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On the Organisation of Translation—An Inter- and Transdisciplinary Approach to Developing Design Options for CO_2 Storage Monitoring Systems

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Abstract: Interdisciplinary and transdisciplinary collaboration has become a common practice in technology development projects. Rarely, however, the integration (and translation) of knowledge from different disciplines and different societal contexts is reported in detail. In this article, we address this gap and present the inter- and transdisciplinary technology development in the international research project "DigiMon—Digital Monitoring of CO_2 Storage Projects" that aims to develop a human-centered monitoring system. Based on interviews, surveys and stakeholder workshops in Norway, Greece, Germany and The Netherlands, we identify characteristics of CO_2 storage monitoring systems that reflect the concerns and expectations of publics and stakeholders. We document the translation of social scientific findings into technical expertise for the design of a monitoring system. We discuss how the interdisciplinary and transdisciplinary process has affected the technology development. In outlining how this process was set up, carried out and validated, we are able to show a viable route for the meaningful incorporation of heterogeneous knowledge in complex energy infrastructures. Furthermore, we discuss the features of the project organization that made this comprehensive process possible. Thus, our results contribute to inter- and transdisciplinary research organization in general and to the development of methods for monitoring CO_2 storage in particular.

Keywords: carbon capture and storage; CCS; CO_2 storage monitoring; interdisciplinary research; transdisciplinary research

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1. Introduction

Interdisciplinary and transdisciplinary collaboration has become a common practice in technology development projects. It is increasingly acknowledged that the incorporation of knowledge from multiple scientific disciplines, stakeholders and publics can help to improve the technology development and make it fairer, accessible and focused on real-world problems [1]. This can refer to interdisciplinary research that builds on the integration of two or more disciplines, or to transdisciplinary approaches. Here, transdisciplinary research is considered as a "research strategy that not only crosses disciplinary boundaries but also enables problems to be framed and solved together with stakeholders from outside the world of academic research" [2]. This inclusion of different perspectives, ideally in all phases of the research process, takes time and requires numerous translation efforts [3]. These translations can refer to several dimensions, actors and constellations: non-experts and experts, experts in different fields and disciplines, knowledge into technology or actual language differences in international projects. Although it is clear that such translations require "different sorts of displacements and transformations" [4], this process and the heuristics guiding it are rarely explored in studies on transdisciplinary technology development, e.g., [5,6].

In this article, we provide a detailed report of the inter- and transdisciplinary translation processes in the international research project "DigiMon—Digital Monitoring of CO_2 Storage Projects". The permanent storage of CO_2 in the subsurface is widely discussed as an option for climate change mitigation and as a crucial technology component for achieving temperature targets, e.g., [7]. CO_2 capture and storage (CCS) "refers to a set of technical solutions to remove CO_2 from industrial processes and to inject it into the subsurface in order to isolate the CO_2 from the atmosphere" [8]. In order to ensure that the sequestered CO_2 is securely stored underground it is necessary to monitor the storage reservoirs, e.g., [9]. The DigiMon project aims to develop options for affordable, flexible, digital and human centered monitoring systems for CO_2 storage sites. It composes of three work packages with distinct disciplinary backgrounds and tasks (see Figure 1).

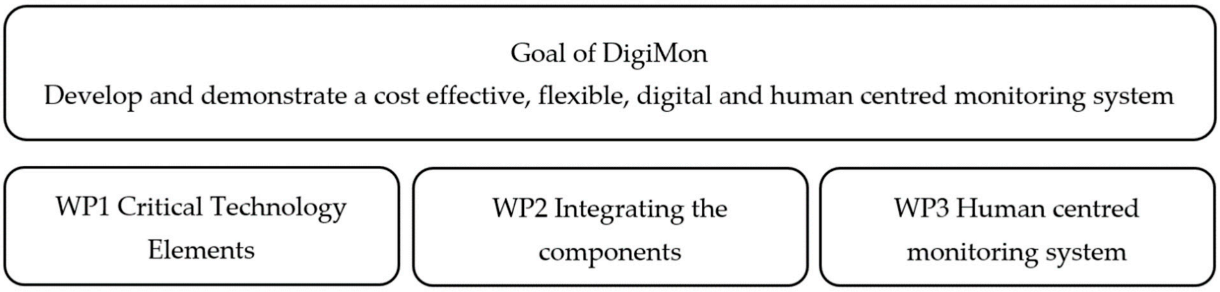

Figure 1. DigiMon work packages and research organization.

The overall objective of WP1 is to develop and improve the technology readiness level (TRL) of component parts for CO_2 monitoring systems. WP2 studies the combination and optimal integration of monitoring technology to achieve holistic, reliable and cost-efficient system solutions. WP3 is dedicated to the study of perceptions and expectations that publics and stakeholders have towards CCS and CO_2 storage monitoring systems. This research focus and the embeddedness in the project structure of this last work package deviates from other social scientific research on CCS [10,11]. Rather than accompanying a research project with predefined implementation ambitions for particular CCS technology, the goal of WP3 is to provide design options for a human-centered monitoring system, based on societal concerns and perspectives.

By turning to societal requirements of CO_2 storage monitoring systems the project and this article add a novel and highly relevant facet to the social scientific research on CO_2 storage. So far, studies on the public and stakeholder perception of CCS projects have mainly focused on topics such as risk perception, communication and social acceptance see [11–13] for an overview. They have not studied preferences towards CO_2 storage monitoring systems and the influences such systems might have on the perception of CO_2 storage projects. Two notable exceptions are studies by L'Orange Seigo et al. that asked for trust in actors responsible for monitoring [14] and assessed the impact of information on monitoring on the perception of CCS [15]. Interestingly they find that more information on monitoring does not have a reassuring effect but instead results in a heightened perception of risks of CCS.

This article provides a detailed report on the transdisciplinary technology development of a CO_2 storage monitoring system and notes the multiple levels of translation in this process. Based on semi-structured interviews, representative surveys and stakeholder workshops in Norway, Greece, Germany and The Netherlands, we identify characteristics of CO_2 storage monitoring systems that reflect the concerns and expectations of publics and stakeholders. An iterative process of interdisciplinary exchange was used to translate the findings from this mixed-methods approach into design options for CO_2 storage monitoring systems. The resulting design options and trade-offs were presented to stakeholders in Norway, Greece, Germany and The Netherlands for further input and validation.

We draw on the experiences in DigiMon to shed light on two research question: (1) how can translations in an inter- and transdisciplinary research process for technology development be facilitated and organized and (2) what are the design options for human-centered monitoring system for CO_2 storage sites. For this purpose, we provide a detailed report on the gathering of knowledge from stakeholders and publics and interdisciplinary interactions within the DigiMon project. We discuss how this interdisciplinary and transdisciplinary process has affected the technology development. Furthermore, we highlight characteristics of the project design (e.g., interlinked but autonomous social scientific work package, social scientific and technological research developed in parallel) that enabled this thorough research process.

In doing so, we not only contribute to a better understanding of translation processes in inter- and transdisciplinary research, but also add a crucial puzzle piece to the study of CO_2 storage perception by exploring the relevance of monitoring systems and proposing design options that reflect public and stakeholder concerns.

2. Materials and Methods

In order to collect sufficient data to understand the perception and concerns of publics and stakeholders about CCS and to identify their expectations towards monitoring systems we used a mixed-method, multi-scalar research design. First, we outline the cases under investigation in the four involved countries. Second, we summarize how the perception of CCS and CO_2 storage monitoring was assessed. The third sub-chapter describes how the translation of the social scientific findings into design options for a CO_2 storage monitoring system was organized in an inter- and transdisciplinary process.

2.1. Case Description

The social scientific work of DigiMon focuses on four national cases: Norway, The Netherlands, Germany and Greece. These four countries were selected since they contrast in various aspects regarding CCS and CO_2 storage monitoring (see Table 1).

In **Norway** the first full-scale CCS project was realized in 1996 by the Sleipner project in the North Sea. From the start the developments in CCS were closely connected to the oil and gas industry. In 2008 Snøhvit in the Barents Sea started injecting CO_2 from the gas extraction process into the Tubåen Formation [16]. In terms of R&D, a carbon capture research facility, Test Centre Mongstad, was established in 2012. Carbon capture technologies have also been used by the livestock and the feedstock industry. In 2020, the Norwegian government launched the Longship project, the first full-scale CCS project based on industrial emitters outside of the oil and gas sector with a flexible transport and storage solution with the aim to develop a European market for permanent underground storage of CO_2 in the North Sea.

In **The Netherlands** CO_2 has been injected in oil and gas reservoirs to increase the yield of the reservoirs since the 1970's. The first project on a global scale to reinject and store CO_2 into the same reservoir from which it originated has been taking place in the K12-B field in the North Sea since 2004 [17]. In addition, the OCAP CCUS project captures CO_2 from industrial plants in Rotterdam, and transports it to greenhouses in the Westland, Lansingerland and Delfgauw [18]. Although full chain rollout of CCS in The Netherlands was envisioned for 2025 [19], most demonstration projects were delayed or cancelled [20], due to regulatory and financial uncertainty and lack of public acceptance. Cancelled projects include Barendrecht, ROAD, Groningen and Athos, the latter being cancelled during the implementation of this study [21]. Currently the first full chain Dutch CCS project is being developed to store ~37 Mton CO_2 in 15 years, commencing operation in

2024. CO_2 from nearby industrial plants will be transported by collective pipelines through the Rotterdam port area, pressurized in a compression station, transported by an offshore pipeline to a platform in the North Sea, ~20 km off the coast and finally injected and stored in depleted gas reservoirs. Aramis, another Dutch CCS project, plans to provide infrastructure for CO_2 transport to unlock offshore storage capacity. It will include onshore CO_2 capture and transport to an offshore storage hub via ships and onshore pipelines [22].

Table 1. Country-specific 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 CO_2 storage and enhanced gas recovery (K12-B)	Successful scientific onshore pilot project (Ketzin), discontinued energy industry projects linking CCS and coal	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) under construction	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 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 recently)	Hamburg (CO_2 transport), previous storage sites (Ketzin, Beeskow)	None

CCS technologies have been studied in **Germany** for about 20 years. The geological storage capacities were assessed in 2003 [23] and Europe's first large-scale onshore CO_2 storage research project was initiated one year later in Ketzin [24]. In subsequent years, larger industrial projects run by energy producers followed. These were aimed at the onshore storage of CO_2 captured at fossil fuel power plants (mostly lignite) and faced strong public opposition and funding problems, e.g., [25]. Eventually, this led to the discontinuation of the projects. Since then, initiatives for CCS in the fossil fuel power sector have not been renewed and due to a law introduced in 2012 the geological storage of CO_2 in Germany—onshore and offshore—is banned [26]. In recent years, discussions on CCS have reluctantly moved towards other fields of application like negative emissions technologies or the handling of residual emissions, e.g., [27,28] and towards the transport of CO_2 captured in Germany to other EU countries (e.g., Norway, The Netherlands) for underground storage in the North Sea [29].

In **Greece** CCS interest commenced and remained strong during the decade 2000–2009 spurred by the interest of the Public Power Corporation (PPC) of Greece to decarbonise its lignite-fired power plants, which at that time accounted for 64 percent of the total electricity production and 30 percent of total CO_2 emissions in Greece [30]. Potential geological storage sites for CO_2 were defined [30–32]. Interest in CCS faded during the following decade 2010–2019, as the political decision was taken to phase out lignite power generation in the country and replace them with renewable energy and less carbon-intensive electricity generation from natural gas. In 2011, CCS was made legally possible, when EU Directive 2009/31/EC on the geological storage of CO_2 was introduced in Greek legislation. CCS interest became evident again in the 2020s when plans for large-scale offshore hydrocarbon exploitation came in the foreground and the TAP gas transmission pipeline to the European market through the country was constructed [33]. Recent developments include the announcement of the first large scale CCS project by ENERGEAN with storage at its offshore depleted hydrocarbon fields, as well as the appointment of the Hellenic Hydrocarbon Resources Management SA (HHRM) as the National Authority for the licensing and monitoring of CCS projects [34].

Taking these contextual differences into account we created a research design that is shared amongst the four countries but still allows for adaptation to the national and local specificities. Therefore, we used a multi-scale approach, which addressed the national (countrywide) and local level in Norway, Germany and The Netherlands. Due to lack of a local case, we only targeted the national level in Greece.

In the local case study for Norway, we focused on the Northern Lights project, which is the transport and storage part of the Longship project [35]. The Northern Lights project is an open-source CO_2 transport and storage infrastructure that in its first phase plans to store CO_2 from the Longship capture sites of Norcem (a cement factory) and Fortum Oslo varme (waste incineration plant). The transport route runs from the two capture sites, both close to Oslo, and along the Norwegian coast to western Norway, where the transmission station is located [36]. We focused the Norwegian local case study on the work region surrounding the transfer site at Kollsnes, Øygarden. This region involves Bergen, the second largest city of Norway.

The Dutch local case study focused on the Porthos and Athos projects. Porthos is a collaboration between the Dutch parties EBN, Gasunie and the Port of Rotterdam, which jointly work towards geological storage in a depleted gas field under the North Sea for CO_2 from industrial plants located in the Rotterdam port area. Athos was an initiative of a steel production plant in the IJmond area and the Dutch parties EBN, Gasunie and the province Noord Holland, in order to geologically store CO_2 emissions from the steel production process. However, as the steel production plant decided to accelerate the transition to sustainable steel production technologies, the Athos initiative did not continue [21].

As there are no ongoing CCS projects in Germany, the site selection is based upon previous onshore CCS sites and potential scenarios, in which CCS could play a role in the future. We focus on the described pre-existing or previously planned onshore CCS sites in Ketzin and Beeskow and on Hamburg as a potential capture, load and transferal site in a European CO_2-storage network with offshore storage in the Norwegian North Sea (The transport of capture CO_2 from Hamburg to storage sites in the North Sea is still hypothetical. Nevertheless, this was chosen as a local case, as it represents the most probable scenario for a role of CCS in Germany under the current regulations since amendments to the London Protocol now theoretically enable bilateral agreements on the international transport of CO_2 for geological storage [37] and CO_2 emitters in Germany (like the steel or cement industry) have expressed interest to export CO_2 to the Norwegian Northern Lights storage project).

2.2. Assessment of CCS and CO_2 Storage Monitoring Perception

For the study of the perception of CCS and CO_2 storage monitoring in the four countries and the local cases in Germany, Norway and The Netherlands, we used a mixed-methods approach combining (1) qualitative interviews and (2) representative surveys for the purpose of additional coverage and cross validation see [38].

1. We conducted semi-structured interviews to gain insights into the perspective of local and national stakeholders on the CO_2 storage projects. The semi-structured interviews enable dialogue with participants and follow whatever angles are deemed important by interviewees, while retaining focus on a particular topic and purpose [39]. The interview protocol (Supplementary Materials S1) is based on the "Societal Embeddedness Level" Framework, which was developed by TNO and tailored to CCS in the DigiMon project and entails the following dimensions: impact on the environment, stakeholder involvement, policy and regulations, market and financial resources [40,41]. The protocol includes questions on how the interviewees perceive the role of CCS in the respective countries, which challenges they see for the development of CCS and how

the interviewees see the relevance of a CO_2 storage monitoring system for addressing these challenges.

The selection of interviewees was based on stakeholder mappings in the four countries and focused on politicians, governmental administration, industry representatives, environmental non-governmental organisations (eNGOs) and scientists. The interviewees either had a direct connection to local cases or were experts with knowledge on CCS or CO_2 storage monitoring that could speak to at least one of the aforementioned dimensions (see overview Table 2). Interviews were conducted online (mostly because of restrictions related to the COVID-19 pandemic) between June and November 2021 and lasted 20 to 90 min. In order to ensure confidentiality and enable an open interview atmosphere the institutions, interviewees and their answers were anonymized in the reports and results. Interviewees gave their consent according to the GDPR rules, either by signing a consent form before or during the interview or by being informed of their rights and giving their consent verbally. Processing and evaluation of the interview material was performed using thematic analysis [42,43].

Table 2. Overview of interview and survey samples.

		Norway		The Netherlands		Germany		Greece
Semi-structured Interviews								
Sample		National and local level, N = 10		National and local level, N = 18		National and local level, N = 15		National level, N = 2
Politics/Governmental authorities		4		8		4		1
Industry representatives		3		3		5		1
NGOs		3		1		3		-
Scientists		-		6		3		-
Surveys								
Survey institute		Kantar AS		I&O Research + Panel Clix		Forsa-Politik-und Sozialforschung GmbH		Metron Analysis
Descriptive statistics (percentage)		**National (N = 1003)**	**Local (N = 400)**	**National (N = 1206)**	**Local (N = 319)**	**National (N = 1001)**	**Local (N = 200)**	**National (N = 1004)**
Gender	*Male*	53.0	51.3	52.9	58.6	53.7	53.6	51.4
	Female	46.0	48.7	47.1	41.1	46.3	46.4	46.9
	non-binary	0	0	0	0.3	0	0	1.7
Age	*18–29*	13.3	8.3	11.7	2.5	9.7	11.6	20.6
	30–39	15.6	20.0	13.4	6.9	10.9	9.2	18.4
	40–49	15.4	15.8	9.1	11.0	18.6	19.3	22.0
	50–64	25.3	28.0	38.7	32.6	29.9	28.5	25.7
	65–79	27.8	24.7	25.5	41.7	27.2	22.7	13.2
	80+	2.6	3.3	1.8	5.3	3.8	8.7	0.1

2. For a comparative assessment on the perception of CCS and especially the monitoring of CCS amongst the general public in The Netherlands, Norway, Germany and Greece, we conducted quantitative surveys. Established survey companies were commissioned to program the online questionnaire, compile the samples and collect the data. Each country aimed for a representative sample of a minimum of 1000 respondents on the national level. The countries with a local case aimed for a minimum of an additional 200 respondents in a coastal area near the off-shore CO_2 storage site or an area with connection to the transhipment and transport of CO_2 to off-shore storage facilities (see Table 2).

To gain insights into the public perception of CO_2 storage projects, we developed an Informed Questionnaire (IQ). An IQ is a suitable method for complex and little-known subjects. In the context of CCS this survey approach has been used before since the knowledge of CCS was repeatedly shown to be limited amongst general publics, e.g., [44–46]. This questionnaire (see Supplementary Materials S2) provided respondents with a base level of information, enabling them to reach an informed opinion on CCS and CO_2 storage and, thus reducing the likelihood of "pseudo-opinions" [44]. The explanations on climate change, global warming, CCS, CO_2 storage and its monitoring were constructed and reviewed by experts. They were included as short text fields in the questionnaire and preceded the questions on the respective topics.

The questionnaire was developed based on previous studies on CCS perception, e.g., [14,46,47] as well as on interviews and literature reviews conducted during the initial phase of the DigiMon project [48]. Since it is the first questionnaire that asks specifically for public attitudes on CO_2 storage monitoring, items concerning this topic were developed in close cooperation with technical experts within the DigiMon project.

The questionnaire consisted of three main parts. The first part of the questionnaire started with an information box on climate change and CO_2 and assessed attitudes on the environment based on a shortened 'new ecological paradigm' scale see [47] and on climate change. The second part focused on CCS and asked for the awareness and knowledge on this technology. Following an introduction box for CCS, CO_2 storage and the societal debate on CCS, participants were asked to state their attitudes towards CO_2 storage. The third part centred on CO_2 storage monitoring and assessed who was seen as a trusted agent responsible for monitoring, monitoring characteristics and if monitoring would affect the perception of CO_2 storage. Socio-demographic information (age, gender, zip code for the place of residence) could be procured from panel data of the survey company.

Before running the survey, the questionnaire was checked for comprehensibility and wording in multiple rounds of interdisciplinary exchange within DigiMon (involving experts from all work packages) and in pre-tests, which were organized by the companies responsible for conducting the online survey. Completing the questionnaire took about 15 min.

2.3. Organisation of Translation

With the aim of developing a human-centred monitoring system, it is necessary to translate the results on CCS and CO_2 monitoring obtained in this mixed-methods, multi-national and cross-scale approach into concrete design options for monitoring technology. For this purpose, we designed an iterative process of inter- and transdisciplinary exchange in Norway, Germany, The Netherlands and Greece (see Figure 2 for an overview).

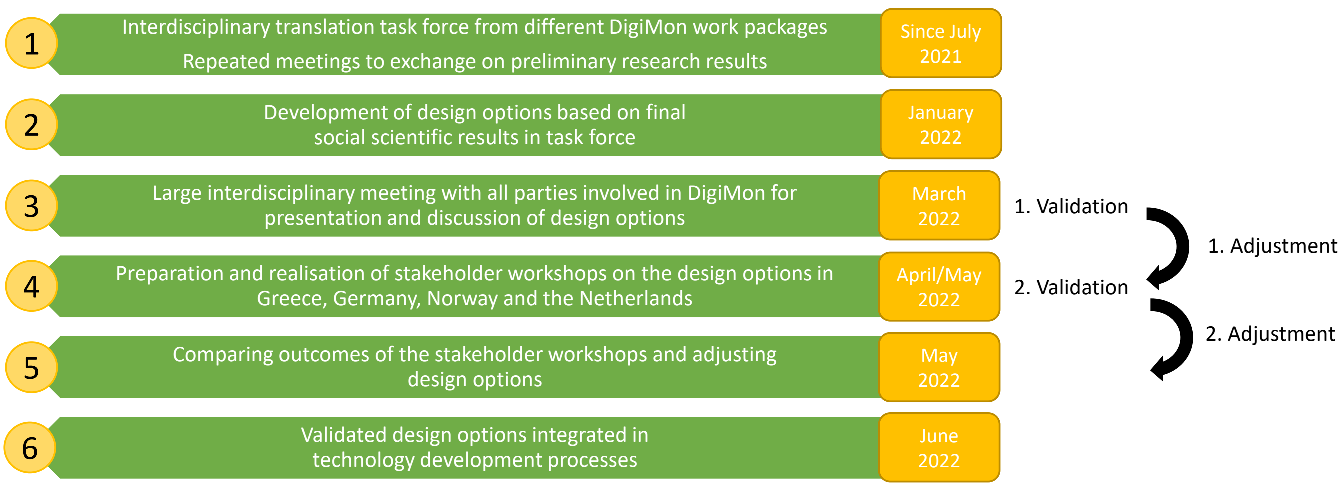

Figure 2. *Overview of inter- and transdisciplinary translation process.*

1. The first and fundamental step in this process was the 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 [40,41].
3. This set of design options was presented and discussed at a large interdisciplinary online workshop with all parties involved in the DigiMon project. This includes a broad range of social, natural and technical scientists working in the project as well as members of the advisory board including industry representatives, scientists from other EU projects on CCS and professional networks on CO_2 storage (e.g., CO_2-GEONET, Global CCS institute). A total of 25 persons participated in this event. It consisted of three short presentations and a longer interactive phase of work in break-out groups. At first the social scientific work package presented the final results of the qualitative and quantitative research on CCS and monitoring perception to the whole group. Secondly, a technical work package provided an overview of the analytical hierarchical process used to incorporate multiple criteria in the monitoring technology development. The third presentation illustrated the first set of design options for a human centred monitoring system. This set of design options was discussed in the break-out groups. Participants were asked to comment on the design options in an online whiteboard tool. These comments were used for a first adjustment to the design options.
4. The adjusted set of design options was presented in online workshops to heterogeneous stakeholders in Norway, Greece, The Netherlands and Germany in order 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. In addition, the invited persons could suggest other persons to be invited to the workshop. This resulted in four national workshops that took place in April and May 2022.
5. While each country team conducted the workshop in their respective national languages, the invitations and presentations were coordinated for comparability between the different countries. During the workshop, participants were introduced to the monitoring technologies studied in the DigiMon project and to the design options that should complement the further technology development. At least one technical expert and one social science expert was present at the meeting for these presentations and to answer questions. After the presentations the participants had the chance to comment on the design options and add more feedback after the workshop session.
6. The outcomes of this second round of validation of the design options were compared across the four country cases. This resulted in a second set of adjusted and validated design options that were used to inform the ongoing monitoring technology development (6).

3. Results

In this section we present the main results of the social scientific research and the translation into CO_2 storage monitoring design options in three steps. Firstly, we focus on the role of monitoring for the perception of CCS and especially on preferred characteristics of a CO_2 storage monitoring system as we found them in our interviews and surveys. In a second step the translation of societally relevant monitoring characteristic into design options is introduced. The third sub-chapter presents the outcomes of the multiple validation and adjustment processes.

3.1. Exploring CCS Perception and Monitoring Preferences

In the interviews and surveys, it became clear that the perception of CCS varied across the four countries, reflecting the previous experiences with CO_2 storage projects and the differences in current CCS project planning (see Section 2.2). Whereas in Norway (successful operational projects) the concerns for negative environmental or societal impacts of CCS were limited, Dutch and Greek, and especially German interviewees voiced concerns about the safety of CCS and its potential impact on climate policies. These differences were also visible in the responses to the survey question: “How concerned are you about the risks of CO_2 storage?” (see Table 3).

Table 3. *Concerns about CO_2 storage and perception of monitoring (percentages, national samples).*

		Norway	The Netherlands	Germany	Greece
		National (N = 1003)	**National (N = 1206)**	**National (N = 1001)**	**National (N = 1004)**
How concerned are you about risks of CO_2 storage?					
	Very concerned	2.0	13.4	19.3	11.1
	Moderately concerned	8.8	21.8	26.6	25.4
	Somewhat concerned	22.4	36.1	31.8	36.0
	Slightly concerned	29.6	16.7	13.4	19.3
	Not concerned at all	24.1	3.8	1.5	2.8
	I don't know	16.1	8.2	7.4	5.5
Do you believe a monitoring system would affect the concerns you have regarding CO_2 storage					
	I am not concerned about CO_2 storage	18.5	8.5	1.5	3.6
	I believe a monitoring system would not affect my concerns about CO_2 storage	16.6	23.5	33.7	13.8
	I believe a monitoring system would limit my concerns about CO_2 storage	49.8	43.4	52.7	62.4
	I believe a monitoring system would increase my concerns about CO_2 storage	0	6.1	5.4	12.3
	I don't know	15.2	18.3	6.6	8.1
I would trust monitoring of a CO_2 storage site to …					
Companies that operate CO_2 capture and storage sites	*Disagree*	32.6	41.1	57.4	28.0
	Neighter nor	18.5	19.6	24.0	27.8
	Agree	42.8	32.6	14.1	42.2
	Don't know	6.1	7.6	4.4	2.0
Government	*Disagree*	16.5	28.4	47.3	42.9
	Neighter nor	14.2	18.4	26.9	24.8
	Agree	64.3	48.3	21.7	30.4
	Don't know	5.0	4.9	4.1	1.8
Scientists	*Disagree*	12.9	7.5	16.2	10.7
	Neighter nor	14.6	12.9	24.6	15.9
	Agree	67.0	75.3	55.8	71.6
	Don't know	5.58	4.2	3.3	1.8
Environmental NGOs	*Disagree*	31.5	23.1	23.3	30.3
	Neighter nor	17.7	16.1	22.2	25.4
	Agree	45.0	56.6	50.6	42.2
	Don't know	5.9	4.3	3.8	2.1

Table 3. *Cont.*

		Norway	The Netherlands	Germany	Greece
A monitoring system should …					
Reliably indicate the movement of the injected CO_2 in the storage site	*not important*	2.1	2.0	1.9	3.2
	neutral	6.7	10.0	6.0	12.0
	important	83.5	83.6	85.1	81.8
	Don't know	7.8	4.4	6.9	3.1
Reliably measure and predict leakages of CO_2	*not important*	1.8	1.4	1.1	3.7
	neutral	5.2	6.1	4.0	9.6
	important	87.3	88.6	88.7	84.2
	Don't know	5.7	4.0	6.1	2.6
Be cheap to install and operate	*not important*	32.7	23.8	24.1	13.8
	neutral	22.4	28.6	29.0	25.8
	important	37.8	41.8	39.0	57.6
	Don't know	7.7	5.8	7.8	2.8
Have a low impact on the environment (e.g., Marine animal life)	*not important*	2.7	1.4	1.2	3.0
	neutral	8.4	7.5	6.1	10.1
	important	82.4	87.1	86.7	84.7
	Don't know	3.6	3.9	5.9	2.3
Include a warning system in case of deviations from the expected values	*not important*	2.0	0.7	1.1	2.8
	neutral	5.2	5.0	4.3	11.2
	important	86.6	90.4	88.6	83.3
	Don't know	6.2	4.0	5.9	2.8
	Total	100.0	100.0	100.0	100.0

The table shows that only 10% of the Norwegian respondents are very or moderately concerned about CO_2 storage, a significantly smaller percentage compared to 35% of Greek and Dutch respondents and 46% of Germans. Besides these differences between the participants in all four countries, we do not find variations between the local and the national level in Norway, The Netherlands and Germany. Based on questions concerning the reason why respondents are concerned about CO_2 storage, we find that safety (e.g., leakages, induced seismicity), political risks (e.g., delaying decarbonisation because of a shift of attention from emission reduction to storage) and uncertainty (e.g., long-term impacts of the storage site) are shared main concerns in all four countries.

In our research, we were interested to learn how a monitoring system for CO_2 storage would relate to these concerns. The results of the semi-structured interviews indicate that monitoring is not on top of the interviewees' minds when talking about CCS. **Norwegian** respondents stress that monitoring is a legal requirement and thus it is in place wherever there are CCS projects, also mentioning that there is extensive experience with the monitoring of offshore CCS activities. Respondents in **The Netherlands** stress that monitoring is an important part of risk management of CCS projects, which is embedded in the regulatory process. Industrial parties stress that there is lot of experience and knowledge about monitoring. In **Germany** as well, monitoring is a not (yet) stated as a central issue in the discussions on CCS. Different monitoring technologies have been tested in previous projects, but the topic of monitoring remains on the side-lines in fundamental discussions about whether or not CCS can actually contribute to limit climate change. Monitoring is mostly seen as an essential regulatory requirement and not as something that could impact public perception. In **Greece**, interviewees state that peoples' trust in the accuracy of the monitoring data depends on the trust in the responsible stakeholder, independent of type (industry, public authorities and scientists).

Taking these interview results and previous literature [15] into consideration, a reassuring effect of CO_2 storage monitoring on the perception of risks related to CO_2 storage cannot be taken for granted and appears to depend on monitoring conditions. The most important conditions mentioned in the interviews in the four countries can be summarised as follows:

- cheap, cost efficient and easy to maintain over a long time
- measure and predict leakages and plume movement
- allowing real-time access to publicly available monitoring data
- reliable access to experts for questions on the data
- external supervision by impartial institutions
- security concept in case of malfunctions

To further study the potential role of monitoring in CO_2 storage perception, we included items on the effects and characteristics of monitoring systems in the survey. We found that a significant share of respondents in all countries believe a monitoring system would limit their concerns about CO_2 storage (Table 3). While the proportion of those who say they are not concerned about CO_2 storage varies widely between Norway (19%) and Germany (1.7%), more than 50% of respondents in these countries believe that a monitoring system would reduce their concerns. This share is slightly lower in The Netherlands (44%) and markedly higher in Greece (62%). We found that about one third of the German respondents expect no effects of a monitoring system on their concerns about CO_2 storage. Less respondents selected this category in the other countries.

In the Greek case, those who believe that a monitoring system would not affect their concerns (14%) is surprisingly about as large as the share of those who believe that a monitoring system would increase their concerns (12%). None of the respondents in Norway selected this category and the share of people who believe that a monitoring system could increase their concerns for CO_2 storage is significantly lower in The Netherlands (6%) and in Germany (5%). It is also notable that the percentage of respondents who stated that they did not know if a monitoring system would affect their concerns, is larger in Norway (15%) and The Netherlands (18%) compared to Greece (8%) and Germany (7%).

Since the interviews indicated that the effects of monitoring on CO_2 storage risk perception would depend on monitoring conditions, we asked the survey respondents to rate several characteristics of a monitoring system (see Table 3). Concerning the importance of technical requirements, we find that reliably measuring and predicting leakages of CO_2, reliably indicating the movement of the injected CO_2 in the storage site, including a warning system in case of deviations from the expected values and having a low impact in the environment are rated as important by more than 80% of the respondents in all countries. The costs of installation and operation were significantly less important compared to the other characteristics. About 40% of Dutch, German and Norwegian respondents and 58 percent of Greek respondents consider installation and operation costs an important factor.

As responsibility for storage site monitoring was discussed during the qualitative interviews and in previous literature [14], we asked the respondents to state to which extent they would trust the monitoring to different actors (see Table 3). We find large differences between the four countries. Whereas a majority of the respondents in all countries would trust the monitoring of a CO_2 storage site to scientists (ranging from 75% in The Netherlands to 56% in Germany), there are major variations for the other actors. More than 64% of the Norwegian respondents trust the government to monitor the CO_2 storage site. Only 22% in Germany and 30% in Greece share this assessment. Companies that operate the storage site are perceived as trust-worthy monitoring operators in Norway (43%) and Greece (42%), while they are seen more sceptically in The Netherlands (33%) and especially in Germany (14%). The trust in monitoring by environmental NGOs is higher in The Netherlands (57%) and Germany (51%) compared to Norway (45%) and Greece (42%).

Since public participation has been discussed as a means for building trust in CCS projects, e.g., [49,50], we wanted to know how the respondents would rate the participation of experts or publics in the monitoring. We asked if they would favour public or expert involvement in defining what is monitoring, how the monitoring is done and who operates the monitoring. Again, we find differences between the countries. The Greek and Dutch respondents tend to leave these tasks mainly to experts, with only about 20% choosing the equal division of responsibility between publics and experts as an option. In Norway, this tendency is even stronger and only about 15% chose the equal division between publics and experts as ideal. In Germany, expert responsibility is also the majorities' choice but the wish for equal distribution of involvement is more pronounced with up to 44% selecting this option. Overall, these results indicate that most of the respondents would leave decisions on monitoring systems to experts, but there is considerable interest for publics to have some form of participation.

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

- Based on the survey results there is a strong argument for the external and independent supervision of the monitoring by actors that are considered trustworthy.
- There is strong evidence for the importance of the connection of monitoring to a warning system and a security concept in case of unexpected monitoring 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 leaned 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 rather small compared to the overall CCS deployment costs).

Since we find variations between the four countries on the importance of some of these characteristics, they need to be adapted and balanced according to particular local project contexts.

3.2. Translation into Design Options

With these characteristics for a monitoring system, the social scientific work package (WP3) entered regular exchange with the technical scientific work package responsible for data processing and component integration (WP2), in order to understand the technical possibilities and connect them to societal requirements. In order to structure the development of design options, we turned back to the Societal Embeddedness Level Framework [40,41] and sorted the characteristics according to the dimensions: Environment, Stakeholder involvement, Policy and Regulations, Market and Resources. Multiple design options and trade-offs were developed for each of these dimensions. 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. This approach does not aim to design a one-size-fits-all monitoring system, but it outlines design options to support the context-specific development of monitoring solutions based on comprehensive social and technical scientific research. Figure 3 shows an overview of the design options and trade-offs per dimension.

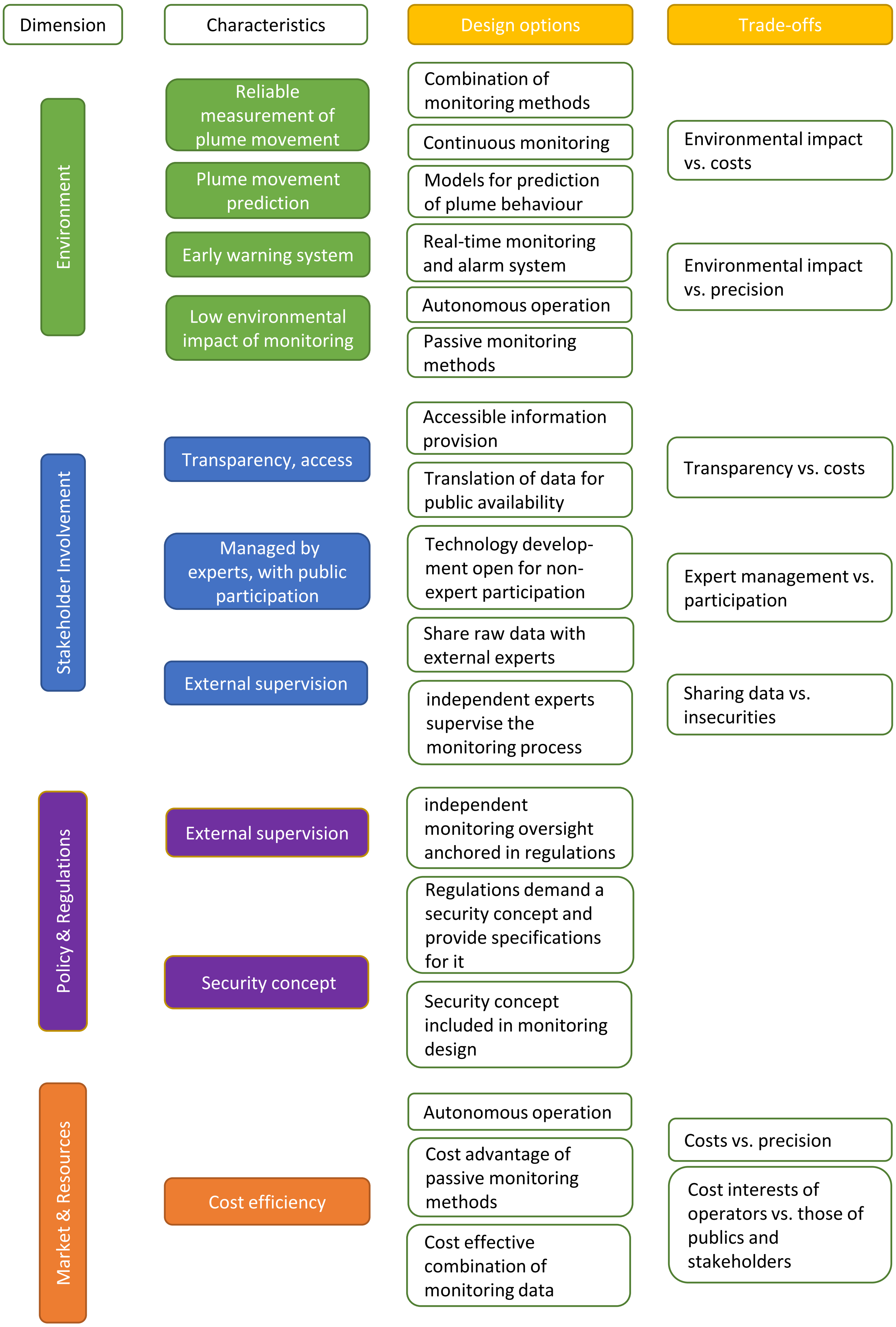

Figure 3. *Overview of design options and trade-offs.*

For the **environmental dimension**, which addresses the impacts on natural and social environments, the following favourable monitoring system characteristics were identified in the interdisciplinary exchange: reliable measurement of and prediction of plume movement, existence of an early warning system and low environmental impact of monitoring. In order to ensure reliable measurements of the plume movement and gain a more encompassing understanding of its behaviour, a combination of different monitoring methods is suggested (e.g., distributed acoustic sensing, hydrophones, pressure sensors, seafloor deformation sensing or microgravity sensing) to counter-balance disadvantages of individual methods. Continuous monitoring—in contrast to monitoring based on individual measurements in time intervals—enables the detection of unexpected and rapid changes in reservoirs and is thus better adapted for reliable measurement and plume movement prediction. Additionally, models calibrated by well data and geophysical monitoring can strengthen efforts for plume movement prediction. The societal expectations towards an early warning system can be met by combining continuous monitoring with an "alarm system" that warns of unexpected measurements. Such a system would need to be communicated carefully to publics and stakeholders in order to underline the long-time dimension of "early warning" regarding CO_2 storage and avoid pictures of sudden gas eruptions. The low environmental impact of monitoring could be achieved by focusing on autonomous operation and passive monitoring methods that reduce the requirement of survey vessel use and the impact of seismic surveys on animal life. We see two trade-offs in connection to these design options between environmental impacts and (1) costs and (2) measurement precision. Further research is required on the synergies between low environmental impacts and reduced monitoring costs arising from passive and autonomous monitoring.

The rationale behind the environmental impacts and precision trade-off is that those methods that could provide the most precise measurements (like constant geophysical monitoring with survey vessels) would have higher environmental impacts. Thus, it is necessary to strike a balance between these factors.

Concerning **stakeholder involvement**, we find transparency of monitoring processes and access to monitoring data, expert management with openness for public participation and external supervision to be highly relevant factors for the perception of monitoring solutions. These criteria can be met by emphasising accessible information provision, meaning information that is comprehensible for non-experts, work with adequate visualizations and initiatives for public interaction like visitors' centres. These aspects are beyond the purely technical scope of monitoring but should be factored in when designing monitoring solutions, particularly regarding communication efforts, long-term costs, required personnel. The survey results show that publics would rather leave the responsibility of setting up and operating the CO_2 storage monitoring systems to experts, but it also indicates that some non-experts would like to be able to access such expert guided processes. In consequence, the design of a monitoring system should take this into account by systematically evaluating if, where and how options for public participation in the technology development and operation are feasible. External supervision is an important factor for the trust in CO_2 storage monitoring. It could be facilitated by including a plan for raw data sharing with independent experts in the monitoring design and opening up monitoring processes for independent oversight. The regulatory requirements for CCS projects demand data sharing with government officials in fixed term. Going beyond these legal requirements could increase the confidence in the monitoring process. In the survey and the interviews, it became apparent that trust in actors to monitor CO_2 storage sites, varies according to national contexts and interests of stakeholders. Therefore, independent experts should be selected with potentially conflicting interests in mind. Trade-offs in this dimension concern: (1) the costs for transparency, since the additional efforts to achieve this transparent monitoring processes will require resources and time, (2) striking a balance between expert management and public participation as moves towards more participatory modes of designing and operating monitoring can be assumed as more time consuming, and (3) general data sharing needs to be evaluated in light of insecurities connected to it, for instance the misuse or misinterpretation of the data.

The aspect of external supervision is directly connected to the **policy and regulations** dimension that frames the concrete technological design of monitoring solutions. To adhere to the societal expectations towards CO_2 storage monitoring it can be recommended to embed the requirement of independent monitoring oversight and the need for a specified security concept more comprehensively in regulations. The actual operational outline of a security concept in case of unexpected value detection should be included in the monitoring system design.

In the final dimension, **market and resources**, the primary characteristic that is important for stakeholders and to a lesser degree for publics is cost efficiency. This can be achieved by the autonomous operation of the system and passive monitoring with permanently installed cables and system components—both leading to less need for survey vessels and human resources. Emphasizing passive monitoring methods (e.g., distributed acoustic sensing or microgravity sensing) can have a cost advantage compared to hydrophone usage. A highly relevant design option is the combination of different data types to allow for flexible balancing of monitoring needs and costs. There are multiple trade-offs related to market and resources, such as between costs and environmental impact of monitoring or costs and transparency, which have been already addressed in other dimensions. Additionally, the different interest of publics (higher interest precision and safety compared to costs) and industrial stakeholders (interest in cost efficiency and safety) should be taken into account when designing a monitoring system since the most precise and secure option might not be the most cost effective for the particular deployment setting.

3.3. Validation of Translations

Stakeholder's workshops were conducted, in order to validate the design specifications developed by the DigiMon project. Since the stakeholder workshops were conducted separately for each country, they also provide country specific preferences for CO_2 storage monitoring configurations.

In all workshops, the qualitative and quantitative results of the DigiMon project on the perception of CCS, CO_2 storage and the monitoring of CO_2 storage met with general agreement among the stakeholders. Likewise, the outlined features of a monitoring system and the translated design options and trade-offs were welcomed and perceived as an opportunity for innovation. In the following, we outline the country specific feedback.

CO_2 storage *monitoring in general and assumptions on its impact on public and stakeholder perception* were a central talking point in the four workshops. In **Norway**, the monitoring of CO_2 storage sites is seen as an important issue to ensure transparency early in the planning and deployment process. Whether monitoring and data sharing will in themselves ensure public support is questionable to the stakeholders. Thus, it was pointed out that it is important to ask what added value there is in developing monitoring systems that go beyond what is already required by law. In the **Dutch** workshop, it was highlighted that the purpose of monitoring is twofold: preventing CO_2 migration and leakage by ensuring that the stored CO_2 behaves as expected and modelled. The participants expressed that it is necessary to strike a balance for the amount of monitoring measures, meaning to find monitoring solutions that either fit regulatory requirements (license to operate) or additionally aim at public acceptance (social license to operate). Likewise, multiple **German** participants state that monitoring should not only be done for its own sake but with a clear goal in mind, be it complying with regulations or taking public and stakeholder concerns into account. However, it became clear that the monitoring of CO_2 storage sites is not a major concern for CCS and CO_2 storage in Germany as political and regulatory barriers are the most pressing issues to consider for the stakeholders involved. The **Greek** workshop concluded that the goal of monitoring should be the reliable measurement of plume movement and ensuring transparency.

The *technical design specifications of monitoring solutions* were not addressed in all countries beyond the acknowledgement of the usefulness of the presented design options. The **Norwegian** workshop participants had no questions concerning the technologies. In the **Dutch** workshop the participants discussed the challenges of monitoring plume movement in depleted gas fields. It was noted that some monitoring technologies (e.g., distributed acoustic sensing, gravimetry) pose a challenge for this setting and proposed to distinguish requirements for depleted gas fields and saline aquifers. Furthermore, Dutch participants indicated the need to differentiate between plume movement monitoring and leakage detection as each would require different technologies. At the **German** workshop, participants confirmed that the presented options and trade-offs reflected many important points, requested clarification on potential "malfunctions" concerning monitoring, and noted that the "real-time" monitoring should be described as "almost real-time". In **Greece**, reliable measurement of plume movement and its projection through reservoir modelling for early warning purposes are essential features for CO_2 storage monitoring. Precision is seen as a priority. A safety and contingency plan should be prepared at each stage of the project and reviewed regularly.

Participants discussed *environmental impacts* related to monitoring in **The Netherlands** and **Greece**. In the Dutch workshop, the potential impacts of monitoring technology on life under sea was seen as an issue that needs to be considered when designing a monitoring system, especially in relation to environmental protection regulations. Greek participants stressed that the trade-off between environmental impacts and costs must be taken into account in order to avoid public and political opposition if the impact on nature is not taken sufficiently into account for financial reasons. As far as the trade-off between environmental impact and precision is concerned, precision measurements are the top priority.

The *costs of monitoring* were not a central talking point in the **German** workshop, but were a point of contestation in the other events. While the survey presented the cost of monitoring as significantly less important than other factors, stakeholders at the **Norwegian** workshop noted that the monitoring costs might be small compared to the general costs of CCS but once costs are borne by the state, they take on a political dimension and are likely to become important to stakeholders and the publics. **Dutch** participants approached the topic of costs from another angle and argued that although there must be a balance with the extent to which monitoring contributes to risk management, potentially high costs for monitoring are legitimated by the high societal costs of CCS and the necessity to verify that the CO_2 stays underground and the technology is safe. In **Greece**, cost efficiency is seen as a matter of political planning. There must be a weighting of the cost of any subsidy for such projects with the resulting profit from the reduction of the cost of pollutants to the government or the specific industry. The relationship between costs and precision should be governed by the margin of error accepted in the international literature and practice. Concerning the cost interests of operators vs. those of the public and stakeholders, local communities should share the general benefits and enjoy some compensatory local benefits.

Data sharing, transparency and participation are recurring themes in all workshops. **Norwegian** participants acknowledged the importance of data sharing and transparency. It was noted that the goal of monitoring is transparency and that this trumps all other concerns. This comment referred to the design options for monitoring, emphasising that the design options that maximise transparency are the most important. It was discussed whether and how much effort should be put into communication and participation when there is limited public interest. In **The Netherlands**, stakeholders noted that data sharing should be possible and that an "information bulletin" with interpreted data and the purpose of the data sampling would be a promising approach. However, sharing data comes with the risk of unintended data interpretations or misuses. Furthermore, participants advice to consider the enormous amount of data generated by a CO_2 storage monitoring system and highlight the challenges of data management and the provision of public data access. Similar to the Dutch debates, the **German** participants discussed the translation of the data and the risks of unmediated access to raw data. Reflecting on the design options for stakeholder participation it was stressed that the sharing of raw data risks misconceptions and that an interpretation of the data (e.g., by experts) would be necessary. Otherwise, the aim for transparency could increase uncertainties instead of creating trust in the monitoring process. Participants in the **Greek** workshop emphasized the importance of transparency and perceive accessible information provision as an important parameter for public communication. Data should only be shared with external experts under certain conditions and with appropriate legal safeguards; data management provisions should be included in the relevant regulations. The trade-off between expert management and participation is important because there must always be a reason for non-expert participation in a project, so that it does not become a source of problems rather than a solution.

Finally, comments concerned *trust and independent supervision* of the monitoring process. Most of these discussions revolved around the question of who could be a trustworthy independent party and how external oversight could be established. **Norwegian** participants agreed with the survey's finding that the public has great trust in governments as responsible actors for monitoring and monitoring oversight. Some of them questioned the ability and biases of environmental organization for such activities. Participants in **The Netherlands** discussed that governments could establish rules for independent monitoring standards, set and controlled by independent certifiers. Another option is to have the monitoring process and/or results validated by a third party, e.g., a knowledge institute. In **Germany,** independent or State-owned scientific institutes, such as the Federal Institute for Geosciences and Natural Resources, were favoured as supervising actors. The participants (including eNGOs) were sceptical if environmental organizations, while trusted by the public, could provide sound supervision of the monitoring process. The **Greek** participants argued that monitoring should be carried out by a management committee composed of experts in cooperation with the representation of local communities. External monitoring should only be used if the managing authority does not have the necessary competences. Independent monitoring oversight could be assigned conditionally, either to a project-related research foundation, institute, or institutional advisor of the state or a certified consulting firm.

4. Discussion

In this study, we set out to give a detailed report on the transdisciplinary process that was used to establish design options for a human-centred monitoring system for geological CO_2 storage sites. The main contribution of this article is to provide a portfolio of empirically based design options for a CO_2 storage monitoring system that takes societal concerns into account. This is an innovation, as this aspect of CCS has not been systematically studied before. It resonates and adds to the previous studies of factors for CCS perception such as trust, e.g., [51–53] or communication [15,54,55] and it will be relevant for the prominent discussions to come on carbon dioxide removal, e.g., [56,57]. Additionally, the article details the organization of transdisciplinary technology research on a highly specialized topic. This allows other projects to build upon and critically evaluate the process used in DigiMon.

4.1. Design Options for a Monitoring System

The list of design options that have been developed for a human-centred monitoring system can be taken as a tentative starting point for monitoring specifications. As previous technical research, e.g., [58] and our social scientific results indicate, it is necessary to adapt CO_2 storage monitoring systems to the environmental and societal contexts of the respective sites. We were able to identify relevant design options for monitoring systems in four different dimensions (environmental, stakeholder involvement, policy & regulations, market & resources). While all these design options were relevant in the four national and three local case studies we analysed, we also found differences that highlight the societal importance of context specific monitoring solutions. A prominent example of these differences is the trust of survey participants in the actors responsible for monitoring CO_2

storage sites. Based on our results, a monitoring solution that relies on governmental actors for independent oversight might be a favourable solution for Norway but meet scepticism in Germany. Likewise, a monitoring system emphasizing cost-effectiveness might suit the monitoring operators but lead to conflicts with publics who valued precision, transparency and the low environmental impact of monitoring higher than costs. As these examples indicate, it will be necessary to balance trade-offs. There are some design options, like the combination of different data types for monitoring or the emphasis on passive and autonomous monitoring technologies that found agreement amongst stakeholders and publics in all four countries and that have been indicated as favourable in the literature, e.g., [59]. Still, these need to be adapted to the local environmental and societal contexts and linked to suitable stakeholder engagement, policy and regulations. The validated list of design options provided in this article can serve as a guide of relevant monitoring characteristics that can be checked and adapted to the particular contexts of CO_2 storage projects. A promising approach for future research would be to study the role and design of monitoring systems in other contexts and countries to learn more about the variability of monitoring preferences. For now, the main policy implications of our study are that monitoring matters for the perception of CO_2 storage sites and that efforts for a context specific monitoring design should be considered in project planning.

4.2. Interdisciplinary and Transdisciplinary Research Methodologies

The DigiMon project followed an inter- and transdisciplinary approach to the development of a CO_2 storage monitoring system in order to develop solutions with societal concerns in mind. This goal was achieved by an iterative process of exchange across scientific disciplines and with non-scientific stakeholders. The problems, goals and potential solutions for monitoring were explored from multiple perspectives and heterogeneous knowledge was considered to introduce new criteria of assessment apart from scientific quality. This aligns well with prominent requirements for transdisciplinarity [60].

Several impacts of the inter- and transdisciplinary work became apparent in the DigiMon project. The frequent interaction amongst different disciplines involved in CO_2 storage monitoring and stakeholders introduced new ideas and concepts to the technology development and assessment. The social-scientific work was much enhanced by the collaboration with technical experts that, for instance, allowed the translation of highly specialized technical concepts into accessible information for other disciplines and especially the design of the informed questionnaire. Vice versa, the social scientific work with publics and stakeholders confronted the ongoing technology development with criteria that had not been assessed before. One example for this is the environmental impact of the monitoring system, which was included based on the survey and interview results and is now integrated in the analytical hierarchy process, e.g., [61,62] used in one of the technical work packages to evaluate different monitoring solutions. This close transdisciplinary collaboration has been beneficial for achieving the goal of designing a human-centred monitoring system. This time consuming process was enabled by the research organisation within the project that emphasized independent social scientific research connected to CCS *during* and not at the end of the technology development see [10]. In this structure, meaningful exchange and impact on the technology design and assessment was possible.

4.3. Limitations

The transdisciplinary process would have been strengthened by more interactive workshop concepts, which were initially planned, but not possible because of the COVID-19 pandemic. Local stakeholders and experts have been consulted through in-depth semi structured interviews to gain insight into their perspective about how CO_2 storage monitoring technologies could enhance the societal embeddedness of CO_2 storage projects. In person stakeholder workshops were not possible and the online equivalents, while easier to organize, did not always reach the same level of interaction that was expected based on live workshop experience. A more intensive transdisciplinary research process can be arranged in the future, potentially in a living-lab structure where experts, local stakeholders and the public are more engaged in the project. Methodologically this study is also limited by minor variations in the method application in the four different countries. These variations, for instance the slightly different sampling methods of survey companies, need to be taken into account when interpreting the results. Furthermore, the focus of DigiMon lies on monitoring of CO_2 plume movement. However, as the societal part of the project showed, stakeholders wonder if a full monitoring system shouldn't also monitor for small leakages (e.g., by using plant growth as an indicator).

5. Conclusions

Based on the analysis of public and stakeholder perception of CO_2 storage monitoring this article outlined design options for concrete human-centred monitoring solutions. Transdisciplinary research and intensive, long-term interdisciplinary exchange enabled a multifaceted study of requirements for and impacts of monitoring systems at CO_2 storage sites. The acquired results promise to be highly relevant for practitioners (e.g., operators of storage sites) as well as for technical and social scientists. Practitioners and technical experts might be most interested in the validated list of design options that this article provides and the clear outcome that there is no one-size fits all solution for monitoring—neither in the technical set up nor concerning societal requirements. The design options can serve as a general guideline that needs to be adapted to environmental, societal and technical contexts. For this purpose, the design options and trade-offs can help to facilitate discussions and development processes. For social scientists and technical scientists alike, the detailed report on the organisation of the transdisciplinary research process shows one way to deal with the multiple translations necessary to come to shared understandings and to mutually increase the research outcomes. The findings of this study underscore the usefulness and necessity of independent social scientific research on climate-relevant technologies such as CCS.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en15155678/s1, S1: Interview protocol; S2: Informed questionnaire.

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