements & design specifications for the DigiMon CO_2 monitoring system

Task 3.3: **Task 3.3: Evaluation of the collaboration process (TNO**, UFZ, NORCE, CRES, UoB)

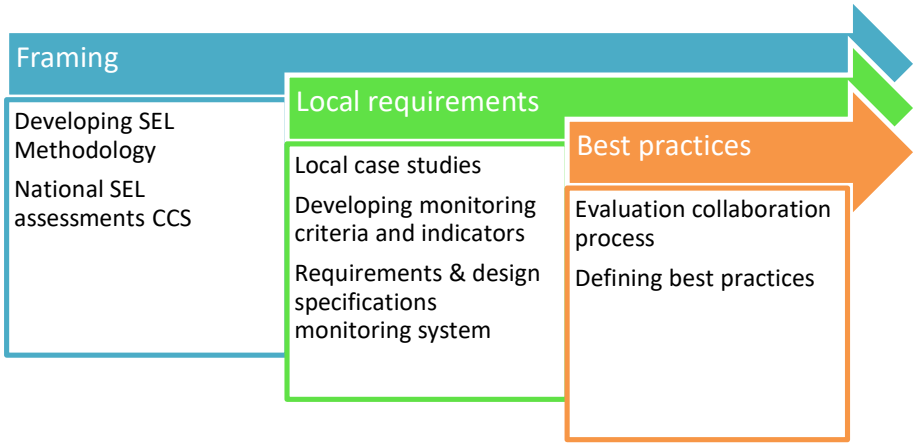


Figure 4 ***Schematic overview of the steps in the WP3 research process***

READING GUIDE

The document is structured as follows:

- In chapter two we elaborate on studying the societal embeddedness of CCS in four countries. We explain the research methodologies and provide a summary of the results of the national case studies. Finally, we provide the main lessons learned at national level, task 3.1.2 in work package 3.
- In chapter three we elaborate on four local case studies for CCS in four countries. We explain the research methodologies and provide a summary of the results. Finally, we provide the lessons learned at local level, task 3.2.1 in work package 3.
- In chapter four we elaborate on the translation of monitoring indicators. We explain the research methodologies and provide a summary of the results. Finally, we provide the lessons learned in this task (3.2.2 and 3.2.3) work package 3.
- In chapter five we elaborate on the interdisciplinary process. First, we provide the lessons learned of work package 3, then we provide interview results and finally the results of the open questions in the surveys are pictured.
- In chapter six we conclude on best practices, lessons learned and recommendations for future interdisciplinary research projects.

Figure 5 shows how this report builds on previous DigiMon work by the WP3 team.

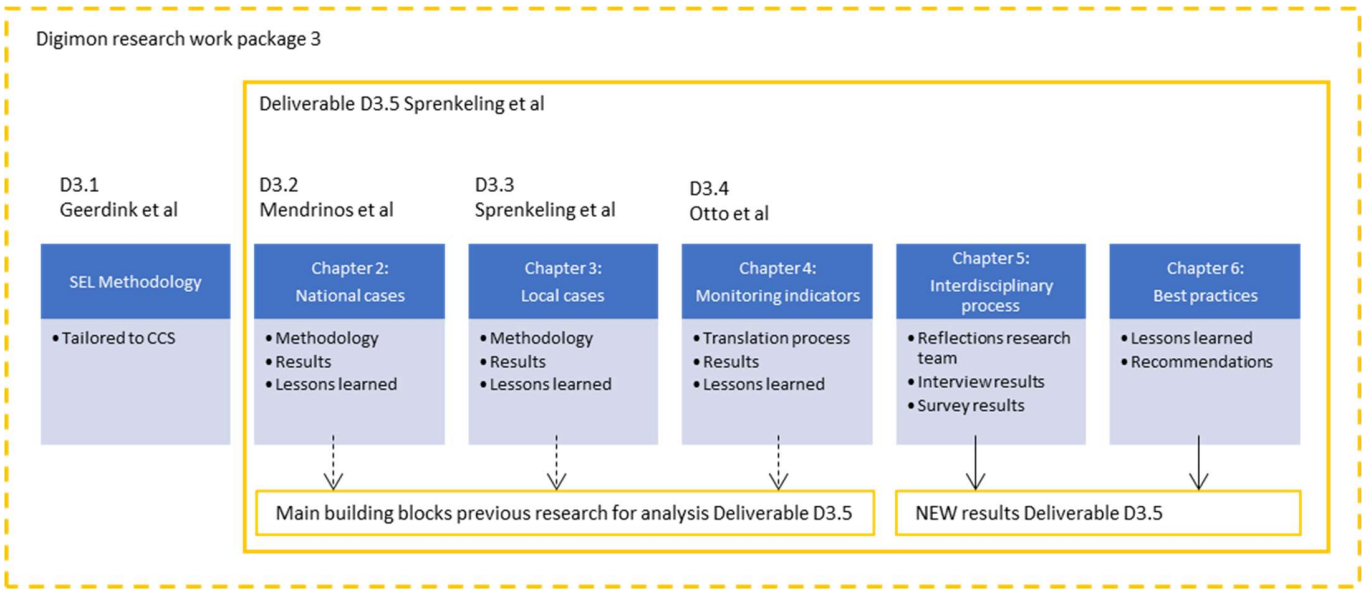


Figure 5 ***Relation research activities and deliverables within work package 3 Digimon project***

2 Studying the societal embeddedness of CCS at national level

In this chapter we present the research on the national case studies. Paragraph 2.1 introduces the methodology for the national case study research. Paragraph 2.2 gives an overview of the main case study results. Paragraph 2.3 shows the main lessons learned from the perspective of the WP3 team with applying the SEL methodology at national level. Paragraph 2.4 continues with summarizing the key challenges with applying the SEL methodology at national level. Paragraph 2.5 concludes with some examples of the added value of the collaborative and interdisciplinary way of working within the DigiMon consortium connected to the case study research at national level.

2.1 Methodology national case study research

Based on a contextualization of CCS for each country, the Societal Embeddedness Level (SEL) was evaluated using the methodology as described in the DigiMon deliverable D3.1 "Guideline Societal Embeddedness Assessment" (Geerdink et al., 2020). The SEL of CCS per country is assessed for four societal dimensions:(1) the impact on the natural, built, and social environment, (2) stakeholders' involvement, (3) legal and regulatory framework and (4) market and financial resources. Doing this, we started with assessing the SEL that corresponds to the average TRL level for CCS development at national level. For each societal dimension, the societal embeddedness level is identified, varying from SEL 1 to SEL 4. An overall SEL level per country is identified based on the SEL values per dimension (Geerdink et al., 2020). The national SEL assessments are performed by desk research (scientific and professional literature) and expert interviews.

2.2 Summary of results

We conducted a SEL assessment (Geerdink, 2020) on CCS developments in Norway, The Netherlands, Greece, and Germany. Each country shows a different societal embeddedness level of CCS, with Norway being at SEL 3 with considerable progress towards level 4, followed by the Netherlands with SEL 2 with several initiatives towards reaching SEL 3 with offshore demonstration projects and then by Greece and Germany with SEL 1 (Mendrinos et al., 2021). The outcomes of the SEL assessments per country show which societal requirements have been met yet in current CCS developments and which ones should be improved towards CCS deployment. According to monitoring of CO2 storage we found that monitoring currently is a regulatory requirement as part of permitting procedures. Furthermore, there is an indication that monitoring may alleviate community concerns on safety, which we further studied in local case studies (Mendrinos et al., 2021). For further information we refer to Mendrinos et.al. (2021)

2.3 Lessons learned WP3 team with applying SEL methodology at national level

The lessons learned of using the SEL methodology to assess the societal embeddedness of CCS in four countries are collected through interviews with work package 3 members in 2021. Therefore, the structure of reporting on the lessons learned differs from the lessons learned of the other tasks in chapter 3 and 4.

In all four countries the WP3 team succeeded in applying the SEL methodology on the national situation of CCS and managed to answer the questions sufficiently to assess the SEL on a national level. The SEL guidelines and framework are followed and where applicable for all countries, even when there are no current CCS demonstrations (in two of the four countries) or no CCS developments (in one of the four countries) at all. The SEL framework is stated to encourage interdisciplinarity according to two of the researchers.

The four societal dimensions (environment, stakeholder involvement, policy and regulations and market and financial resources) and associated SEL framework represent the societal aspects which are essential for societal embeddedness, and the results of the assessments offer an in-depth and detailed view on the national situation of CCS according to all countries.

Three of the researchers emphasize that the SEL assessment guideline is structurally used during the execution of the national assessment.

According to one researcher, the SEL framework offers a structured approach and way of thinking when studying the societal embeddedness of CCS in a country.

Although the answers on the questions in the framework consist of a ‘yes’ or ‘no’, and the SEL outcome a number, three researchers state that the explanations behind the outcomes of the assessment offer the most valuable insight in the societal embeddedness of CCS.

Finally, one researcher questions whether the methodology will be just as applicable for someone who does not have in-depth knowledge about the methodology or was not involved in the development of the methodology.

2.4 Perceived challenges in using the SEL methodology

While conducting the SEL assessment for CCS at the national level the researchers experienced multiple challenges, which are pictured in table 1. The most frequently mentioned challenges related to the connection between the SEL and TRL, the time needed to conduct the assessment, different interpretations of the SEL framework and applying the SEL on a national level instead of a specific technology or project at a local site are elaborated in this chapter.

Table 1 Perceived challenges using the SEL methodology

Challenges	Explanation
Identifying the SEL/TRL reference point	The SEL/TRL reference point can only be identified according to the SEL assessment guideline if the TRL of all technologies is known.
Challenges to applying the SEL on a national level	This involves: • The SEL/TRL reference point; • Having no specific CCS projects in the duration of the assessment; • The way the questions in the framework are framed to a specific application.
Time needed to conduct the assessment	Depending on how much information is available, the search, reading and analysis of documents is time consuming. If little information is available, the interviews are time consuming.
Different interpretation of milestones and questions	A word in a milestone or question can have different meanings for different people. The value of an outcome can be experienced different as well.
Dealing with outdated knowledge	Scientific articles on former CCS projects or developments can be outdated
Hard to obtain sufficient information	Not enough information available
Covid-19 related challenges in	Not being able to do face-to-face interviews

Challenges related to application on CCS at national level

Several challenges were related to the application of the SEL methodology on a national level. First, identifying the TRL with the purpose of setting the TRL/SEL reference point is not easy to do for a chain of technologies with no specific application. The capture, transport and storage of CO_2 can contain all kinds of technologies, of which the TRL is not specific on a national level. All countries have struggled with this issue. However, they all found a workaround to estimate the SEL reference point.

Second, some of the questions were found to be very project or site specific, by one of the countries. For example, the level of stakeholder involvement can vary across the different projects. For this reason, one of the countries failed to answer some of the questions in the dimension environment (concerning the social environment), which resulted in not being sure about whether the country is in SEL 1 or 2.

Third, not all countries had a running CCS project during the assessment. For one of the four countries this meant that historical cases had to be studied. Another country had no history of CCS demonstration projects at all, for this reason CCS was still in SEL 1.

Connection TRL and SEL: The connection between the TRL and SEL was an important challenge. For the researchers in all four countries, the SEL/TRL reference point was hard to apply on a national level, as the TRL is based on a single technology, while CCS is a chain of technologies (CO_2 capture, transport, and storage), for which there is no fixed TRL. Additionally, as the SEL is assessed on a local level, three of the four assessments did not focus on a specific application of CCS, which made it more challenging to make statements about the TRL.

Time needed for assessment: The time needed to perform the SEL assessment has been a challenge for three of the four countries, in diverse ways but all related to the process of data gathering. The research process includes searching, selecting, and reading documents and literature and approaching and interviewing experts.

Second, as the SEL framework contains many questions, posing all questions from the framework demands lots of time from the respondents. However, this depends on how many questions need to be answered by experts. When many documents and literature are available, the interviews are more compact, because the national case study protocol prescribed that information which could not be sufficiently retrieved from desk study research should be retrieved from interviews.

Finally, finding the right experts who are willing to participate in the assessment can be time consuming. Although looking at technology development interdisciplinarity is the purpose of the SEL methodology, one of the countries states that the need for interdisciplinary knowledge can be a hurdle in the research process. At the same time, you must assume that the knowledge delivered by the expert of that discipline is reliable.

Different interpretations of milestones and questions within the SEL Framework: According to all four countries, some questions in the SEL framework are open to interpretation in two ways: First, whilst reading the questions it might be possible that the meaning of words are interpreted different by diverse people. In an interdisciplinary team this is even more of a problem than in a team of social scientists. Second, the value of an answer can be experienced differently by different parties. For example: a project developer could feel like he involved stakeholders at the right time, when stakeholders prefer to be involved earlier in the process. This as well can occur with questions in the dimension market and financial resources: when the government states that the right policy framework is in place, project developers can still experience regulatory barriers.

Outdated knowledge: For the assessment of the SEL in each country, written documents are analysed. However, scientific articles as well as documents about former CCS projects, can be outdated. Information that was written, for example, 10 years ago, is not always represented for the current situation. Two countries mentioned this in the interviews.

2.5 Added value interdisciplinary research approach national cases

To provide more insight in the added value of the interdisciplinary research approach, we present 2 examples of how the interdisciplinary way of working added value to planned outcomes.

Example 1: Co-creation SEL Assessment Guideline. In the phase of designing the research approach for the national case studies, we hosted a DigiMon interdisciplinary training event on the societal embeddedness level methodology (March 2020 – Amsterdam), which was open to attend for all DigiMon partners. During this training we created a collective understanding of the SEL methodology within the DigiMon consortium and provided insight in how the methodology was going to be applied as part of the DigiMon research. Through the conversations among the DigiMon partners and exchanging questions and reflections regarding the methodology, we were able to enrich and improve the guideline for applying the SEL methodology in DigiMon. Based on the additions from the DigiMon consortium, we improved the Societal Embeddedness Assessment framework (Geerdink et al 2020) and increased the tool's replicability. The training event also contributed to identifying important crosslinks between work packages and individual tasks and giving insight into how the outcomes of the national case study research based on the SEL methodology could feed into other tasks.

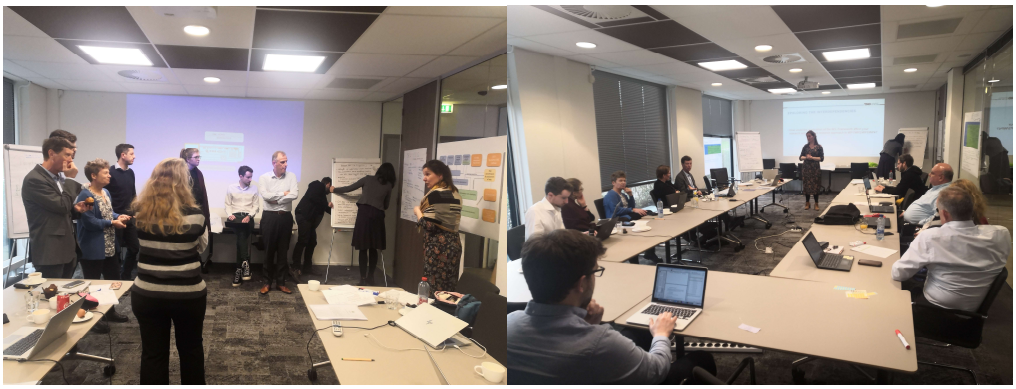


Figure 6 ***Researchers from the DigiMon consortium working together during the interdisciplinary training event on the societal embeddedness level methodology, March 2020, Amsterdam, the Netherlands***

The training event learned that the SEL Assessment Framework is comprehensible and works intuitively. Participants experienced that it was achievable to define the SEL at national level in a generic way. The training provided valuable suggestions for improving the distinctions between the different SEL levels and in-dept feedback on the milestones per SEL dimension. Finally, the training gave insight into possible new topics to be added to each of the SEL dimensions.

Figure 7 *Outcomes of group work for improving the distinction between SEL levels and defining milestones per dimension and per SEL level during the training event, March 2020, Amsterdam, the Netherlands*

The inputs from the training event in Amsterdam resulted in the following improvements of the societal embeddedness level assessment framework:

- The four SEL levels and dimensions are more clearly defined;
- An explanation about setbacks is added: can an innovation fall back to a lower SEL level?
- New milestones are added to the dimensions and SEL levels;
- A stepwise process for applying the SEL assessment is developed;
- The SEL guideline's focus description is improved: introduction of the SEL methodology and application of the SEL assessment framework.

To summarize, the added value of this 1st interdisciplinary training event for all DigiMon partners was shown in the specific result of an improved assessment framework for assessing the societal embeddedness level of CCS initiatives at national level as well as in the improved scoping of the assessment guideline and its application in Digimon (figure 8).

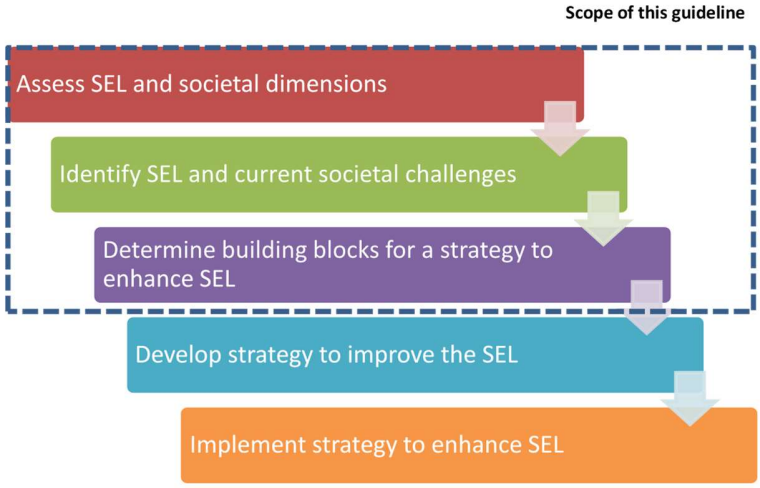


Figure 8 *Improve scope of the assessment guideline for assessing the Societal Embeddedness Level at national level (Geerdink et.al.2020)*

Example 2: Co-valuing outcomes of national assessments. Another example of the interdisciplinary approach's added value can be found in the phase of analysing the collected data of the national case studies. In March 2021 we held a (online) 2nd interdisciplinary event with the DigiMon consortium, to collaboratively value the outcomes of the national case studies for improving current monitoring practices. (Figure 9)

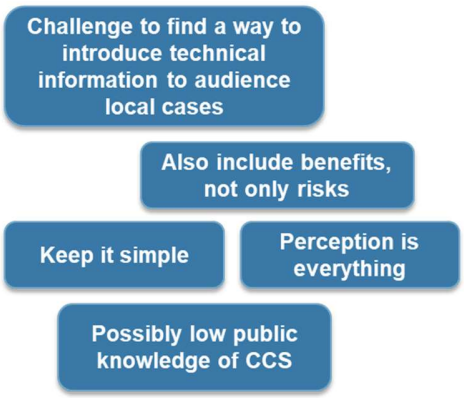


Figure 9 ***Quotes from DigiMon partners during an interdisciplinary event***

The exchange of ideas and reflections among the Digimon partners during this 2nd interdisciplinary event led to first indications on how to design the local case studies (next research phase), to ensure the best possible outcomes for the further development and implementation of the DigiMon monitoring system in work package 1 and work package 2. During this event we experienced and collected:

- Good interactions between DigiMon partners;
- Suggestions for applying the SEL methodology in other policy domains;
- First ideas for setting up the four local case studies, building on the outcomes of the national assessments;
- New insights among DigiMon partners regarding interconnections between technical and societal requirements for CCS.

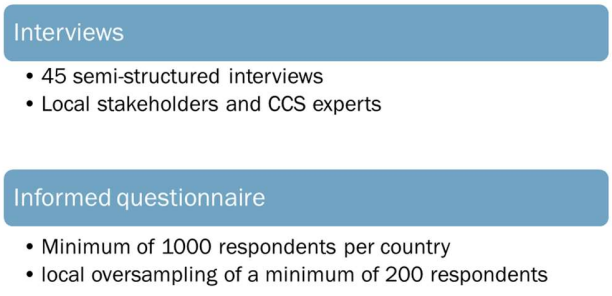
3 Insight into the societal embeddedness level of local CCS initiatives in four countries

In this chapter we present the outcomes of the local case studies. Paragraph 3.1 introduces the process and methodology for the local case study research. Paragraph 3.2 gives an overview of the main results of the local cases. Paragraph 3.3 shows the main lessons learned from the perspective of the WP3 team. Paragraph 3.4 concludes with an example of the added value of the collaborative and interdisciplinary way of working within the DigiMon consortium connected to the case study research at local level.

3.1 Process and methodology local case study research

By doing local case studies for CCS in Norway, The Netherlands, Germany, and Greece, we studied the local context on the four SEL dimensions more in-depth and we studied how monitoring of CO_2 storage could contribute to the societal embeddedness of CO_2 storage projects (Sprenkeling et al., 2022).

For the design of the local case study approach, we used a combination of qualitative and quantitative research methods across the four countries: semi-structured interviews with (local) stakeholders and CCS experts and a survey among the public designed as an Informed Questionnaire (IQ) (see figure 10). We conducted 45 semi-structured interviews with local stakeholders and CCS experts in four European countries to gain insight into stakeholder experiences and preferences concerning CCS and monitoring of CO_2 storage. To be able to compare the preferences and responses of citizens in the four countries, we conducted an experimental survey study in the form of an Informed Questionnaire (IQ). Both in The Netherlands, Greece, Germany, and Norway the IQ has been used to gain insight in the opinion of the public at national level: input of 1000 respondents per country was received. For the Dutch, German, and Norwegian case studies, we were also able to conduct an additional local oversampling of a minimum of 200 respondents per country, close to previous or actual CO_2 storage initiatives.



Type of stakeholder	Number of interviewees
Government (politicians, governmental employees)	10
Industry	10
Scientist (technical/social)	4
Controlling bodies	5
eNGO 's	7
Project team local case	5
Consultants	1
Local community	3

Figure 10 *Methodologies for local cases*

Table 2 National contexts of CCS

	Norway	The Netherlands	Germany	Greece
Previous projects CCS	Successful offshore projects on industrial scale (Sleipner, Snøhvit) since 1996, CCS application	Discontinued past onshore (Barendrecht, Groningen) and offshore projects (ROAD, Athos) Successful offshore CO2 storage and enhanced gas recovery (K12-B)	Successful scientific onshore pilot project (Ketzin), Failed industrial projects	None
Previous CCS application	CCS connected to gas extraction at offshore platforms, Carbon capture project from industry (Yara)	CCS connected to enhanced gas recovery	CCS connected to coal fired power plants	None
Planned CCS projects	Large scale CCS project (Longship), Flexible large scale carbon transport and storage project (Northern Lights)	Large scale Offshore carbon capture, transport and storage projects planned (Porthos, Aramis)	CO_2 storage banned in Germany, Plans for the transport of CO_2 to offshore storage hubs in other EU countries	Offshore storage planned in depleted hydrocarbons field
Planned CCS applications	Negative emissions technologies, residual emissions	CO_2 capture (from industry), transport, utilization and storage (offshore), negative emissions technologies.	Negative emissions technologies, residual emissions	CO_2 capture coupled to hydrogen production unit from natural gas (blue hydrogen)
Local case	Bergen work region (Northern Lights project)	Rotterdam (Porthos project), Amsterdam (Athos project, stopped during research phase)	Hamburg (CO_2 transport), previous storage sites (Ketzin, Beeskow)	None

3.2 Summary of results local case studies

Considering the qualitative (interviews) and quantitative (IQ surveys) research results, we identified the following characteristics for an innovative monitoring system:

- Based on the survey results, there is a convincing argument for the external and independent supervision of the monitoring by actors that are considered trustworthy by the public.
- There is convincing evidence for the importance of the connection of monitoring to a warning system and a security concept in case of unexpected data or malfunctions.
- Transparency and access to the monitoring data (if possible real-time) are seen as relevant factors for a monitoring system in the interviews and the survey.
- Enabling meaningful public participation in the development of a monitoring system could strengthen trust and support. While most of the respondents in all four countries tended towards expert responsibility for the set up and configuration of the monitoring system there is also a considerable group that wishes for public participation in these processes.
- Although the costs of monitoring were not rated as important as reliability and safety, they remain a relevant factor for stakeholders (even though the costs for monitoring are minor compared to the overall CCS deployment costs).

In the four countries, there are varieties in local societal and technical contexts. The importance of the characteristics also varies. The characteristics of the monitoring system need to be adapted and balanced according to local societal and technical contexts. For further reading see Sprenkeling et al., 2022.

3.3 Lessons learned WP3 team with applying SEL methodology in local context

First we will discuss the lessons learned based on the informed questionnaires. Last we will highlight the lessons learned derived from the interviews with local stakeholders.

Informed questionnaire

The development of the informed questionnaire is perceived as a challenging task. The team had to coordinate between four different national contexts with four different survey institutes. As the technical knowledge of the WP3 team lacked in some respects, the informative texts that are embedded in the survey had to be co-designed by technical experts to provide trustworthy information for respondents. After this, the technical information had to be translated to make it understandable for non-experts. This made the development of the questionnaire an intensive co-creation process. In an ideal situation the technical information would be provided by actors that are considered trustworthy by the participants, and cognitive interviews should be conducted to gain a better understanding of how the questions and information were perceived by respondents. Because of the multiple review loops the development of the questionnaire took longer than expected.

Semi-structured interviews

A semi structured interview protocol which included the societal dimensions of the SEL methodology is followed. At the same time, the interviews were open for national and local context in the conversations to provide room for different perspectives. There have been some different focus points among the four countries, which shed light on what issues have the most attention at that moment. During the interviews knowledge from different stakeholder perspectives came together and the importance of translation of the technology to the public became clear.

Among the four countries there was quite a difference in which actors were recruited and which were most active and had the most to say. Also, there was a substantial difference in how many stakeholders were interviewed in the four countries (due to e.g., resource limitations, lack of relevant stakeholders and Covid-19). This has affected the qualitative assessments in each country and the extent to which we were able to compare the results. Additionally, the varying national contexts made it hard to compare the results. Writing a narrative was a good instrument to shed light on all aspects.

As social scientists, the team gained more (crucial) technical knowledge about CCS and CCS monitoring during the interviews (especially those with technical experts on CCS). This strengthened the understanding of the DigiMon project as well as CCS and subsurface monitoring in general and made it easier to participate in technical discussions and set up a knowledge integration process to develop design options for a societally embedded monitoring system.

3.4 Added value interdisciplinary research approach local case studies

To give more insight in the added value of the interdisciplinary research approach, we introduce an example of how the interdisciplinary way of working added value to planned outcomes.

Example 3 – Implications outcomes local case studies. During another interdisciplinary meeting on the outcomes of the local case studies the expertise and experiences of the full DigiMon partner group were used to identify building blocks for the translation process towards societal monitoring requirements. The WP3 researchers introduced an approach to identify not only indicators for monitoring but also trade-offs that might occur based on the local case study outcomes. This distinction was well-received by the DigiMon consortium. During this interdisciplinary meeting it was also suggested to form an interdisciplinary research team consisting of researchers from work packages 1, 2 and 3 for designing the research process towards societal monitoring indicators as well as reflecting on intermediate results and making optimal use of the WP3 outcomes for ongoing research activities in WP2.

4 Towards societal monitoring requirements

This chapter gives insight into the outcomes of and experiences with working towards societal monitoring requirements and indicators. Paragraph 4.1 introduces the process and methodology of this translation process from national and local case studies towards societal monitoring requirements and indicators. Paragraph 4.2 gives an overview of the main results of this translation process. Paragraph 4.3 shows the main lessons learned from the perspective of the WP3 team. Paragraph 4.4 concludes with an example of the added value of the collaborative and interdisciplinary way of working within the DigiMon consortium.

4.1 Explanation of process and methodology

Based on mixed methods, multinational and cross-scale research methodologies (Otto et.al. 2022), we identified characteristics for an innovative monitoring system. We translated these characteristics to design options in an iterative process of inter- and transdisciplinary exchange in Norway, Germany, the Netherlands, and Greece (see figure 11 for an overview).

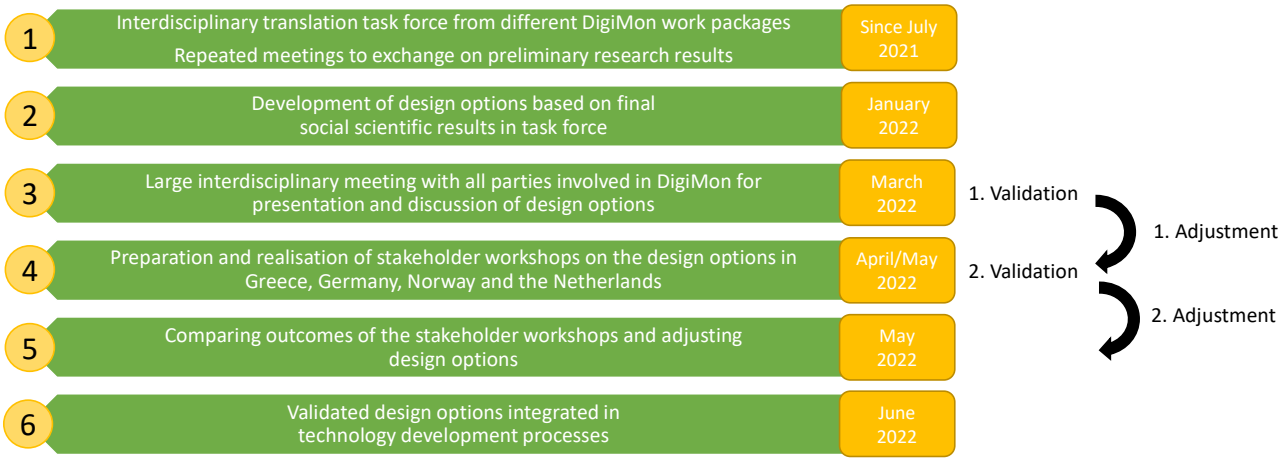


Figure 11 ***Overview of inter- and transdisciplinary* translation process**

(1) First, we organized regularly exchange on preliminary research results in the technical and social scientific work packages of DigiMon in an interdisciplinary task force. It was set up in July 2021 to develop a shared understanding of the tasks and timelines in the different work packages and to find a common language to arrive at design options for a monitoring system.

(2) The task force developed a first set of design options based on this long-running collaboration and the final social scientific research results in January 2022. To structure and organise our debates, we used the four dimensions established in the "Societal Embeddedness Framework": impact on the environment, stakeholder involvement, policy and regulations, market and financial resources (Geerdink et al. 2020).

(3) This set of design options was presented and discussed at a large interdisciplinary online workshop with all parties involved in the DigiMon project. 25 people participated in this event. It consisted of three short presentations and a longer interactive phase of work in break-out groups. In this event the research results were shared, and the design options were discussed.

(4) The adjusted set of design options was presented in online workshops to heterogeneous stakeholders in Norway, Greece, the Netherlands, and Germany to collect feedback from actors in different contexts. All persons interviewed to determine CCS perceptions and monitoring preferences in the four countries (see above) were invited to participate in the workshop

(5) The outcomes of this second round of validation of the design options were compared across the four countries, resulting in adjusted and validated design options that were used to inform the ongoing monitoring technology development

4.2 Summary of results translation process towards monitoring indicators

The translation process with the interdisciplinary task force worked towards a set of characteristics, design options and trade-offs, structured alongside the societal dimension of the SEL framework. The task force developed multiple design options and trade-offs for each dimension (figure 12). Design options show which technical specifications are relevant for the design and implementation of the system. Trade-offs point out which balances and interactions need to be considered when designing and implementing the monitoring system. The design options offered by this approach support the context-specific development of monitoring solutions based on comprehensive social and technical scientific research.

The design options and trade-offs as displayed in figure 12 are validated and discussed in stakeholder workshops in all four countries. This resulted in discussions about (among others) the purpose of monitoring, how data can be translated and shared with the public, the difference of CO_2 storage in gas fields related to aquifers and the challenge of monitoring plume movement, the costs of monitoring and how these relate to a license to operate, and which parties would be suitable to function as trusted party.

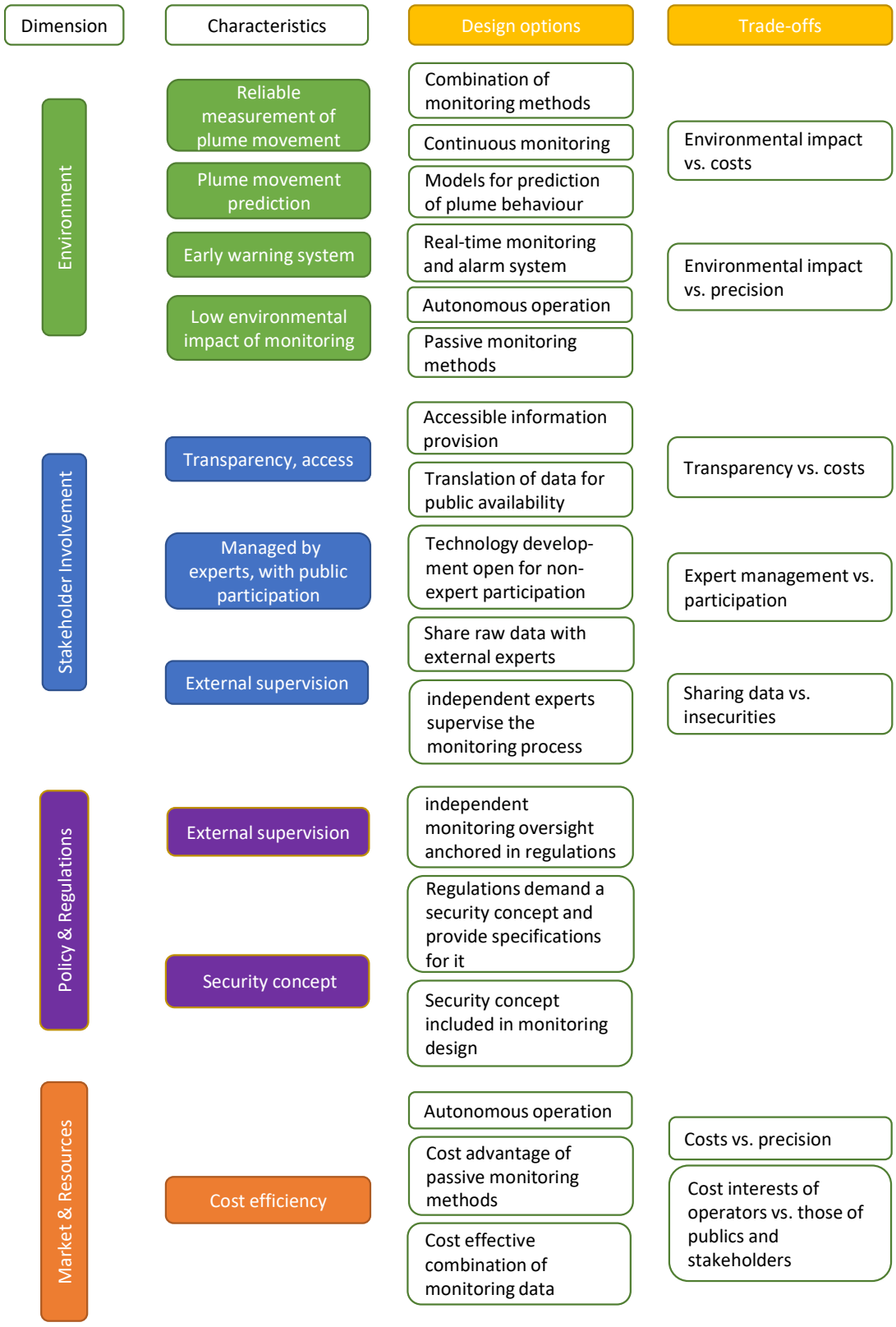


Figure 12 *Overview of design options and trade-offs*

4.3 Lessons learned WP3 team with developing societal monitoring indicators

In this section we will highlight the lessons learned derived from four different research activities: setting up an interdisciplinary taskforce, sharing and discussing results within the DigiMon consortium, local stakeholder workshops and last Integration of results to analytical hierarchy process.

Setting up an interdisciplinary taskforce

After analysing the results of the local case studies and translating them in design requirements, WP3 started a process of validating these requirements and developing design options for a societally embedded DigiMon system. To do so, an interdisciplinary task force was set up with participants from each work package. This task force was dedicated to collaborating on this set of design options and integrating knowledge from all WP's. The co-creation process that was set up by this task force is perceived as a crucial step in the knowledge integration process in DigiMon.

The interdisciplinary task force really succeeded in developing a shared language, especially between WP 2 and 3. It helped WP3 gain a better understanding of the technical aspects of monitoring. The small group was flexible and therefore able to plan meetings at short notice if there was something urgent to discuss. The team found that a small task force of people who are able and willing to work on interdisciplinary exchange and knowledge integration can add extensive value to the research results. Working on this task raised the understanding of social aspects of CCS monitoring for technical project members.

Sharing and discussing results within the DigiMon consortium

When presenting the work, which was co-created with other WP's, the team was able to get into a more in-depth discussion and find each other and share a language. Interaction with other technical scientists, but with different technical disciplines, helped to understand the key features and limitations of the DigiMon monitoring system and communicate them within and out of the consortium.

Local stakeholder workshops

The local stakeholder workshops were moments of transdisciplinary working with non-scientific stakeholders. The workshops were to share and validate the results of the local case studies and discuss the design options for a societally embedded monitoring system developed by the interdisciplinary task force.

Technical experts from the DigiMon team were invited to each workshop to present the technical features of the DigiMon system and take part in the discussions. This made the workshops interdisciplinary and transdisciplinary at the same time and helped bridging the gaps between social and technical knowledge. The local stakeholder workshops facilitated a discussion between the local stakeholders as well, which felt like paving the way to a shared language. The combination of different disciplines among the local stakeholders contributed to interesting discussions.

A lesson learned is that it is valuable and necessary to set and communicate clear goals at the front and during the workshop and break the process of the workshop down in clear steps, to make the purpose and process clear for all participants.

It was challenging to engage local stakeholders in the DigiMon project for longer periods of time, for interviews and workshops. Due to digital working, there was less feeling of engagement than in a situation where physical meetings are organized. In a situation where we would have been able to have regular (physical) meetings, stakeholders could have been more engaged in the project, in for example an innovation atelier/living lab setting, this would enhance the transdisciplinary knowledge integration. Additionally, stakeholders could be involved in an advisory role for the local context they are involved in.
At the Greek stakeholders' workshop, as new developments on CCS evolved in Greece during the last phase of the DigiMon implementation and hence new stakeholders evolved who were invited to the workshop, the stakeholders were more interested in learning about CCS and monitoring technology, rather than validating the conclusions of the interviewees, who although they were present did not make any remarks. The real validation came from one interviewee of the earlier phase of the project (SEL application in Greek CCS market) who delivered written input on the design options of the monitoring system. This reflects that organizing transdisciplinary stakeholder workshops facilitates a discussion about subjects that are relevant at that moment in time in a specific context.

Integration of results to analytical hierarchy process

The results of the WP3 research are integrated in the WP2 work through an analytical hierarchy process. This methodological decision in WP2 was key to the further interdisciplinary work in DigiMon. It reflects how the results of the social research really influenced the knowledge creation in other work packages and shows how research on societal concerns can trigger considerations that were not on the agenda before, for instance the relevance of thinking about the environmental impacts of the monitoring procedures. Nevertheless, there was limited time available to integrate the results of the social research in WP 1 and 2.

Although the analytical hierarchy process was a key point in the interdisciplinarity of the DigiMon project, it would not have been this successful if WP3 had not tried so hard to understand and integrate the other WPs' knowledge throughout the project. This reflects that for a sufficient integration of social research results into the technical work packages to take place, a decent amount of interdisciplinary work needs to be put down along the way. For this to be a success it is important that the researchers in all work packages are open-minded and constructive to collaborate and to try to understand each other.

The team reflects that to further integrate results of social research into technical development, more time is necessary. Additionally, to thoroughly integrate knowledge from the multiple disciplines into one monitoring system, the timeline of a project should be carefully considered. The simultaneous implementation of WP3 with other work packages made it challenging for WP3 to develop tools and carry

out the necessary surveys and interviews before communicating the gained knowledge to the technical WPs.

4.4 Added value interdisciplinary research approach towards societal monitoring indicators

To give more insight in the added value of the interdisciplinary research approach we describe an example of how the interdisciplinary way of working added value towards developing societal monitoring requirements and indicators.

Example 4 – Connecting technical and social research tasks. The co-creation process that was set up by this task force is perceived as a crucial step in the knowledge integration process in DigiMon. The interdisciplinary task force really succeeded in developing a shared language, especially between WP 2 and 3. The exchange within the task force raised the understanding of social aspects of CCS monitoring for technical project members. Furthermore, interaction between technical and social scientists with diverse backgrounds helped to understand the key features and limitations of the DigiMon monitoring system and communicate them within and out of the consortium.

5 Reflections on the interdisciplinary research process

For deriving best practices from the interdisciplinary research process, three steps were undertaken:

1. We collected reflections on the interdisciplinary research process from the researchers involved in work package 3 (see par. 5.1).
2. We analyzed the outcomes of the evaluation forms (surveys) filled in by the participants after each interdisciplinary DigiMon event (see par. 5.2).
3. Interviews were held with a group of DigiMon partners to capture their experiences and insights regarding the interdisciplinary workflow. (See par. 5.3).

Based on these building blocks we derived best practices and main lessons learned for designing future interdisciplinary research processes (see chapter 6).

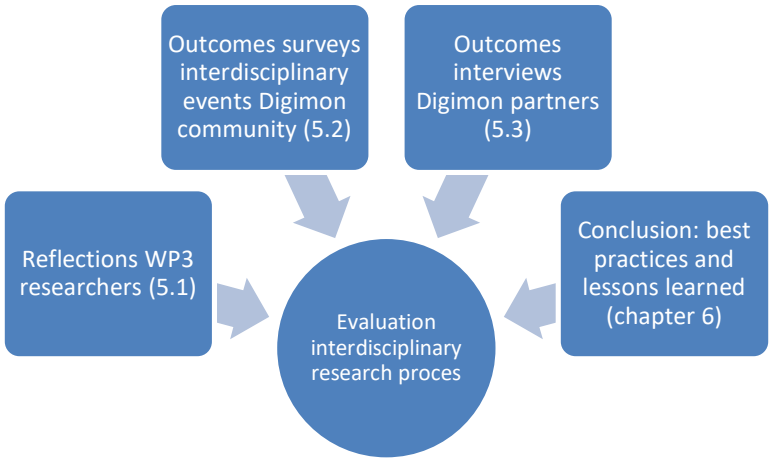


Figure 13 ***Building blocks for evaluation of the interdisciplinary research process***

5.1 Lessons learned from perspective WP3 team

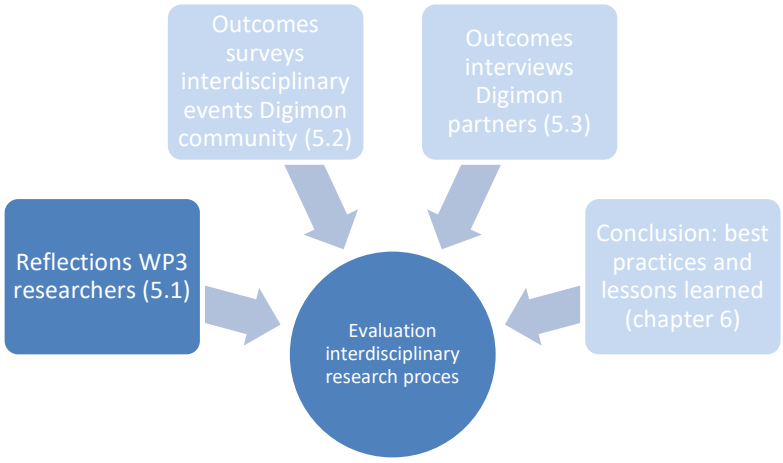


Figure 14 ***Reflections of work package 3 researchers as a building block for evaluating the interdisciplinary research process.***

The lessons learned from the research team of work package team focus on the following topics:

- Interdisciplinary research process within the WP3 team (par. 5.1.1);
- Interdisciplinary research process within the DigiMon consortium (par. 5.1.2);
- Knowledge sharing and integration in interdisciplinary meetings (par. 5.1.3);
- Best practices and lessons learned on interdisciplinary exchange during Covid-19 (par. 5.1.4).

5.1.1 Interdisciplinary process within the WP3 team

The WP3 team has had three physical working sessions to share results of the national and local research and design the working methodology. This has been experienced as helpful by the team members. Having physical working sessions provided a chance to learn about the different local contexts and work on a shared language and a common ground for developing design requirements.

Within the social science disciplines, there are huge differences in empirical and theoretical approaches and concepts as well. The disciplinary backgrounds of the researcher in the WP3 team varied from psychology to sociology and politics. The WP3 team itself had to develop a common language to work with, which took considerable time and effort. Having physical meetings accelerated the shared understanding of the concepts in DigiMon and the development of a shared language. Additional to the in-person meetings, regular digital meetings have been organized to keep on track and have continuous tuning within the WP. The team reflects that to develop a shared language, it is helpful to avoid jargon that is used in the various disciplinary backgrounds.

5.1.2 Interdisciplinary process within the consortium

The WP3 team found that it takes time, energy, flexibility and much talking to learn to speak the same language between the various social and technical disciplines. It takes effort from a team of social scientists

with different social backgrounds but takes even more effort from teams with different disciplines. Respecting each other's disciplinary background and expertise is also key for a good interdisciplinary collaboration to take place. In the beginning there seemed to be an understanding among some researchers in the project that social scientists working with social acceptance do something close to communications work to convince people that they should be positive towards CO2 storage. The team reflects that it took some time to create an understanding of the purpose and position of the social research in DigiMon. The overall vision is that the DigiMon team succeeded to find a common language to inform each other about scientific results and make steps to knowledge integration, for example in the information questionnaire, the process of developing design options and the analytical hierarchy process. Additionally, the team reflects that it is a strength of the DigiMon project that one discipline is not subordinate to another, and that the scientific input from all disciplines is evenly valued in the project results.

Setting up an interdisciplinary process alongside the main research tasks takes time and requires sufficient budget and structure in the project. The WP3 team reflects that it is crucial that this interdisciplinary process is embedded in the research design and that a person or a team should be responsible for this to secure the process. To optimize results of the process, it is helpful when interdisciplinarity is translated to a core task or deliverable in the project. This was the case in the DigiMon project. As a result, the development of design options for a human centered monitoring system forced all work packages to participate in a knowledge integration process. It particularly forced WP3 to take a pro-active role in this process. The team reflects that it showed that interdisciplinary exchange and the incorporation of different perspectives worked best if clear questions and goals were defined for the interdisciplinary process. It should also be clear what will be the outcome for all people involved.

Although the WP3 team was strongly engaged in the interdisciplinary process, many project members of DigiMon were not (active) part of this process. The team reflects that it takes time, effort, and intellectual flexibility to engage in an interdisciplinary knowledge integration process and that it is not necessary that every research member has the capacity to be active in this process, but a group (minimum of 1 per WP) who leads this can achieve sufficient results.

5.1.3 Knowledge sharing and integration in interdisciplinary meetings

The bridge to knowledge sharing and knowledge integration is hard to make. The team found that in most interdisciplinary meetings they got stuck on knowledge sharing and getting a better understanding of each other's work and interdependencies. The step to follow up this understanding after these events is important to reach knowledge integration. The team reflects that it works well to have large interdisciplinary events for knowledge sharing and getting an understanding of each other's work and language and organize follow up activities for knowledge integration in a smaller committee of people from different disciplines who are dedicated to spend time and energy in designing innovative solutions. Additionally, during large interdisciplinary meetings, it is important that interdisciplinary discussions are led well, otherwise the discussions tend to focus on one discipline.

The interdisciplinary meetings were organized mostly by members of the WP3 team. It would be interesting to see what it would mean for the interdisciplinary level when different work packages and thus different disciplines would organize meetings. This could be varied for each separate meeting.

5.1.4 Best practices and lessons learned on interdisciplinary exchange during Covid-19

The Covid-19 pandemic (starting early 2020) caused delays in the implementation of the project, especially regarding the European and international project partners, who had to remain in quarantine for a long time. In-person meetings were replaced by teleconferencing and digital meetings, office work by teleworking, but mainly the scheduling of work in CO_2 geological storage areas was postponed due to the travel restrictions. The situation was eventually normalized, and the partners adapted to the new conditions, with the result that the work of the project to be carried out smoothly and most of the lost time was recovered. Covid-19 difficulties caused an overall delay to the project implementation by 4 months, as all deliverables will be completed by the end of the year 2022, instead of August 30, 2022. The pandemic had implications for internal WP co-creation sessions, interdisciplinary knowledge exchange events, interviews, and stakeholder workshops.

Online interviews The team was forced to adopt a new way of doing qualitative interviews. Interviews are done online. After getting used to it, online interviews worked out very well. Once a practice for online interviewing was established it was much more efficient and convenient as traveling time and expenses were saved and it was easier to set dates. Nevertheless, it needs different comparative methodological analysis on the outcomes of online and offline interviewing.

Digital meetings are sometimes found to be more accessible. People who would not be willing to travel a lot, or do not have the time to attend physical events, can more easily join in a digital event.
However, it was found challenging to get into an in-depth discussion with (a group of) people who have never met in real life before. Forming a team and developing a shared language, is found to succeed better in physical meetings. Especially in settings where attendees have different opinions, operate in different contexts, or have different disciplinary backgrounds. Additionally, it is challenging to assure active participation from online participants. At the same time, we found that while working online, it is easier to join or leave in the middle of a meeting or event. To create more participation overviews, it could be helpful to ask participants to announce if they must leave early.
It is stated that it benefits the efficiency of the (online) meeting when expectations of the subject and purpose of the meeting are shared.

Online tools for collaboration One of the strengths of physical meetings is that it is easy to use tools such as flip-overs and whiteboards to add visual content to conversations. There are multiple online tools available to set up creative sessions and gather input. The team reflects that it is important to make sure that the tool is accessible for all participants without needing to log in, that the online environment is not too complicated and to keep a focus on what really matters. When working with the same group of people for a period, it is helpful to stick to one online tool instead of switching from one to another over time.

Online working needs a whole different kind of organization of meetings to get and keep everyone in the online environment, prepare online whiteboards and avoid technical errors during the meeting.
It takes time to establish a shared language across different disciplines. Doing this digitally is even more challenging. When facilitating online discussions, for example by using break-out rooms, the WP3 team found that enough time should be reserved to get into discussion.

Changing timelines for the field work for the technical work packages and the interviews and workshops for work package 3 posed multiple challenges. Although all work packages were able to achieve their own empirical goals, it took longer than expected, leaving less time for interdisciplinary exchange. Additionally, some crucial moments of interdisciplinary interaction were delayed and changed from in person to digital.

5.2 Evaluation by DigiMon consortium through questionnaires

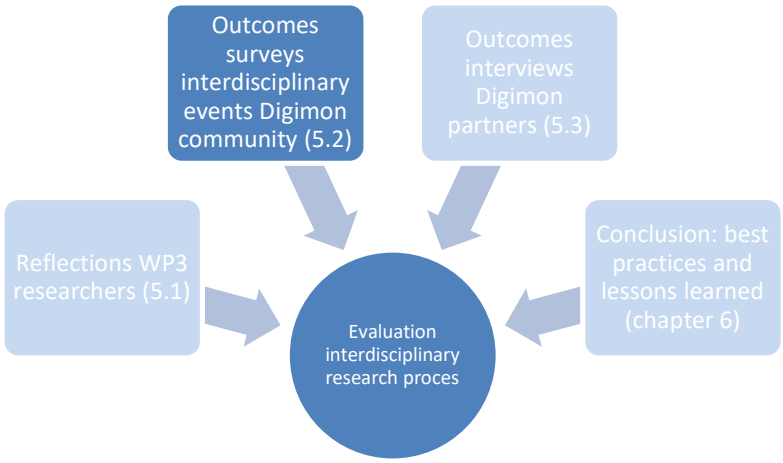


Figure 15 ***Outcomes from the surveys filled in by individual participants of the interdisciplinary DigiMon events as a building block for evaluating the interdisciplinary research process.***

After most interdisciplinary knowledge sharing events within the DigiMon consortium, surveys (attachment 2) were set out to individual participants to evaluate on the organization of the events and to capture the experiences and gained insights from the perspective of the participants. Due to Covid-19 we had two physical and two digital interdisciplinary events. In the first digital event we have not set out the regular questionnaire. In this chapter we elaborate on the outcomes of the open questions of the questionnaires. These questions relate to (1.) challenges experienced in the interdisciplinary work in DigiMon, (2.) what has been learned from collaboration with other disciplines in DigiMon so far and (3.) if new knowledge or insights are gained during the event. With these questions we hope to learn what best practices of interdisciplinary work in DigiMon are and what can be further improved in future projects. As only three events have been evaluated this way, and the participants of the projects and events changed during the time of the project, we decided to only analyze descriptive results.

For the analysis of the experiences of the participants, we made use of the evaluation forms of the following interdisciplinary events with the DigiMon partner group (see figure 16).

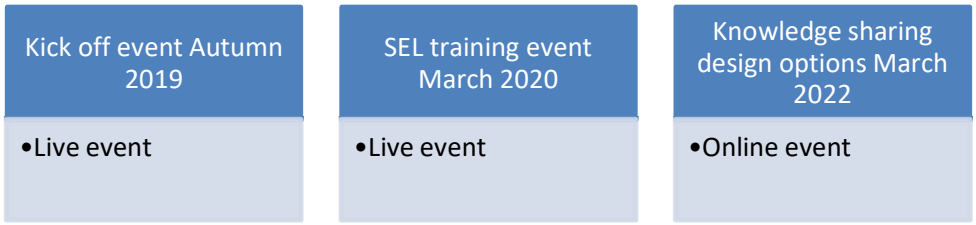


Figure 16 **Overview of events used for evaluating interdisciplinary process**

In the next paragraphs we will elaborate on the main challenges, experiences with interdisciplinary collaboration and new knowledge of insights through the perspective of the participants of the three events (Kick off, par. 5.2.1; SEL training, par. 5.2.2; design options, par. 5.2.3). We will conclude the paragraph with some overarching observations based on the survey analysis (5.2.4).

5.2.1 Kickoff event 2019

Challenges

Experienced challenges related to harmonizing (disciplinary) language, understanding of the project and its tasks, understanding of the end goal of the project, ambitions and expectations and the timeline of the project. Related to this, there are different priorities among the disciplines, which must be integrated in one product.

Collaboration between partners who speak another (disciplinary) language, come from different countries with diverse cultures and different companies (market vs research) is found challenging in this stage of the project.

Main challenges: languages, understanding of project and tasks and end goals, harmonizing ambitions and expectations

Lessons learned from collaboration with other disciplines in DigiMon so far

Some participants state that it is too early to comment or have formed a solid opinion about this, and that more time is needed to get on track, as this is still the beginning of the project. However, expectations are good and an openness to collaboration is experienced. During the kick-off event participants stated to have learned about the structure of the DigiMon project, for example about gaining an overview of stakeholders in the project and their potential concerns and objectives, who are working in the projects and what their skills and expectations are, who has the expertise to help with certain tasks and an understanding of the methodologies and technologies used in DigiMon.

Additionally, participants state that they learned that natural and social scientists speak different languages and have different goals in DigiMon, and that for experts it is hard not to focus only on scientific questions, challenges, and developments. However, it is emphasized that it is difficult but important to understand each other and to understand the other disciplines and tasks in DigiMon and that everyone

should work towards the same goal. Participants state that needs concerning public engagement and decision makers should be considered.

Finally, the importance of being specific and narrowing things down is mentioned. And the expectation that it is complex to develop a full-scale CCS monitoring system that will be accepted by society in most countries is expressed.

New knowledge or insights

Although for some participants it was too early to have a solid opinion, most of them gained new knowledge or insights.

Participants stated to have gained a better understanding of the project as a whole and how the different tasks are linked. New methodologies and approaches are introduced, and social scientists learned more about the technical work packages and vice versa. The complexity of the big picture of the project became clearer and participants state to have gained a good appreciation of the other participants and their objectives.

The importance of interdisciplinarity is mentioned, and how the topics in DigiMon need both technical and social insights. Participants gained a better understanding of the cross disciplinary requirements and how to combine knowledge and people with different disciplinary backgrounds and nationalities, but also the difficulties to find a working method that satisfies all interested parties.

Finally, participants state to have gained a better insight in the different stakeholders and interests concerning CCS and in the different technologies of the DigiMon project

5.2.2 SEL training event 2020

Challenges

At the time of the SEL training, after the first 6 months of working in DigiMon, challenges are experienced concerning different disciplinary languages and vocabularies and diverse ways of thinking, concerning both technology as methodologies. It is still experienced as challenging to find shared definitions and communication. Participants state to have a lack of knowledge on each other's tasks and find it hard to define connections and dependencies between disciplines and align on the scope of the project and deliverables.

Lessons learned from collaboration with other disciplines in DigiMon so far

Participants state that they experience a will to learn from each other and that all disciplines are receptive to input from others and timely with their own contributions. Until this moment participants have learned about diverse ways of thinking and team working, and interlinkages between the disciplinary fields and got further in finding a collective understanding of key aspects of DigiMon. Thinking processes connected to the SEL methodology and societal acceptance of CCS and a monitoring system are exchanged. People learned more about each other’s disciplines. The importance of a shared vision of the end-product is

mentioned, but also that this is something that has not been reached at the time of this event yet. A participant states that everyone is still having different thoughts on what the DigiMon system should exactly look like, and it is necessary to make this more explicit, or try to visualize the intended end-product to reach consensus on this. Nevertheless, participants state to have learned how the technical input to the project will affect society and stakeholders and have learned from collaboration between social and technical stakeholders and have learned about social sciences and different technologies. Although participants found that concerning social issues people have different opinions, participants learned novel approaches to see and solve challenges. Awareness is gained on how different disciplines view challenges with moving CCS technologies further towards (full scale) implementation.

New knowledge or insights

New knowledge is gained during the SEL training. First, knowledge is gained about the SEL methodology and how this connects to the technical work and how the social and technical work can influence each other. Insight is gained about interdependencies and necessary connections between the work packages. The meeting helped to consider how input in the project can improve the societal embeddedness of CCS, but also how stakeholders can influence the technical work.

Different opinions from participants have been shared. However, participants from technical disciplines were underrepresented compared to social disciplines. This might have caused a bias in social discussions during the meeting. Nevertheless, it was considered an important meeting to try to keep everyone on the same page and to clarify the importance of societal embeddedness.

On a more practical level, participants learned more about the complexity in social aspects including the SEL dimensions, the status of CCS technology in the different countries, and gained an understanding of the need for working on a national and local level in the social work package.

5.2.3 Knowledge sharing event on design options 2022

Challenges

Challenges that are experienced concerning interdisciplinarity about halve a year before the end of the DigiMon project are to understand the thinking and mindset of other disciplines, to reconciliation the views of social vs technical disciplines, to find the common goal of the project. The difference between the disciplinary languages is mentioned multiple times, stating that social scientists have a more descriptive language, while technical scientists use engineering terms. Words and expressions often have a slightly different meaning, and it is challenging to make sure whether we are talking about the same thing and to understand each other's concepts. Basic principles are challenging to align.

Additionally, it is mentioned to be challenging to Integrate the social scientific outcomes into the optimal monitoring solution, instead of something to consider in a project approach, and to figure out which (social) elements have most impact on a ccs project and how to find solutions to make it successful.

Lessons learned from collaboration with other disciplines in DigiMon so far

Participants remark that DigiMon consists of a group of people that are keen to learn from each other and each other's perspectives, and that the social and technical work comes together in a helpful way. interdisciplinarity adds an extra dimension to the collaboration and lifts the discussion to a higher level, but some of the scientific specific details are lost in these discussions. Participants learned that premises in one discipline may directly affect the research in other disciplines and learned a way of thinking and working.

One participant states that only intensive communication and operational collaboration at task level between the natural and social scientist on the design of optimal monitoring solutions can prevent from blind spots and subsequently technology implementation problems. A pitfall is to become convinced of an optimal technical design and understanding of the risks and control mechanisms, that basic attitudes become: 'we know what is best and we just have to tell the public or to decide what is best for them.'. Interdisciplinary collaboration with social scientists (at task level in the stage of technology design) technological scientists can learn to properly deal with public concerns.

On a more practical level, participants have learned about carbon capture storge, monitoring the underground, the state of the art of DAS technology, about the SEL methodology and social aspects of CCS projects and differences of CCS per country.

New knowledge or insights

On the one hand, the meeting has helped to clarify the public perceptions of CCS and helped to understand how WP3 can guide design options and development of a narrative for the DigiMon project. However, the meeting helped comprehend the perspective of the technical experts and industrial partners in the Digimon project. For the social work package, this helped for working with the feedback they got from different societal stakeholders and publics.

For some, the interdisciplinarity became clearer during this meeting. To learn how different disciplines view a topic and gaining more clarity in understanding issues linked to interactions between different disciplines, but also that it strengthened the belief in actual interdisciplinary operation.

It is stated that it is crucial to achieve the aim to get to a joint narrative for the DigiMon project. However, a participant states that the way WP2 and WP3 describe the monitoring is still different, and that the next step is to get this closer together. Another participant states that some technical details have not been properly explained to the social scientist, causing the perception of monitoring to be still different in some ways. Wording and language are important in this matter.

5.2.4 Conclusions based on the surveys

As new participants started working in DigiMon throughout the entire project, some challenges, lessons learned, and insights kept coming back through the various events. The challenge of understanding each other and finding a common language was present throughout the project and will remain a point of

attention in future interdisciplinary projects. However, there is a progression as well, starting with the challenge to oversee the project and interlinkages between the disciplines at the earlier stages of the project, and finally the challenge of integrating the scientific outcomes later in the project.

During the project, knowledge is exchanged between disciplines and technical disciplines gained more knowledge about social concerns, like the SEL methodology, stakeholder perception and how social concerns can influence a technical project. Social scientists also learned a lot about CCS technologies. Participants repeatedly remark on the willingness to learn from each other's work and perspectives. This eventually resulted in a collective understanding of how technological and social sciences come together in CCS (monitoring) projects and how both influence each other. Nevertheless, it remains challenging to get from knowledge sharing to knowledge integration. Understanding how disciplines influence each other's work appears to be a bridge between the former and the latter. It takes intensive collaboration to get interdisciplinary knowledge integration on task-level.

Knowledge and insights which are gained during the interdisciplinary events are mostly about the (structure) of the DigiMon project, (social) scientific outcomes and the perceptions of participants from other work packages. We find that the events have worked well for knowledge sharing and getting a better grip on each other's work, outcomes, perspectives, and disciplinary languages, but during the events there has been no knowledge integration. Nevertheless, the events led to a feeling of urgency and an understanding of why and how knowledge integration is needed.

5.3 Insights from interviews with DigiMon partners

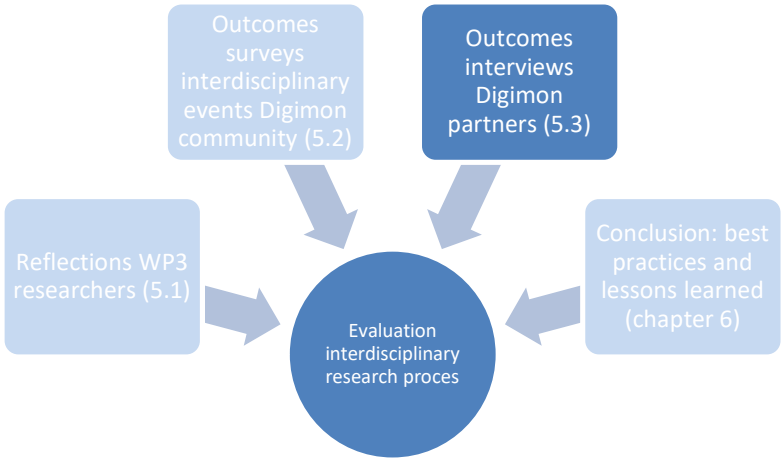


Figure 17 ***Outcomes from interviews with individual DigiMon partners as a building block for evaluating the interdisciplinary research process.***

To understand how the interdisciplinary work and knowledge integration process in DigiMon is perceived by the individual DigiMon partners, interviews with six participants of the DigiMon project were held. The participants included: one member of the project management, one member of the steering committee, one member of the quality control group, one member of work package 1 and two members of work

package 2. Minor adaptations are made to the interview protocol to adapt the protocol to the role of the interviewee in the DigiMon project.

In presenting the outcomes of the interviews, this paragraph highlights the following topics:

- understanding and expectations of interdisciplinary processes (5.3.1);
- understanding of interdisciplinarity in DigiMon (5.3.2);
- challenges regarding interdisciplinarity in DigiMon (5.3.3);
- how interdisciplinarity progressed the work in DigiMon (5.3.4);
- activities for interdisciplinarity (5.3.5);
- relation interdisciplinary activities to understanding of interdisciplinary research (5.3.6);
- working during Covid-19 (5.3.7).

Finally, this paragraph summarizes some general recommendations from the perspective of the interviewees (5.3.8)

5.3.1 Understanding and expectations of interdisciplinary processes

Common way of working: Participants expect to be creating and working with a common framework, common language and reaching symbiosis between technical and social perspectives. Expectations of the disciplinary process in DigiMon include seeing a wider picture and understanding of the subject, get new perspectives on the same problem, gain a more holistic understanding and challenge own perspectives instead of focusing on what you already know.

Challenges: There were some expected challenges as well. First, gaining a common language. This kind of challenges need planning, for instance by having people responsible for the interdisciplinary work. Another expected challenge was that the picture would become too wide, and little room would be left to get deep into specific issues.

Expectations of result: All in all, interdisciplinary working results to coming to more coherent and comprehensive solutions, which lead to different outcomes and approaches then thinking from only technical perspective would do and leads to better informed scientists. In the end this leads to clearer messages to policy makers, regulators, and stakeholders.

5.3.2 Understanding of interdisciplinarity in DigiMon (how important is it? Why is it important? Which disciplines are important to involve?)

Focus on technical-social: Technical as well as social sciences involve multiple disciplines. Although the focus of interdisciplinarity within DigiMon lies on collaboration between social and technical sciences, participants experience collaboration within and between technical work packages as interdisciplinary exchange. The collaboration between technical and social sciences is experienced as most innovative and valuable in DigiMon and added to having a complete picture instead of just a technical or social discussion.

Sense of urgency: It is stated that not all DigiMon partners had the same feeling of urgency towards the knowledge integration process, which complicated the process. How important interdisciplinary is being

experienced in DigiMon varies per work package. WP2 collaborates closely with WP1 as well as WP3. WP2 is a middle position with the task to bridge technical and social sciences by integrating knowledge. This makes interdisciplinarity an important part of the work of WP2. The interdisciplinary process is mostly led by WP3. This work package needed input from the other work packages throughout the process and was responsible for organizing interdisciplinary events.

Importance of social scientific outcomes: One respondent emphasizes that often in technical projects the technical scientists tend to think for stakeholders, instead of studying their perspectives. Being conscious of the real stakeholder perspectives can help working towards a strategy to get all stakeholders onboard, and to gain a license to operate for CCS projects. This is deemed necessary for successful projects and draws to the urgency of interdisciplinary work in technical projects like DigiMon.

5.3.3 Challenges regarding to interdisciplinarity in DigiMon

Lack of knowledge and experience: Some scientists had a lack of knowledge of and experience with interdisciplinary working and the organization around this process and therefore found it challenging to start this.

Intensity of the collaboration: Other challenges are experienced in the intensity of the collaboration. As the disciplines were divided into different tasks and WP's, interactions between disciplines had to be actively searched for. It was mostly WP3 who initiated interdisciplinary interaction throughout the project. It is found that (more intensive) interdisciplinary conversations helped to get the process forward.

Common language: A challenge experienced by multiple participants is the difference in wording between disciplines and the establishment of a common language understood by social and technical scientists as the public. A complicating factor was that we had to operate in a Covid-19 context which limited the physical meetings that might have been important for cross-disciplinary work.

Division in work packages: In the project design it was decided to divide the different tasks and disciplines into work packages, instead of working with interdisciplinary teams for every task. This means you must search for interaction actively. The intensity and effectivity of how this was done in DigiMon is hard to measure. The overall picture is that we did well. However, it would be interesting to explore what the outcomes would have been in a different structure/task division. Nevertheless, not every activity should be done by interdisciplinary teams. Sampling data during technical field work, for example.

5.3.4 How interdisciplinarity progressed the work in DigiMon

Not measurable: It is stated by two respondents that it is difficult to say whether the interdisciplinary process and knowledge integration process between the different disciplines has led to valuable or innovative scientific outcomes for DigiMon, a there is nothing to compare the outcomes with. It is stated that the interdisciplinary working within the DigiMon consortium has brought some movement in the way of working of some of the involved scientists, but not all of them.

SEL methodology: Working with the SEL methodology is perceived remarkably interesting and relevant. By using the SEL methodology, we have developed a vocabulary and quantified tool that integrates social

understanding in this kind of project. It is as well an organized tool that is easy to communicate. This offers the opportunity to approach projects which impact the living environment more controlled.

Broader perspective: The interdisciplinary working has broadened the perspective of the people involved. The work became more holistic, especially regarding communication in relation to CO_2 storage monitoring and getting an understanding of the perceptions and concerns that need to be addressed. Additionally, the different disciplines and tasks are now seen in a broader context, and the complete picture shows how the work is interconnected. Nevertheless, the interdisciplinary process has not had any effect on the individual technologies.

Dynamic playing field: The playing field of the innovation is very dynamic. The social and political sentiment of an innovation can change because of important developments. So, if you do social scientific research as an integrated part of technological development, this will not guarantee that the social context of the innovation will not change over time.

Different perspectives between industry and scientists: One respondent states that from an operator perspective, monitoring for the sake of monitoring, is a problem. Operators are not interested in overspending financial resources on monitoring. Therefore, not all options for monitoring and all additions that would be relevant from social and technical perspectives are possible. The understanding of technical and economic feasibility in social sciences research is therefore perceived as less realistic. This might be a lack of operator perspective in the interest of the social sciences research. There is a split between social and technical sciences and between technical sciences and operators. Technical sciences tend to be more interested in potentials, while operators must deal with multiple possibilities.

5.3.5 Activities for interdisciplinarity

Activities for interdisciplinarity were undertaken in all work packages. WP1 paid attention to interdisciplinarity in two deliverables. One of them was aimed at policy makers and regulators and the other highlighted the results of WP1 which were relevant for the other work packages. WP2 was in the middle of WP1 and 3 and integrated the scientific outcomes in one DigiMon system. Meetings were set up to understand the technical and social scientific factors for a monitoring system. WP2 changed its' working methodology for knowledge integration along the project, as the interdisciplinary feedback and scientific output from WP3 included new factors that were not part of the DigiMon system yet. Most interdisciplinary activities were organized by WP3. This involves the organization of interdisciplinary events for knowledge sharing and integration, setting up an interdisciplinary task force to develop design options for a societally embedded DigiMon system and organizing stakeholder workshops. Finally, a joint publication between WP2 and WP3 has been delivered.

What do you consider the most crucial factors for enhancing interdisciplinarity or scientific integration in DigiMon?

People Motivated and committed researchers working closely together are mentioned key factors for enhancing interdisciplinarity or scientific knowledge integration in DigiMon. These researchers need to have and take time for a learning process to exchange ideas and results about the research, in a way

(shared language) that is understandable for all involved disciplines, so that people who communicate with each other understand and agree with each other. At the same time, individual researchers need to understand advantages and limitations of the technologies and processes they use, and be able to interact about this, and researchers need to understand (beyond their own discipline) how the various parts of the DigiMon system fit together.

Understanding In all work packages there should be an understanding of a common task, a common research question and common deliverables. This enables understanding of the need of interdisciplinarity, the understanding of each other's work and the development of a shared language.

Formal position in project It was emphasized that starting the interdisciplinary way of thinking at the beginning of the project instead of at the end is a crucial factor to enhance interdisciplinarity throughout the entire project. This means that interdisciplinary expertise is needed in the proposal phase of the project already. By setting common goals and deliverables, the interdisciplinarity gets a formal position in the project. The project lead must advocate for the interdisciplinarity and acknowledge its value. Having the interdisciplinary process pushed by a person or a team who is responsible for the process secures the results. Within DigiMon the initiative for interdisciplinary exchange is taken by WP3. It might have enhanced the project if other disciplines

Resources Interviewees state that time is needed for a learning process to talk about the research project and gain a shared language. Having common tasks forces researchers from different disciplines to communicate, have meetings and exchange and integrate results. It takes time to facilitate the finding of a shared task. Looking for regular connection between disciplines takes time but enables a more direct collaboration which enhances knowledge integration.

SEL Methodology The SEL methodology helped to connect the social and technical sciences by connecting a societal embeddedness level to the technology readiness level. This overview and its' visualization made it easier to adapt.

5.3.6 How did the interdisciplinary activities in DigiMon relate to your understanding of interdisciplinary research?

Expectations vs reality: It was mentioned that during the proposal phase, the disciplines have been separated due to a lack of resources to already have interdisciplinary interaction in that stage of the project, and that the actual outcome of the interdisciplinary work in DigiMon turned out much richer than anticipated. Although there was limited knowledge on CCS and monitoring of CO2 storage, the scientific outcomes of the social research in DigiMon pointed towards relevant problems and topics not on the agenda before. One of the respondents states that the interdisciplinary approach was interesting, and she has not been in a project that has been so well organized/systematic when it comes to the interdisciplinary exchange, as initialized by the DigiMon WP3 team. It took some time before it became clear what was really going on in the social sciences part of DigiMon. About a year ago it became more integrated in the technical work. At first, the expectation was that the social sciences part would be more on the side compared to the other disciplines, but this changed in the last year. DigiMon differed from previous

interdisciplinary projects because the social scientists and technical scientists really interacted. It also helped that the technical and social sciences were balanced well, with two technical work packages and one social work package. It is emphasized that the international and social dimensions in interdisciplinary activities in DigiMon were new for some researchers, and less theoretical than they were used to working before. Although the covid-pandemic forced the project to digital working, respondents are positive about the international collaboration within the DigiMon project.

5.3.7 Working during the Covid-19 pandemic

Other way of working: Due to the covid pandemic there was a lack of physical meetings. Although this was a new way of working, it is emphasized that the project adapted to digital working in an effective way, and not flying around the world so much is positive as well. In the project accessible digital tools are used, and digital meetings were arranged more often than physical meetings would have been arranged in a 'normal' situation. After two years of digital working, the scientific outcomes have proven to be good and digital working has proven to be effective. Additionally, it has been stated by multiple respondents that working with an online tool helps, especially when this is the same tool over time, where people get used to. Online meetings enable easy participation for consortium members and people who want to join out of interest in the topic. Respondent states that working with online break out groups was a big advantage in the online format, as it is easier to switch between groups, mix groups up or add people to groups than it is in physical meetings.

More interaction: One respondent reflects that the interdisciplinary work between the technical tasks has not been very cooperative. Due to covid-19 lots of digital meetings have been set up, which all members from the WP could join. If there would not have been a pandemic, these meetings would not have been digital, and there would have been less collaboration between the members of the work package who must work from different countries. Currently, digital meetings have become normal and are not experienced as burden. Without Covid there would have been more physical meetings, but still this would be less interaction than has been reached now with Digital meetings, due to travelling time and costs.

Limits of digital collaboration: Although digital working has proven to be effective, digital communication is reflected as more effective between people who have physically met each other in real life before. Also, in live meetings people are more able to get into in-depth discussions. Some other drawbacks of digital interactions are that, although it is easier to reach out to a broader public, the interaction is less dynamic, and participants are less engaged in discussions.

Timeline of the project: The Covid-19 pandemic has impacted the project's timeline, but this was mostly due to getting used to a new situation. It is stated that the technical fieldwork is most affected by travel restrictions, but the overall project not that much. In the end, all field tests were done.

5.3.8 Recommendations from perspective of interviewees

Part 1 - Options to broaden and deepen the scientific knowledge integration

Interdisciplinary task force: A lot of interaction took place between an interdisciplinary task force existing of three people (from WP1, 2 and 3), this built a bridge between the different work packages and disciplines. It might be valuable to explore whether expanding such a group to broaden the exchange within interdisciplinary projects adds value to the integrated scientific outcomes.

Interdisciplinary teams: In DigiMon the tasks are divided into work packages. Two respondents mention that it might be interesting and even recommendable to mix this op. First, to define tasks that are not separate for each research institution, and secondly to have different disciplines within the tasks. Mixing the teams would strengthen the need for collaboration and enhance interdisciplinarity.

Contact and visibilities between work packages: In the case of DigiMon it took some time until it became clear what was really going on in the social sciences part of DigiMon and the work got more integrated. It might have helped if there was more contact between the work packages and more visibility from the social sciences side in the project. The interdisciplinary events organized by WP3 were mostly designed to share and integrate scientific outcomes from the social research in WP3. It would be good to have more regular workshops to discuss the results of the different work packages within the consortium.

Kick-starting the interdisciplinary work: Another workshop in the beginning of the project could have helped to harmonize the work, but due to Covid-19 this was not possible. Another option is having conversations about interdisciplinary work in an early stage of the project to get everyone on board on the interdisciplinary process, and to make sure that the value for everyone is clear and heave the knowledge integration developed more throughout the process.

Starting and finishing with a shared deliverable An early common interdisciplinary deliverable might as well help to kick off the interdisciplinary work, for example in the form of a pre-report. We do not have an interdisciplinary end-product yet, for example a shared deliverable. This is something that can be further developed this year.

Understanding of each other's work: A more in-depth technical understanding in the social sciences team would have enhanced the knowledge integration process, but on the other hand it is emphasized that the knowledge sharing from the technical disciplines lacks as well.

Looking beyond social and technical sciences: Within the technical WP, there has been interaction within the same group (e.g., among seismologists) but not between different technologies. As a steady basis for the interdisciplinary exchange, interaction should be organized between researchers who work on different technologies. Additionally, in DigiMon we did not focus on the economic aspects of the technology. This is a relevant subject to better embed in future projects.

Keep the knowledge integration going: The playing field of CCS and CCS monitoring is very dynamic. Social and political sentiment can change because of (context dependent) developments. Integrating social research into technology research and development does not guarantee that the societal context of the

innovation will not change over time. Just as technologies need maintenance, it is important to stay aware of the changing social context as well. For example, by engaging local stakeholders in the project design and in the monitoring process. If something changes in the perception or acceptance of a project, that should be responded to. Integrating social sciences in technology development and project design is an important investment for the future. Another lesson learned from this project is that the technical and social sciences aspect of the project/technology development must be stated clearly from the beginning by interdisciplinary collaboration. This interdisciplinary collaboration must be very well maintained during the project/development.

Part 2 - Recommendations concerning digital collaboration due to Covid-19

Benefits of digital working: One respondent states that the way of working, with digital meetings, which was adopted during Covid-19 should be taken forward, even when societies are open again and travel restrictions are lifted. Especially future projects which require the same amount of exchange between technical and social sciences.

Focus on one tool for interaction: A recommendation for digital meetings is to focus on one tool for interaction. Doing this, people get used to one tool, stick to it, and strengthen the learning effect. The whiteboard tool that was used for an online DigiMon meeting worked well, but it needed a bit of practice. The online meetings required a bit of learning, especially since different tools were applied. This leads to a time loss because people need to get acquainted with the tools.

Facilitate in-depth discussions: Online meetings often tend to be shorter (halve a day) than physical meetings (entire day), which results in less time for in-depth discussions. It is emphasized that for online sessions too, enough time should be taken to facilitate in-depth discussions, for example in breakout rooms that take 45 minutes instead of 20 minutes.

6 Conclusion: best practices and lessons learned regarding interdisciplinary research processes

We have reflected on the interdisciplinary process in DigiMon by doing six qualitative structured interviews, analyzing open questions from surveys taken at three interdisciplinary events and exchanging lessons learned concerning the tasks in work package three and the interdisciplinary work with the work package 3 team. We combined the results of these three reflective exercises and conclude with overall best practices (par. 6.1), lessons learned, pros and cons of working during the Covid-19-pandemic (par. 6.2) and recommendations for future projects (par 6.3).

6.1 Best practices

It was important for the DigiMon project that the interdisciplinary approach was adopted successfully. A larger, wider, and varied audience was reached. In addition, DigiMon presentations are of interest to a broad audience. A varied audience can follow the content presentations, as they do not only refer to geophysical exploration methods. The DigiMon narrative is improved through interdisciplinarity. The interdisciplinary collaboration between scientists in DigiMon enhanced the awareness of how challenging it can be to comprehend each-other's disciplinary language and improved the clarity of presentations. Additionally, whilst very in-depth technical knowledge is hard to grasp for a wider audience, social sciences outcomes are often understood easier.

We distinguish the following topics for drafting best practices:

- interdisciplinary process embedded in the project;
- regular exchange between disciplines;
- task force for knowledge integration;
- working with the SEL methodology;
- scientific collaboration between disciplines and co-creation with non-scientific stakeholders;
- fit for purpose.

Interdisciplinary process embedded in the project

It was a major strength of DigiMon that the interdisciplinary process was embedded in the project. WP3 really felt responsible for organizing this process and exchange. Making someone (or a team) responsible for this in time, budget, and deliverables has helped secure the process's outcomes.

Regular exchange between disciplines

Regular exchange between the work packages, in the form of interdisciplinary events, has been organized to share scientific outcomes. These events kept the conversation going and secured awareness of the usefulness and necessity of interdisciplinary process for the DigiMon project. It has contributed to see the

different tasks in the context of the entire project, the understanding of the participants, the sharing of scientific outcomes and the alignment of and interaction between the tasks.

Task force for knowledge integration

During the project we found that more action was needed to leap from knowledge exchange to knowledge integration. An interdisciplinary task force has been set up to engage in a knowledge integration process to translate social scientific outcomes to design options for a DigiMon system. This task force consisted of three people who represent all three work packages.

Working with the SEL methodology

The SEL methodology has provided a vocabulary to bridge between technical and social sciences. It is stated to encourage interdisciplinarity. The SEL framework offers a structured approach, way of thinking and vocabulary that guides the conversation in the interdisciplinary process. The four societal dimensions (environment, stakeholder involvement, policy and regulations and market and financial resources) represent the societal aspects which are essential for societal embeddedness of CCS, and the results of the assessments offer an in-depth and detailed view on the national and local situation of CCS.

Scientific collaboration between disciplines and co-creation with non-scientific stakeholders

In the DigiMon project we did not only integrate scientific knowledge from social and technical disciplines, but we also collaborated with the industry, experts and (local) stakeholders and consulted the public. We did this by (1.) inviting industrial project partners to interdisciplinary events, (2.) having interviews with local stakeholders and experts (3.) having stakeholder workshops and (4.) consulting the public by informed questionnaires in four countries. Doing this provided us with a broad picture of perspectives and lots of valuable input for our scientific activities. By having reflective and evaluative discussions as well, we also have a clear view of what our results lack and what we could improv in future processes.

Fit for purpose

As an international scientific community, we operate in different (and changing) contexts. This relates to societal aspects (cultures, political situation, history with CCS) as well as technical characteristics of storage sites and industries. During the research process as well as in composing our scientific outcomes, we kept this in mind. (1.) we adapted the interview protocols and interviewees to the national context, (2.) we adapted the survey sampling to the local context, by adding a local oversampling around CCS projects (3.) instead of making comparisons on set subjects, we composed a narrative for four countries to display the results of the local case studies (4.) We organized stakeholder workshops to validate and discuss the results in all four countries. Although local contexts were important in our research, we put a substantive effort into aligning the methodologies over the four countries as much as possible. In our results we introduced a fit-for-purpose monitoring system, with design options that can be adapted to multiple societal and technical contexts.

6.2 Lessons learned

For drafting lessons learned, we focused on the following topics:

- A common language – a common challenge
- Disciplines within disciplines
- Bridging between scientific community and industry
- Digital (online) collaboration

A common language – a common challenge

Finding a common language has been a challenge that kept coming back during the entire project. Although it most certainly progressed some of the participants more than others felt like having found a common ground, even in the end of the project some participants state that there are issues with wording and really understanding each other's concepts.

Disciplines within disciplines

Within DigiMon we focused on collaboration between social and technical sciences. However, there are multiple technical and social disciplines. This is something to keep in mind. Within work package three we succeeded in creating a shared understanding and language. We did so by very frequent interaction and avoiding jargon.

Bridging between scientific community and industry

Within DigiMon we focused on bridging the social and technical sciences. However, the is a gap between scientific perspective and perspectives of the industry (like CO_2 storage site operators) as well.

Lessons of digital collaboration

More frequent interaction with increased accessibility: We found that although we had to adapt a new way of working, the digital collaboration turned out very well. It is easier to engage multiple partners in one meeting and it takes less time and costs for travel. This was experienced in collaboration within and between work packages.

Less in-depth interaction and less commitment: Although digital interaction is more accessible and less time consuming, we found that it is more challenging to engage in in-depth discussions while talking online, especially with participants who have not met each-other in person before. Creating a collective understanding about complex matters is more challenging online.

Getting used to a new way of working: With Covid-19 we adapted a completely new way of working. At first, with most countries being in strict lockdowns, this resulted in decreased availability for all teams. Then, we had to get used to digital collaboration, within as well as across teams and country boundaries. In the beginning this resulted in a search for a 'new normal', including technical problems. We have worked with multiple platforms and tools and eventually succeeded in stable interaction and a rich toolbox of

instruments for online sessions. Finally, reflecting on this period, we are also able to see the benefits of digital collaboration as a valuable addition to the classical way of working.

6.3 Recommendations

Our recommendations focus on:

- a kick-start for the interdisciplinary process;
- exchange within work packages;
- how to embed the interdisciplinary process even better in the project and teams;
- excel in digital collaboration.

A kick-start for the interdisciplinary process

Although the interdisciplinary process was strongly embedded in the DigiMon project, we found that it took some time to get an understanding of each other's work and find each other to engage in knowledge integration processes. Additionally, we found that not everyone had the same sense of urgency of interdisciplinary exchange. It might be helpful if the interdisciplinary process is kick-started in an earlier stage of the project, for example by having an early-stage interdisciplinary workshop, or an interdisciplinary deliverable, to get to know each other and each other's way of thinking and working.

Exchange within work packages

Although within DigiMon we focused on the exchange between technical and social sciences, we acknowledge that within the technical and social sciences, there are multiple disciplines, and often multiple institutes with multiple nationalities working within these disciplines. A strong baseline of exchange between technical disciplines and social disciplines, which include a common disciplinary language and being aware of each other's perspectives, offers a stable common ground for collaboration between social and technical disciplines as well.

How to embed the interdisciplinary process even better in the project and teams

Option 1: Having a broad interdisciplinary task force responsible for scientific knowledge integration. Interdisciplinary exchange, like we did in the interdisciplinary events, is relevant and interesting for all participants. However, we found that it requires time, effort, willingness, and intellectual flexibility to engage in a scientific knowledge integration process. We also found that it is not necessary for every participant to be involved in this process. An interdisciplinary taskforce was set up for translating the social scientific outcomes to design requirements for a monitoring system. This task force managed to bring the disciplines together. Such a team, with a minimum of one participant per work package, could engage in interdisciplinary processes during the entire project to broaden and deepen the interdisciplinary work. In this way, the initiative for the interdisciplinary exchange would not only be at one discipline and knowledge input in the interdisciplinary knowledge exchange events is broadened.

Option 2: In DigiMon we have worked with work packages and tasks, which represented one discipline (either technical or social) and one institute responsible per task. Mixing this up would drive the exchange between disciplines as well as between institutes.

Excel in digital collaboration

During the Covid-19 pandemic, digital collaboration has proven to be effective and led to increased exchange within and between disciplines. Although we find that real-life meetings and exchange are unabated valuable to engage in in-depth discussions, cross-boundary collaborations can be enriched with frequent digital exchange. We recommend having frequent meetings, sticking to one digital tool (like miro, whiteboard or padlet) and facilitating in-depth discussions by securing enough time and engagement in breakout groups.

7 References

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Attachment 1: interview protocol

This interview protocol has been used to reflect on the learnings and impact of the interdisciplinary research process with 6 individual Digimon partners.

QUESTIONNAIRE

General Introduction

During the DigiMon project we followed an interdisciplinary research process in order to develop design options for a human centered monitoring system. During this process we organized activities for knowledge integration. We are now reporting on the best practices of this way of working and would like to ask you some questions about how you perceived this process.

Introduction questions

1. How would you describe your role in DigiMon?
2. What is your disciplinary background?

Questions about the interdisciplinary process

3. What do you expect from interdisciplinary research processes and knowledge integration?
4. Why in particular is interdisciplinarity and integration of scientific information important in your WP?
5. What do you think are the most valuable disciplinary backgrounds to intertwine within R&D in this kind projects?
6. Did you experience any challenges regarding to interdisciplinarity and knowledge integration? (if yes, what challenges and were they tackled?)
7. Do you think that integration of knowledge from other disciplines or interdisciplinarity has progressed your WP?
8. Did you undertake activities for interdisciplinarity/ integration of scientific information in your WP? (if yes: examples?)
9. What do you consider as the most important factors for enhancing interdisciplinarity or scientific integration in DigiMon? (Table below)

	Mentioned? Y/N	Examples
Common understanding or shared language		
Shared framework that covers the input of different disciplines Interaction between researchers organised?		

Steps in the research process interactively undertaken?		
Researchers are able to think and act beyond their disciplinary background		
Other…		

10. How did the interdisciplinary activities in DigiMon relate to your understanding of inter-disciplinary research?
11. The covid pandemic regulations had a large influence on the work in DigiMon and the inter-disciplinary activities we were able to organize. In the light of this situation, what do you take away from the mainly digital interdisciplinary and knowledge integration process in DigiMon?
12. Are there any other things on interdisciplinarity or scientific integration in your WP that are important to mention?

Attachment 2: questionnaire

This questionnaire has been used at the end of every interdisciplinary event within the Digimon community to capture the experiences, insights and lessons learned of the individual participants.

Digimon

Questionnaire 1 on knowledge integration in Digimon

Introduction to the survey

Dear participant of the Digimon research project,

In the next pages you will find a questionnaire by which we will follow the progress of knowledge integration in Digimon. This monitoring of knowledge integration is part of the activities of WP4 and will provide the overall project management and WP-leaders feedback information on the progress of the integration process during the lifetime of the project.

The questionnaire will take about 5 minutes to fill in. Respondents will stay anonymous.

For more information about the survey, you can contact Adriaan Slob [adriaan.slob@tno.nl] or Marit Sprenkeling [marit.sprenkeling@tno.nl].

Questions to track the data

Explanation

The following questions are used to track the data in time. Respondents stay anonymous, only the questionnaires themselves are coded in order to follow the data! We will ask you to provide the first letter of your father's and mother's name. Together with the year of birth we are able to code the questionnaire.

1. What is the first letter of your father's first name. Please circle one of the letters below

A—B—C—D—E—F—G—H—I—J—K—L—M—N—O—P—Q—R—S—T—U—V—W—X—Y—Z

2. What is the first letter of your mother's first name. Please circle one of the letters below

A—B—C—D—E—F—G—H—I—J—K—L—M—N—O—P—Q—R—S—T—U—V—W—X—Y—Z

3. What is your month of birth? (1-12)

General control questions

4. Broadly defined, I consider myself a

- Natural scientist
- Social scientist

5. What is your disciplinary background? Please tick one category: choose the disciplinary category in which you are mostly educated.

- Physical sciences (includes hydrology, physics, earth sciences, chemistry)
- Life sciences (includes biology, genetics, medical sciences)

- ☐ Environmental sciences
- ☐ Engineering
- ☐ Social sciences (includes economics, sociology, political science, psychology)
- ☐ Humanities (includes philosophy, history, arts)
- ☐ Other, please specify

6. How many years of experience do you have in <u>interdisciplinary</u> research projects?

….. year(s)

7. In which work package are you mainly participating? (one answer possible)

- ☐ WP 1 Critical Technology Elements
- ☐ WP 2 Integrating the components
- ☐ WP 3 Design a human centered monitoring system
- ☐ WP 4 Project management

<u>Questions on knowledge integration in Digimon</u>

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8. What are to your opinion the main challenges in the cooperation between different disciplines in Digimon so far?

9. What have you learned from the collaboration with other disciplines in Digimon so far?

10. On a scale from 1 (not useful at all) to 10 (very useful), how would you rate interdisciplinary event? Please elaborate why

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

11. To what extent do you agree or disagree with the following statements?

		strongly disagree	somewhat disagree	not sure	somewhat agree	strongly agree
a	The meeting offered a balanced and comprehensive mix of interests					
b	The location was convenient for me					
c	The overall programme was suitable					
d	There was not enough time for discussion					
e	I felt comfortable during the meeting					
f	The other participants were willing to listen to my contributions					
g	The meeting helped me to get to know the other participants better					
h	The meeting helped me to learn about the project					
i	The meeting helped me to share my views and opinions with others					
j	The meeting helped me to structure my own thoughts					
k	This meeting helped me to learn from other disciplines					
l	This meeting has improved my understanding of other disciplines					
m	This meeting has improved my appreciation of other disciplines					

12. Has this meeting helped you to gain new knowledge and insights? If so, how would you describe these?

Thank you for filling out this questionnaire!