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Article

Understanding Societal Requirements of CCS Projects: Application of the Societal Embeddedness Level Assessment Methodology in Four National Case Studies

Dimitrios Mendrinos [1,*], Spyridon Karytsas [1], Olympia Polyzou [1], Constantine Karytsas [1], Åsta Dyrnes Nordø [2], Kirsti Midttømme [2], Danny Otto [3], Matthias Gross [3], Marit Sprenkeling [4], Ruben Peuchen [4], Tara Geerdink [4] and Hanneke Puts [4]

1 Centre for Renewable Energy Sources and Saving—CRES, 19009 Pikermi, Greece
2 Norwegian Research Centre—NORCE, 5838 Bergen, Norway
3 Helmholtz Centre for Environmental Research—UFZ, 04318 Leipzig, Germany
4 Netherlands Organisation for Applied Scientific Research—TNO, 2595 DA The Hague, The Netherlands
* Correspondence: dmendrin@cres.gr

Abstract: The DigiMon project aims to develop and demonstrate an affordable, flexible, societally embedded, and smart digital monitoring early warning system for any subsurface CO_2 storage field. The societal embeddedness level (SEL) assessment is a novel methodology which provides insight into the societal requirements for technological innovation to be deployed. The SEL assessment framework was applied in four case studies, concerning CCS development in Norway, the Netherlands, Greece, and Germany. The resulting societal embeddedness levels of CCS, on a scale of 1–4, were SEL 3 in Norway with considerable progress towards level 4, followed by the Netherlands with SEL 2 with several initiatives towards offshore demonstration projects, and then by Greece and Germany with SEL 1. The outcomes of the SEL assessments show which societal requirements have been met in current CCS developments and which ones should be improved for CCS deployment. They also show that monitoring currently is a regulatory requirement as part of permitting procedures, while it may alleviate community concerns on safety, provided that it has certain attributes. The insights from the four national case studies are further used in the DigiMon project to develop the innovative societal embedded DigiMon monitoring system.

Keywords: societal embeddedness; societal requirements; DigiMon; subsurface monitoring; SEL; public acceptance; CCS

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1. Introduction

The DigiMon project, "Digital monitoring of CO_2 storage projects" [1,2], aims to develop and demonstrate a societal embedded, smart, affordable, flexible, and socially acceptable early warning measuring system for monitoring any CO_2 geological storage project. It covers both CO_2 plumes in reservoirs and caprock integrity. It integrates a broad range of technologies for subsurface monitoring, such as distributed fibre-optic sensing (DxS), seismic point sensors, and gravimetry, combined with Ethernet-based digital communication and near-real-time, web-based smart data processing.

In parallel, DigiMon uniquely considers the possibilities of monitoring technologies for carbon capture and storage (CCS) from the point of view of societal embeddedness by identifying which societal requirements are important from the perspectives of the general public and of other key stakeholders for the development of CCS projects and their corresponding monitoring system. Such a monitoring system is desired by the CCS, the geothermal, and other industries exploiting subsurface resources, as an instrument to alleviate safety concerns of social partners, stakeholders, and local societies.

DigiMon is supported by the ACT international initiative http://www.act-ccs.eu/about-us (accessed on 15 May 2022). The DigiMon project is implemented by an international and interdisciplinary consortium of leading research institutes and industry representatives from Norway, the Netherlands, Germany, the United Kingdom, the United States, Romania, and Greece as follows:

- NORCE, Norway (coordinator);
- NTNU, Norway;
- OCTIO ENVIRONMENTAL MONITORING AS, Norway;
- Centre for Renewable Energy Source and Saving, Greece;
- SEDONA Development, Romania;
- Helmholtz-Centre for Environmental Research UFZ, Germany;
- University of Bristol, UK;
- University of Oxford, UK;
- TNO, Netherlands;
- Geotomographie GmbH, Germany;
- Lawrence Livermore National Laboratory, USA;
- Silixa Ltd., UK;
- EQUINOR ASA, Norway;
- REPSOL NORGE AS, Norway.

Although various readiness tools are available, they primarily address technological aspects [3]. The TRL, the most prevalent tool, has its limitations, including failing to take maturity setbacks into account; putting too much emphasis on product development, rather than on focusing on changes related to manufacturing, commercial, and organization aspects; failing to adapt the scale to certain purposes; and focusing on a single technology [4]. Moreover, other readiness level tools are also available, such as the market readiness level (MRL) [5] and the demand readiness level (DRL) [6], but they do not properly address societal issues.

Although attempts have been made to handle diverse aspects of what can be called "societal readiness," this concept is even more recent and less developed than TRL and MRL. However, there are a handful of studies that examine these issues. For example, Kobos et al. [7], by expanding the TRL tool, developed the regulatory readiness level (RRL) to consider the regulations impacting the commercialization of innovative technology. Moreover, Viks et al. [8], focusing on the assessment of new agricultural technologies, developed the balanced readiness level (BRL) which complemented the TRL with market, regulatory, acceptance, and organizational-readiness levels. Holden [9], working on innovations for a sustainable circular bioeconomy, proposed a method integrating life cycle thinking with frameworks for technology, innovation, and societal-readiness levels.

In any case, it is undeniable that the research on readiness level tools is unbalanced, with the large body of research being available on TRL [8]. On the other hand, there is limited work available on readiness evaluations for social challenges posed by new technology. However, the emergence of new technologies can bring about both expected and unexpected positive and negative outcomes [10]. Hence, it is clear that both technical and societal aspects of emerging technologies must be considered. Based on this, the societal embeddedness level (SEL) methodology puts a special emphasis on the societal elements that are essential for the advancement of technological innovation.

The SEL assessment is an interdisciplinary novel methodology, developed by TNO in late 2020 for technological innovations that impact the environment, which provides insight into the societal requirements for the development and deployment of technological innovation [11]. To create a comprehensive methodology that integrates technological, environmental, social, economic, policy, and regulatory aspects, the SEL methodology expands upon the TRL and incorporates elements from other readiness level tools such as the market readiness level [12] and systems readiness level [13]. The SEL method complements the technology readiness level (TRL) scale, summarized in Table 1, which provides a measure of the development maturity of new technology from initial idea to market introduction [14].

Table 1. Technology readiness levels (TRL).

TRL 1	Basic Principles Observed
TRL 2	Technology concept formulated
TRL 3	Experimental proof of concept
TRL 4	Technology validated in laboratory
TRL 5	Technology validated in relevant environment
TRL 6	Technology demonstrated in relevant environment
TRL 7	System prototype demonstrated in operational environment
TRL 8	System complete and qualified
TRL 9	System proven in operational environment

Source: [15].

The SEL methodology was created by TNO through the study of pertinent, already-existing readiness level methodologies, consultation with numerous innovation experts with multidisciplinary expertise, and execution of a case study in the energy sector (i.e., solar parks) [16] to further test the SEL methodology. The SEL approach was created by applying technology from the energy sector, but it may also be used in other sectors [3]. The method was tailored to CCS by an interdisciplinary team of DigiMon partners within the DigiMon project [3]. A detailed description of the SEL methodology is provided in Sprenkeling et al. [17].

The main objective of this research is to analyse the societal embeddedness level (SEL) for CCS at the national level in four countries: Norway, the Netherlands, Germany, and Greece [18], through:

- Literature review;
- Interviews with CCS experts.

Other objectives of the national assessments are:

- Identify the main challenges towards further improvement in the SEL for CCS in each country;
- Identify main focus areas for a societal embedded CCS monitoring system, the DigiMon system;
- Provide feedback on the SEL methodology implemented;
- Review CCS context and its future perspectives in each one of the four countries studied.

2. Materials and Methods

The SEL methodology distinguishes four societal dimensions and four levels of societal embeddedness. SEL societal dimensions are (1) environment, (2) stakeholder involvement, (3) policy and regulations, and (4) market and financial Resources. Each dimension corresponds to a set of identified nontechnological barriers that have hindered the implementation of CCS, geothermal, and other innovative technologies from entering the market. These barriers are adverse environmental impacts, such as induced microseismicity, emissions of gas pollutants, etc. (SEL dimension environment); public resistance (SEL dimension stakeholder involvement); lack of political support and regulatory uncertainty (SEL dimension policy and regulations); market conditions, such as the absence of a local market, intense competition, etc.; and rising costs and limited availability of financial resources (SEL dimension market and financial resources).

The four societal embeddedness levels are SEL 1 Exploration, SEL 2 Development, SEL 3 Demonstration, and SEL 4 Deployment. SEL 1 concerns the exploration of the possible impact of the innovation concept on each SEL dimension. SEL 2 reflects the assessment of the impact of the technology on each SEL dimension. SEL 3 concerns the integration of societal needs into designing the technology and its system. Finally, SEL 4 corresponds to technology and its system fully meeting all essential societal requirements.

In each dimension, the four societal embeddedness levels are characterized each by a set of milestones, the fulfilment of all of which is necessary for the achievement of the corresponding level. The fulfilment of each milestone is determined by answering a set of questions allocated in each milestone. Finally, based on the SEL values per dimension, an overall SEL value is identified as the minimum value of all 4 dimensions (Equation (1)).

$$SEL_{overall} = \min\left(SEL_{env}, SEL_{sta}, SEL_{pol}, SEL_{mar}\right) \quad (1)$$

where

$env = environment$

$sta = stakeholder\ involvement$

$pol = policy\ and\ regulations$

$mar = market\ and\ financial\ resources$

An overview of the SEL methodology is presented in Table 2. The SEL is assessed for each one of its dimensions, starting from the SEL that corresponds to the average TRL for CCS development at the project, local, or national level. For each dimension, the so-called societal embeddedness level is identified, varying from SEL 1 to SEL 4.

Table 2. Overview of the SEL methodology framework. It comprises 4 levels and 4 dimensions. For each pair of SEL and dimension, a set of milestones and questions have been defined. The SEL in each dimension is evaluated by answering these questions and deciding which milestones have been achieved. The last line of the table presents the desired matching between SEL and TRL [3].

Societal Embeddedness Level:	**SEL 1 Exploration**	**SEL 2 Development**	**SEL 3 Demonstration**	**SEL 4 Deployment**
SEL Dimension Environment Stakeholder Involvement Policy and Regulations Market and Financial Resources	exploration of the possible impact of the CCS concept	assessment of the CCS technology impact	integration of societal needs into designing the CCS technology and its system	CCS technology and its system fully meet all essential societal requirements
Matching TRL:	1–3	4–6	7–8	9

Based on the contextualization of CCS for each country the societal embeddedness level (SEL) was evaluated using the above methodology. The assessment was performed by combining the results of desk research based on a literature review and insights from interviews with CCS experts. In Norway, the evaluation of the SEL was based on one particular project demonstrating the full value chain from capture to storage, while in the other three countries, the assessment concerned general CCS developments at the national level, based on previously tested CCS technology chains or current CCS developments.

As the DigiMon project concerns the development of an integrated monitoring system for CO_2 geological storage fields, the SEL methodology channels (literature review and experts' interviews) were also used to identify the desired features of such a monitoring system corresponding to its dimensions, e.g., in terms of environmental requirements, stakeholder needs, needs of supervising authorities, market needs, and costs.

The SEL assessment was conducted in 11 steps, as follows:

1. A SEL reference point was determined, which corresponds to the expected SEL, based on the current TRL; see Table 1.

2. Desk research was carried out by gathering information about the topics mentioned in the Introduction section above. The following approach was adopted for the desk research:

- Google Scholar was used as a search engine;
- Websites of ministries were searched;
- Partner internal documents were used;
- Reference lists of publications and snowball searching were used.

The search words considered were “CO_2 Storage”, “carbon (capture) storage + country”, and “CCS + country”, also adding dimensions “policy and regulations”, “Market and Resources”, “Environmental” and/or “Stakeholder involvement”. The search terms were adapted to the specific circumstances of each country. A maximum of 20 articles were selected per country based on the following criteria listed in order of priority: reports, published/reviewed articles, white papers, and recent publications. Conference abstracts were excluded from the study.

3. The national CCS context was drafted. It included historical experiences with CC(U)S, latest developments at the political level including discussion on onshore and/or offshore projects, financial and political support, regulations and legislative framework, general public opinion, what provisions have been considered for CCS monitoring, type and number of actual CC(U)S projects (capture, transport, and/or storage), and description of CC(U)S applications. Local cases are mentioned as examples.

4. The SEL assessment was conducted based on literature reviews. Questions and milestones outlined in the SEL assessment framework, as described in [3], were used to guide the desk research. If required, questions and milestones were adapted in a country-specific manner.

5. Additional questions concerning monitoring were asked for all SEL dimensions to facilitate the next step of local SEL assessments. They included:

- Environment: In what way (how) is the impact on the environment monitored? Additionally, what are the requirements for environmental monitoring?
- Stakeholder involvement: How does (or: could) monitoring affect the stakeholder attitude towards CCS? How can monitoring contribute to reducing societal concerns? Is there any experience with participatory monitoring?
- Policy and regulations: What is the position of monitoring in the current regulatory framework?
- Market and financial resources: How does the monitoring of CCS affect the financial circumstances and market position? (i.e., more expensive; more funding opportunities)

6. Knowledge gaps were identified if it was not possible to answer questions based on the desk research. The additional information needed was specified.

7. An interview protocol was set up to gain the information needed to finish the SEL assessment. For this purpose, milestones were turned into questions, or questions behind milestones were used when additional information beyond the milestones was needed. Additional questions were asked concerning prospective developments of CCS in the country.

8. CCS experts were invited for interviews on specific topics regarding CCS to collect additional information regarding the identified knowledge gaps. The combination of desk study and the interviews led to the identification of the SEL for each dimension. Based on this, the overall SEL was derived as well as related societal challenges. The interdisciplinarity needed for the assessment was organized by selecting experts with different backgrounds and expertise in each of the four dimensions with different scientific or professional backgrounds.

9. The main challenges for further improving societal embeddedness of CCS in each country were analysed based on the SEL assessment results.

10. Based on the findings in the SEL framework and the context, a forecast of future developments (social and technology) was attempted, using the supporting policies/subsidies that are available in each country. This scenario was drafted on the national level and then the most likely developments and implications at the local level were added.

11. Finally, methodological challenges that were encountered during the SEL assessment were highlighted, together with dimensions or subjects that could not be addressed, including justification. The application of the SEL assessment at the national level was evaluated. Improvements were suggested when needed.

Limitations

The starting point for an SEL assessment is an estimation of the current technology readiness level (TRL) for CCS at the national level. However, such an estimate is ambiguous, due to the broad CCS concept consisting of different technologies in each phase of the CCS chain (capture, transport, and storage), the dependence of TRL on individual technologies considered, and the international nature of technology research and development. A complex technological system such as CCS can include multiple components with different TRLs and it is hard to assess an overall TRL.

Some of the research questions for assessing the milestones in each of the SEL dimensions were open to multiple interpretations. This could have consequences for the comparability of the results in the four country studies.

In Greece, the accuracy of the SEL assessment is bound by the limited availability of literature for the desk research, as only 15 relevant papers and reports were identified in total, all of which were used in the assessment. Furthermore, there was limited availability of CCS experts due to the little experience with CCS developments in the country. In Greece, no projects have been implemented yet, and there were no CCS activities during the last 10 years.

3. Results

3.1. SEL Assessment

A summary of the outcomes of the SEL assessments for the four national case studies in Greece, the Netherlands, Germany, and Norway is shown in Figure 1. This Figure shows the outcomes per SEL dimension in each country.

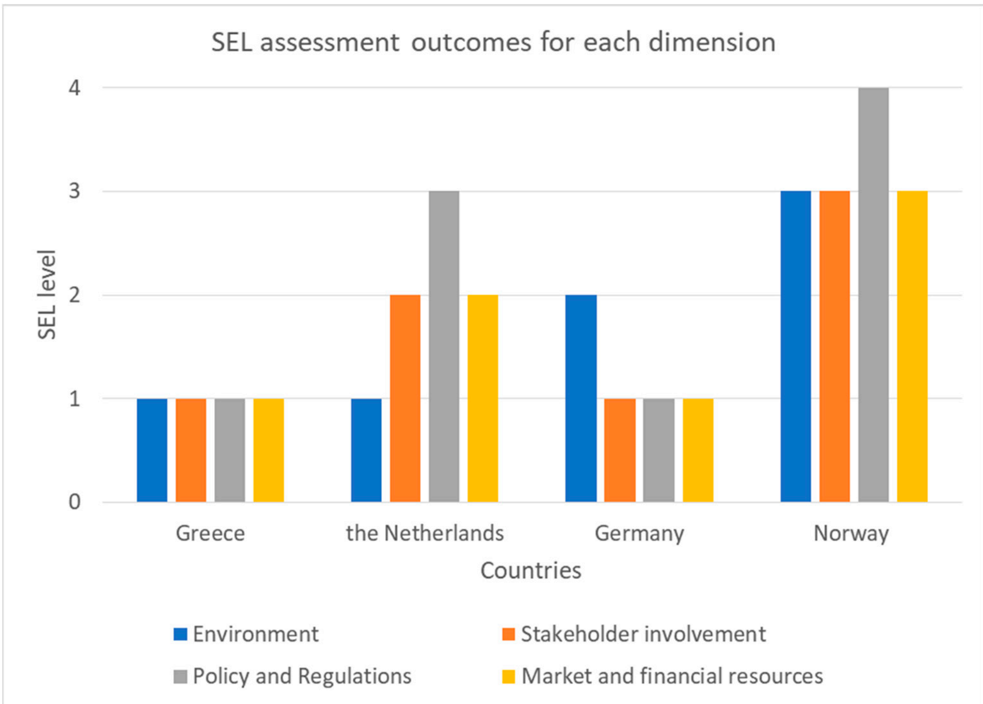

Figure 1. Outcomes of the Social Embeddedness Level (SEL) Assessment in Greece, the Netherlands, Germany, and Norway per SEL dimension.

Figure 1 shows each one of the four countries assessed and the societal embeddedness level of each dimension. The SEL per dimension is set by the extent to which the milestones corresponding to each level have been reached or not. Only if all milestones of the SEL have been reached, is the SEL achieved. Furthermore, no overall SEL is visualized in Figure 1. For example, in the Dutch case study, for the first dimension "impact on the environment", nearly all milestones within the second SEL have been met; nevertheless, the SEL for this dimension has been set to SEL 1 in Figure 1.

As mentioned in previous sections, the SEL assessment started with identifying the current TRL for CCS per country.

- In Greece, where no demonstration or lab experiments concerning CCS have taken place [19], the TRL was set to 2—technology concept formulated, which corresponds to a starting SEL of 1, as shown in Table 2.
- In the Netherlands, over the last few decades, several research and/or industry projects have been developed in every phase of the CCS chain, namely capture, transport, and storage, and contributed to technical-oriented improvements for CCS deployment [20–22]. Furthermore, in two industrial areas in the Netherlands, new CCS initiatives are in development to capture, transport, and store CO_2 from industrial processes for which there are currently no sustainable alternatives, such as oil refineries and the chemical sector. Nevertheless, there are currently no full demonstration projects in which capture, transport, and storage are integrated into one CCS initiative [23–25]. Therefore, the TRL for CCS in the Netherlands was set to 5—technology validated in a relevant environment, which corresponds to a starting SEL of 2 (see Table 2).
- The TRL for Germany was set to 6 (technology demonstrated in relevant environment) because the first large-scale onshore CO_2 storage project was in operation from 2004 to 2013 at Ketzin, located 70 km west of Berlin. The Ketzin project combined oxyfuel capture at a brown-coal power plant, truck transport, and storage in saline aquifers [26,27] and encountered no notable public opposition [28,29], which also corresponds to a starting SEL of 2 according to Table 2.
- In Norway, which is the leading country in CCS technology with more than one demonstration project already in operation [30–34], the TRL was set to 7, the matching SEL of which for starting the assessment is 3; see Table 2.

The reasoning behind this first step in the SEL assessment is that each TRL is matched to a certain SEL. Table 2 presents the connection between the TRL system and the SELs, as introduced in the SEL Guideline [3]. Based on the current TRL, the corresponding SEL reference point could be determined, as a starting point for getting insight into the societal aspects that should be developed in close connection to the techno-economic developments toward CCS deployment.

The SEL assessment was carried out by answering the questions corresponding to the milestones associated with the SELs for each dimension, starting from the SEL reference point mentioned above. The results are summarised in Figure 1.

In Norway, where CCS has been on the agenda for more than 30 years, SEL is at level 3 in the environmental dimension (for both natural and social environment) in complete alignment with the SEL reference point, while dimensions of stakeholders' involvement and market and financial resources are more advanced and dimension on policy and regulations has reached the maximum level of complete support towards CCS, which corresponds to the SEL reference point for full CCS deployment.

In the Netherlands, the market and financial resources dimensions are at SEL 2, in alignment with its reference point, while the environmental (both natural and social environment) dimension is nearly there (at SEL 2). The stakeholders' involvement dimension is also at SEL 2, although has advanced midway towards the next level. The policy and regulations one is also at SEL 3, ready for the forthcoming offshore demonstration projects. In the case that the CCS industry proceeds towards demonstration in the country, attention should be paid to improving the environmental, market, and financial resources, and the stakeholders' involvement dimensions to the next level 3, which is the corresponding SEL reference point for demonstration.

In both the Netherlands and Norway, the CCS driver has been the hydrocarbon industry, with continuing interest in the technology. New CCS demonstration projects are underway, all of them offshore, as onshore CO_2 transport and geological storage facilities face strong public opposition.

In Greece, where CCS has been on the agenda for around 20 years now, the CCS driver has been the coal-fired power generation industry. However, as the national policy has shifted toward abolishing coal-fired power plants soon, CCS interest stopped. During the implementation of this research (the year 2021), the SEL was evaluated as slightly less than 2 for the environmental dimension, but much less than 1, below the SEL reference level in all other dimensions. The advancement of the environmental dimension is probably attributed to the experience the power company gained from the renewable power generation sector. Further CCS development in the country towards pilot demonstration, which has an SEL reference point of 2, should therefore be accompanied by efforts to improve SEL in these dimensions (stakeholders' participation, legal and regulatory frameworks, and market and financial resources). The first step toward this direction was evident in early 2022 when Hellenic Hydrocarbon Resources Management S.A. (HHRM S.A.) was appointed by law 4920/2022 as the competent authority for the licensing and monitoring of carbon (CO_2) storage (CCS) projects.

Similar to Greece, the capture and storage of emissions from coal-fired power plants were the main drivers for the development of CCS in Germany. A scientific pilot project operated successfully for several years. However, follow-up projects in the power industry faced strong public opposition. As a consequence of these protests, funding problems, and the looming coal phase-out, the political and industrial interest in CCS diminished. New regulations that limited and, from 2017, banned new CCS projects in Germany led to further complications driving back SEL in the corresponding dimension, also dragging the market and financial resources dimension behind. As a result, despite the CCS technological development in the country, the reference SEL 2 has only been exceeded in the environmental dimension and almost reached in the stakeholders' participation dimension, but in the policy and regulations and the market and financial resources dimensions, the SEL has dropped far below the reference point, even below level 1 (due to new legislation forbidding CCS projects and the resulting withdrawal of market interest of developers). This implies that, if in the future, the legal status changes and CCS will proceed to the demonstration phase in the country, a lot of attention should be paid to these two SEL dimensions.

Comparing the estimated TRLs with the outcomes of the SEL assessments per country, Table 3 shows to which extent each country meets the SEL corresponding to the estimated TRL. Note that in the case of the Netherlands, Equation (1) was deliberately not followed, as it was only one milestone out of the many that were not reached which caused the SEL for the environmental dimension to be 1 instead of 2.

Table 3. Comparison between the estimated TRL for CCS and the outcomes of the SEL assessment per country.

	Greece	**Netherlands**	**Germany**	**Norway**
TRL (estimated)	2	5	6	7
SEL (outcome assessment)	1	nearly 2	1	3
Comparison SEL-TRL link	in line	nearly in line	not in line	in line

3.2. Findings Related to Monitoring

SEL research was accompanied by research towards identifying the stakeholders' preferences for a CO_2 geological-storage-monitoring system, the development of which is the main objective of the DigiMon project. According to the literature review that was carried out, such a monitoring system is a legal obligation in the EU member states considered (SEL dimension on policy and regulations), and it was found that under conditions, it may alleviate stakeholders' concerns on safety (SEL dimension on stakeholder involvement) while also affecting the costs of CO_2 storage (SEL dimension on market and financial resources).

Monitoring can help to estimate storage efficiency, provide information on the CO_2 plume location, movement, and pressure in the subsurface and its evolution over time. Methods include (i) 4D (time-lapse 3D) seismic monitoring of the reservoir to image subsurface CO_2 movements, as well as (ii) monitoring wellhead pressure and flowrate plus temperature and stress to depth within the injection well. Experience from Sleipner and Snøhvit CO_2 storage sites in saline aquifers with time-lapse 3D seismic monitoring provided confidence in the technology to detect any major CO_2 leakages into the overlying cap rock. New technologies used are distributed acoustic sensing (DAS). Monitoring is perceived as an important safety measure helping to control CO_2.

There are several methods to monitor the storage of CO_2, ranging from relatively affordable to very expensive monitoring technologies. In addition, monitoring costs can be reduced by reusing the existing infrastructure of offshore oil and gas production facilities. Currently, there are no extra funding opportunities associated with more extensive monitoring.

In the Northern Lights project in Norway, public funding for monitoring has not been provided, other than a provision after the project end due to lack of CO_2 supply. Therefore, monitoring always adds to the costs of CCS. However, the extensiveness of the monitoring will depend on the risk profile of the CCS site. The higher the risk profile, the higher the monitoring costs will be. Based on current legislation, the expenses of monitoring can have a significant impact on the additional costs of a CCS project. When a market party has to cover the additional expenses for monitoring, as well as the provisions for covering unknown risks, the actual costs for CO_2 storage can be higher. Furthermore, due to the lacking regulations about the transfer of liability, the financial risks regarding long-term monitoring are high.

Regulations are in place at the national, EU, and international levels. The project owner must control the CO_2 distribution in the reservoir, detect possible leakages below the surface (seabed or ground surface), and take the necessary corrective measures. Legislation mainly focuses on aquifer CO_2 storage and has no provisions for storage in depleted gas fields. Although monitoring is compulsory and its results should be shared with the authorities, there are no specifications, clear standards, duration, and safety criteria in place.

Previous research shows that the general public is concerned about CO_2 leakages. Therefore, CCS monitoring should increase public support for CCS developments, although there is no study available yet about the influence of monitoring on the social acceptance of CCS. Regarding the DigiMon project, an important research question, therefore, is how a low-cost, innovative monitoring system—the DigiMon system—could contribute to better embedding CCS projects in the societal context. In addition, there is a lack of experience with the participation of external stakeholders in CCS monitoring. Public opinion surveys, however, identified a general belief that monitoring alleviates safety concerns and that it is perceived positively among the general public.

In Germany, monitoring is not seen as a key instrument to overcoming the CCS barriers. It is not perceived as a potential measure that could primarily increase social acceptance and trust but as a simple regulatory requirement. Some of the experts that were interviewed even argued that too much emphasis on monitoring may increase doubts and endanger distrust towards the safety of projects. This aspect is also in line with literature—see for instance L'Orange Seigo et al. [35].

If monitoring should play a role in trust-building and outreach activities, it should have the following characteristics:

- Be cheap, efficient, and easy to maintain over a long time;
- Measure and predict leakages and plume movement;
- Be transparent and allow real-time access to monitoring data;
- Provide reliable access to experts for questions on the data continuously, not just at outreach events;
- Be externally supervised by impartial institutions;
- Be connected to a safety concept that states what happens when the data divert from normality.

In the Netherlands, the topic of (participatory) monitoring becomes more and more important related to the safety of geo-energy projects. Gas production in the Groningen gas field and the corresponding seismic events as a consequence of gas extraction decreased the trust of local communities in the operating company as well as the supervising authorities; local entrepreneurs started developing low-cost monitoring sensors to increase the local involvement in monitoring activities and safety management strategies. Currently, with the seismic events in the Groningen area in mind, geothermal developments are also facing many questions from local communities regarding the safety of the foreseen geothermal project related to seismicity. As part of the European research project ENOS (enabling onshore CO_2 storage), the topic of monitoring CO_2 storage activities has also been discussed with a focus group of citizens in the Rotterdam area (the Netherlands). These citizens were given a general introduction to CCS monitoring and how CCS monitoring is part of Dutch legislation for CO_2 storage (Mining Act). The citizens concluded that CCS-monitoring experts seem to have sufficient knowledge to recognize and manage the technical and geological risks as well as to design an appropriate monitoring program to reduce the identified risks. Their concern was mostly with the operational risks of a project. How is the monitoring program executed and how are monitoring data used to improve the operations of a project? In a second meeting about monitoring with this group, the value of participatory monitoring was explored. The main research question in this meeting was if the citizens thought that an approach for participatory monitoring could be a way of including citizens' questions, concerns, and perspectives into the strategy for developing a new CO_2 storage project. The citizens emphasized that their interest to be involved in the design and implementation of a monitoring program would increase when trust in the operators and/or authorities is low. When trust in the operators and/or authorities is not an issue, they had less interest to become involved. They would, however, like to have more insight into what happens with the collected monitoring data. Who decides whether more or less CO_2 is injected, or that a project is being cancelled? These questions are connected to the use of data during the operation of a CO_2 storage project.

4. Discussion: Societal Challenges for CCS Development

The outcomes of the national societal embeddedness assessments give insight into the main societal challenges for continuing CCS developments in the four countries: Germany, Greece, the Netherlands, and Norway. In this chapter, we will give an overview of the main challenges, based on the national SEL assessments, for improving the societal embeddedness of CCS developments. In essence, Figure 1 provides guidance for which societal aspects should be integrated into the ongoing CCS development, to have a smooth acceptance (initially) and adoption (finally) of CCS by the local and national community.

In Norway, the complete societal embeddedness of CCS, and thus for the SEL to reach 4 in all its dimensions, needs development of a CO_2 market, securing unanimous support or consent for CCS by all stakeholders, and mitigating all environmental impacts in the entire CCS value chain. The latter awaits the commencement of operations at the Longship project, which will provide a complete experience from a full-scale integrated CCS demonstration. Concerning policy and regulations, a framework providing full support for CCS commercial operation has already been put in place, as indicated by the SEL 4 shown in Figure 1.

In the Netherlands, as TRL is progressing towards demonstration, reaching SEL 3 is the objective in the short run. SEL 3 has already been achieved by the current policy and regulations framework, as shown in Figure 1. Societal-embeddedness efforts should, therefore, focus on the other three SEL dimensions. Concerning the SEL dimension on the environment, where most attention should be given, as is the one behind all others (see Figure 1), the focus should be on assessing the requirements for the social environment. In the market and financial resources dimension, societal aspects need to be introduced. However, a newly introduced subsidy scheme for CCS will raise the SEL for this dimension. Regarding the stakeholders' involvement dimension, efforts should focus on achieving stakeholder participation in discussions of CCS merits towards mitigating climate change and regional development.

To enable CCS in Germany, a reform of the current regulatory framework is needed to lift the ban imposed on new carbon storage projects. This is also expected to drive the market and financial resources dimension upwards. The short-term objective should be to assess market needs and trends, as well as to establish a business case for demonstration and update the research on the societal perception of CCS. Concerning stakeholders' involvement, stakeholders' participation should be sought to take their considerations and concerns into account for future CCS initiatives. De-coupling CCS from coal power generation and stressing the application of CCS for residual industrial emissions or negative emission technologies, such as bioenergy with carbon capture and storage (BECCS) promises to aid this process.

In Greece, further CCS development towards a pilot facility should be accompanied by SEL improvement towards level 2. The short-to-medium-term objectives should be to assess the concrete impact on the physical and social environment, identify interests, attitudes, perceptions, and concerns of stakeholders; assess present policy and regulatory framework in terms of posing barriers and drivers to CCS development; evaluate the possible market impact and financial needs; as well as assess market needs and trends and establish a business case for pilot demonstration.

The insights from the four national case studies and the corresponding overarching analysis have been further used in the DigiMon project to develop the innovative societal-embedded DigiMon monitoring system.

Beyond DigiMon

The experiences with applying the SEL methodology for assessing the societal embeddedness level of CCS developments at the national level provide valuable insights and reflections for further improving the SEL methodology. On the one hand, the insights so far raise new research questions regarding the upscaling of CCS and which role the SEL methodology could play in this upscaling process. On the other hand, the continuous exchange of experiences and perspectives among DigiMon partners also gives insight into new methodological research questions regarding further improving the SEL methodology and accelerating its applicability in new policy domains. It seems valuable to continue this reflection and research to improve the applicability of the SEL methodology, both for CCS developments and also in other policy domains.

Some of these reflective questions are listed below:

- Consider connecting the outcomes of the national SEL assessments to the broader European/global context: Each of the teams is briefly touching on some major change process happening now in Europe or the world: the EU's sustainable finance initiative is encouraging both investors and civil society to demand more transparency and disclosure in a language they understand; CCS is discussed as a key enabler for a European hydrogen industry; environmental justice is particularly pressing in the US right now but Europe continues to struggle to balance climate protection and citizen/workers' rights. The direction of travel is clear: in Europe, there will be an increasing need for monitoring, reporting, and verification of environmental performance as a matter of business success.
- How we talk about CCS: Is it a technology or a supply chain? While a few years back, CCS was designed and construed as a set of three technologies to be demonstrated locally/nationally, new CCS projects are more and more designed as cross-border supply chains, e.g., capture happening in the UK, transport across the North Sea, and storage in Norway. How does this influence the design and applicability of the SEL framework?
- Europe's emerging model of strategic industrial leadership is in the process of a big change: From unempathetic technology development to user-driven development driven by sustainability. What does this imply for Europe's industrial leadership? US and Asia are not there yet. Can the SEL methodology be a key enabler of Eu-

rope's strategic industrial leadership in the emerging industries of hydrogen, batteries, recycling, CO_2 and methane monitoring, biotech, etc.?

- Do you need to research the correlation between SEL and governance systems or technological maturity? Norway, the Netherlands, and Germany all have very decentralized governance systems, in some cases, regions might be stronger than the national/federal government and all three teams struggled to align the SEL framework with their governance systems while the Greek team had less of an issue. Is there merit in testing the SEL framework in a few more "Napoleonic", centralized structures, e.g., France, the UK, etc.? The other reflection was that both Germany and Greece struggled less with the SEL methodology and had the lowest technology maturity. Do lower technological maturity levels offer a better sweet spot for TRL-SEL alignment from the project initiation phase?
- The role of civil society: In NL and DE, Millieudefensie and Deutsche Umwelthilfe can sue you into extinction; this is not the case in Greece or Norway. Is it worth exploring if there is a correlation between the role of civil society and the SEL methodology taken up by industry?
- The share of public vs. private finance in project financing and the role of private investors: Most CCS projects in Europe are publicly funded with private investors playing a minor role for now. Is it worth exploring the relationship between the structure of financing and the SEL take-up by industry? Another reflection is whether it is worth exploring the role of investors in SEL take-up by industry. The Netherlands is home to most of the world's ESF funds and they tend to be very active in setting ESG performance expectations on their portfolio companies. Norway's oil fund is an important institutional investor whose voice cannot be ignored. Is it worth exploring them in a future project?
- Amplification of results and roll-out across sectors: The way the DigiMon project is designed and the application of the SEL methodology represent a first-of-its-kind project attempting to understand the major shift currently underway which is that of taking society in the direction of technology development from the start, ensuring society co-creates instead of being on the receiving end with no agency to influence anything. This novel methodology might be of very high relevance to European innovators. The SEL methodology has the potential to be a game changer; it is extremely important that both Horizon Europe and national/regional budgets keep this line of research funded and used.

5. Conclusions

The SEL assessment for CCS in Norway, the Netherlands, Germany, and Greece established different SEL scores for each country. Based on desk research and expert interviews, we found the highest level in Norway (SEL = 3), followed by the Netherlands (SEL = 2), Germany (SEL = 1), and Greece (SEL = 1). In each country, the SEL also varied among its four dimensions: physical and social environment, stakeholders' involvement, policy and regulations, and market and financial resources.

Although the Norwegian and Dutch teams faced some challenges to set an overall TRL and identify the corresponding SEL reference point, it is interesting that there seems to be alignment between TRL and SEL in both countries, where the main driver for CCS development has been the hydrocarbons industry. In Norway, a full demonstration project is in development (high in TRL), corresponding to high scores for the different SEL dimensions; in the Netherlands, preparations for CO_2 capture and storage projects are being conducted in two geographical areas (mid-range in TRL), corresponding to the outcomes of the SEL assessment. Further SEL advancement is needed towards the next level (3 for the Netherlands and 4 for Norway), to align with an expected TRL increment towards demonstration in the Netherlands and full-scale implementation in Norway. Both countries focus their efforts on the offshore deployment of CCS.

In Germany and Greece, where CCS has been on the agenda for the last 20 years and was mainly driven by the local power industry (which operates lignite-fired power plants), the SEL has remained low. For the Greek case, this is attributed to the strategic political decisions taken towards phasing out lignite power generation, which resulted in not developing a CCS legal framework. Despite successful scientific pilot projects in Germany, CCS connected to coal power plants faced public opposition, funding problems, and political as well as regulatory scrutiny. The latter resulted in a legal barrier to CCS implementation from 2017 onwards. If CCS returns as a national objective in Greece or Germany, this time potentially driven by other actors and goals (e.g., hydrocarbon industry, residual emissions from industrial processes), SEL advancement is needed to correspond with expected TRL development towards pilot (Greece) or demonstration plants (Germany). New insights on the societal challenges and barriers provided by the SEL could guide the setup of new CCS projects and, in the German case, help to avoid problems previous projects faced.

The SEL methodology can also be applied in other policy domains in different research projects, including geothermal [36–38], where a significant number of projects have been abandoned or never started due to an adverse impact on the local environment, public opposition, legal barriers, lack of financing, or lack of support from key stakeholders.

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