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Market Potential of Nanoremediation in Europe – Market Drivers and Interventions Identified in a Deliberative Scenario Approach

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Abstract

A deliberate expert-based scenario approach is applied to better understand the likely determinants of the evolution of the market for nanoparticles use in remediation in Europe until 2025. An initial set of factors had been obtained from a literature review and was complemented by a workshop and key-informant interviews. In further expert engaging formats – focus groups, workshops, conferences, surveys – this initial set of factors was condensed and engaged experts scored the factors regarding their importance for being likely to influence the market development. An interaction matrix was obtained identifying the factors being most active in shaping the market development in Europe by 2025, namely "Science-Policy-Interface" and "Validated information on nanoparticle application potential". Based on these, potential future states were determined and development of factors discussed. Conclusions are offered on achievable interventions to enhance nanoremediation deployment.

1 Introduction

Globally, technologies have been developed to remediate contamination in soils and groundwater. However, the cost and challenge associated with the treatment of groundwater in site-specific soil-sediment-water systems on the one hand and the increasing awareness or emergence of so far unknown contaminants call for a continued improvement and innovation in remediation technologies. Such innovations – in particular when compared to established state-of-the-art practices – offer opportunities but also can pose threads that determine the actual market penetration potential.

Nano-particles (NPs) based/enhanced remediation approaches, so-called nanoremediation, are a recent example of such an innovative technology. Different NPs – with a dimensions of less than 100nm (cf. Rauscher et al. 2014) – have been tested and developed to support reduction, oxidation, sorption or a combination of these processes as *in situ* treatment of contaminated groundwater and soil. The first documented field trial of nZVI, in 2000, involved treatment of trichloroethylene in groundwater at a manufacturing site in Trenton, New Jersey, USA (Elliott & Zhang 2001). Several commentators anticipated that nZVI technology would take off rapidly because of its perceived benefits, such as rapid and apparent complete contaminant degradation. In 2007, a European report forecasted that the 2010 world market for environmental nanotechnologies would be around six billion US-Dollars (Rickerby & Morrison 2007). However, the uptake of the technology has been relatively slow compared to other contemporary process based technologies.

Bardos *et al.* (2011) identified just 58 projects documented worldwide at pilot or full scale. The use of nZVI in remediation practice was largely a niche application for chlorinated solvents in aquifers, competing with more established techniques such as *in situ* bioremediation, chemical reduction and granular ZVI (e.g. in permeable reactive barriers). The limited adoption of nZVI was linked to cost uncertainty of the technology considering the unclear balance of benefits versus risks of NP use in remediation and a lack of well documented / validated field scale deployments. Whereas advocates emphasize the promising possibilities offered by the unique characteristics of NPs for extending the range of available *in situ* remediation technologies, offering particular benefits in certain applications (O'Carroll *et al*. 2013, Bardos *et al*. 2011), critiques raise concerns related to cost uncertainty and due to insecurity related to behaviour, fate and toxicity of NPs: Some disputants point out unforeseen contamination, potentially caused by the release of NPs to the environment – a notable dread that might cause reluctance also amongst regulators (Bardos et al. 2016).

Various external determinants from economy, technology development, politics and society affect the industry for contaminated land remediation (cf. van Liedekerke et al. 2014). The risks and benefits of nanotechnology in general (e.g. Groves 2013; Robinson 2009; Ronteltap et al. 2011; Selin 2007; Wiek et al. 2013) and NP supported options augmenting the remediation market have been of increasing interest (Karn et al. 2009, Bhawana & Fulekar 2012, Bardos et al. 2014). Yet, it is highly uncertain what the drivers of this market are and how they develop in the future.

In order to understand the nanoremediation market characteristics and the uncertainties central to its development, the opportunities for exploitation and routes for better regulation have to be identified. Existing scenario studies on nanotechnology have been criticised for being "studies more inspired by fiction than by science" (Wiek et al. 2009: 285). Therefore, we applied a "scenario" approach that provides insights into the diversity of factors that potentially influence the future development of the nanoremediation in Europe - including its institutional setting. Dialogue with stakeholders has been crucial in the applied scenario development process. Their cross-sectorial and transdisciplinary expertise was gathered to identify and evaluate determinants of the development of the nanoremediation market – an approach that can be applied also in other innovative technology assessments. It is based on a (grey) literature review and (expert) stakeholder involvement via interviews, questionnaires, focus groups and workshops to conclude on interventions in the market development. The overall approach is discussed in more detail in Bardos *et al.* (2015).

This contribution identifies key factors that foster or inhibit the evolution of the nanoremediation market in Europe by 2025 based on the application of an exploratory, deliberative scenario approach. Our goal is to identify achievable interventions to enhance nanoremediation deployment offering insights for "real-world" business development, deducing strategies for market activities, informing policy development and/or regulatory authorities and add a case study to the scenario literature. Section 2 provides a general background on the scenario methodology and data used in our approach. Section 3 presents the results of the expert involvement activities and how these led into the identification of key market development determinants. Section 4 offers a conclusion on key lessons and suggests specific achievable interventions based on the identified scenario development.

2 Methodology and data

Scenarios can be defined as "internally consistent stories about ways that a specific system might evolve in the future" (March et al. 2012: 127). Scenarios are applied to uncover and examine the pertinent complexity of a system – in this case the nanoremediation market. Scenario analysis builds on both i) a system thinking approach, which means it is acknowledging that actors are part of a complex network of manipulable and uncontrollable drivers, which are connected to each other; and ii) the ability to think in multiple futures, i.e. actors do not reduce strategic thinking to merely one precise anticipated future, instead, they insure alternative futures are generated and applied in strategic management (Gausemeier et al. 1998). Scenarios help to understand i) what drivers are, ii) what the extent of their impact is, iii) how they are interlinked. These insights allow systematising these drivers and the uncontrollable and persistent uncertainties related to them. For example, regulation might be a decisive driver in the case of nanoremediation, yet only if policy making is uncertain, it becomes an ambiguous element.

Deducted scenario storylines support identification of alternative development trajectories (Priess & Hauck 2014) and can serve as a basis for concluding planning-oriented, responsive or proactive strategies for enterprises (Gausemeier et al. 1998, Güemes-Castorena et al. 2013). Moreover, they allow for detecting routes by which the development of the future can be governed by policy makers (Priess & Hauck 2014, Volkery & Ribeiro 2009). Our goal is to identify achievable interventions to enhance nanoremediation deployment.

Scenario design and analysis differ (see for example van Notten et al. 2003 or Alcamo 2009), but usually comprise a stepwise approach including: i) a present situation analysis via ii) systemising, i.e. understanding and filtering, the key factors and iii) their potential progression into the future to iv) elaborating internally consistent stories about ways that the system might evolve in the future to v) deducing strategies and governance guidance. Scenarios can be established through participatory or through individual, often analytically based research approaches (van Notten et al., 2003; Alcamo 2009). A participatory approach captures the high diversity of drivers affecting the system and identifies potential adaptations (March et al. 2012). The advantage of the participatory approach is to support a realistic identification and feedback on the assessment of socio-economic drivers and the recommendations deduced from the discussion of drivers to be relevant for the stakeholders. Involving in particular experts ensures the relevance of the work for practical stakeholder needs, decision support as well as for recommendations on exploitation strategies.

Given the novelty and complexity of the nanoremediation market case, we selected a methodology that considers the challenge of significant (perceived) uncertainties regarding NP use as such and a foresight investigation utilising the advantages of participatory scenario techniques. Guidelines in Rizzo et al. (2015) were considered for i) identifying stakeholders; ii) differentiating between and categorising stakeholders; and iii) investigating relationships between stakeholders as a preliminary step. Different expert engagement formats were utilised. Based on the differentiation by Enengel et al. (2012) between i) information, ii) consultation, iii) knowledge co-production and empowerment, the selected degree of engagement is mostly the "consultation" level, consisting of gathering information from participants (Alexandrescu et al. 2017, Rowe & Frewer 2000). Three methods were adopted in order to leverage a wide knowledge flow from experts that bring in a wide range of competencies: i) personal key-informant interviews (Gilchrist & Williams 1999), ii) structured questionnaires and iii) meetings in the form of workshops, conference special sessions and focus groups. In fact, it is a common practice to use a combination of methods (NOAA Coastal Services Center 2009), in particular combining meetings with questionnaires (Morgan 1996, Rizzo et al. 2015). Interviews and questionnaires were used to collect information and identify potential factors, whereas workshops and focus groups were of key importance to understand the interrelation of drivers. The applied method is summarised in Figure 1.

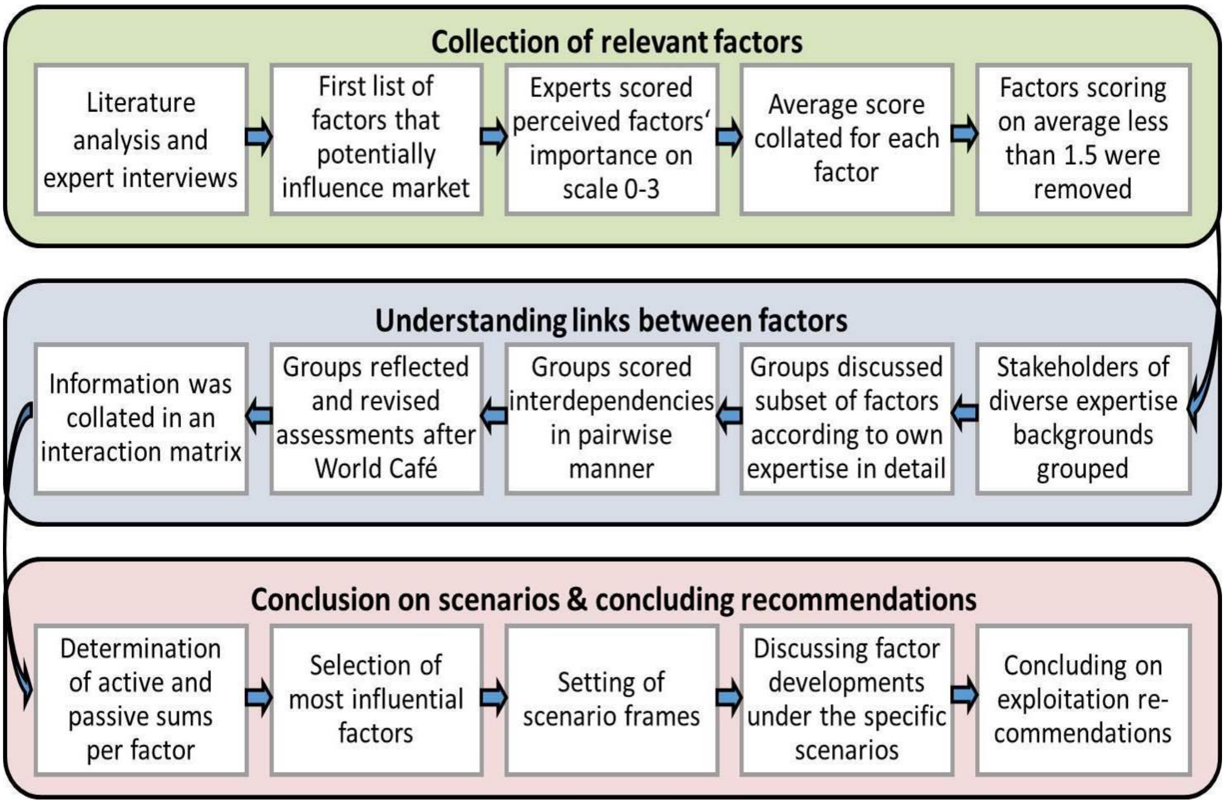

Fig. 1: Scenario development process in NanoRem project

First, following the general step-wise approach of scenario development, the current situation of the research object – the nanoremediation market – had to be outlined to ground the definition and interpretation of scenarios. This inquiry is usually based on a *literature analysis*. We mainly built up on previous work by Bardos et al. (2014) – and augmented this in a participatory approach with information collection from conducting *an expert meeting and semi-structured key informant interviews* (Gilchrist & Williams 1999). Although the accessible literature permits for deductions about general conditions and drivers for NPs production and application in remediation projects, the main purpose of these interviews with at least three experts representing different backgrounds (scientist, NP producer, regulator) was 1) to deliver a practitioners' check and extension of the literature results, and 2) to identify specific stakeholder/ market needs and interests regarding nanoremediation. The result of the step was the collection of a *first list of factors that potentially influence the nanoremediation market system*.

The second step was to systematise the initial set of drivers by revealing the importance of and linkages between identified factors. Questionnaires were designed and distributed 1) project internally and 2) at several topic-related events with the aim to include experts' knowledge in the (broader) field of nanoremediation. The survey asked to 1) add "missing" drivers and 2) to indicate the kind of dependency between drivers.

Third, to understanding the links between factors, information on factor relations was collated in an *interaction matrix* (cf. Gausemeier et al. 1998), which comprises the assessment of the strength with which each variable affects the other variables and is in turn affected. Visualising the results of this assessment in such a system grid, each factors' relative role and degree of integration in the system can be discussed and evaluated. In a workshop, experts were brought together. They were introduced to the objective of the study and were asked to 1) review the linkages of drivers, 2) select those drivers that significantly influence the system's development, and 3) disclose potential future developments of these variables. According to Wiek et al. (2009) future projections can be based on extrapolation from present trends, prognoses, transfer of circumstances from similar systems, and existing scenarios. However, most important in our approach were the expert opinions as collected in the workshops. Extreme and opposed projections were particularly interesting, because these highlight drivers and inhibitors most clearly.

Forth, based on these results, several focus groups of experts with different backgrounds reviewed the interim results and discussed the potential developments of factors into potential future states. At these occasions, the aim was to compile the projections of the key drivers into four scenarios based on identification of two critical uncertainties (cf. Kelly et al. 2007; Tietje 2005). These scenarios formed simple narrative descriptions of the potential future market situations and the developments leading from the present to these alternate futures (Gausemeier et al. 1998). As Rizzo and colleagues (2015) describe, focus groups are a special type of stakeholder engagement used to collect information from a limited number of members of a clearly defined target audience. Participants are guided by a facilitator through a discussion focussing on several related topics in order to collate opinions and expertise of group members in a comfortable environment (Rennekamp & Nall 2003). Such settings enable participants to define and frame their individual points of view by comparing them to others' perspectives (Rizzo et al. 2015).

The fifth step of the analysis consists of interpreting the future scenario states and collating feedbacks from experts to derive recommendations for interventions for nanoremediation exploitation. Interim results were presented at the AquaConSoil conference in 2017 for review.

Table 1 summarizes the expert engagement means and provides an overview of the database for the results reported in the following section.

Table 1: Overview of input sources for the scenario development and assessment indicating times, scenario development stages as well as characteristics and methods of input.

What	When	Characteristics / methods of input
Present situation analysis – identification of preliminary list of market influencing factors	06-10/2014	• (Grey) Literature review based on Bardos et al. (2014) • Project meeting (9 pers), Reading, UK, 14/07/2014 • Semi-structured interviews with 3 key informants (1 scientist, 1 regulator, 1 public perception/risk expert)

		• Questionnaires distributed project internally and at conferences CSME-2014/SARCLE-2014, San Diego, USA, 02-04/09/2014, and CABERNET-2014, Frankfurt, DE
Systematising factors: identification of links (interaction matrix), conclude on scenario framing factors	11/2014-07/2015	• Workshop (36 pers), Oslo, NO, 02-04/12/2014 • Online survey
Review of dependencies and discussion of different plausible developments of the significant factors	02/2015-09/2016	• Focus group (14 pers), Berlin, DE, 11/03/2015 • Special Session at AquaConSoil 2015 (ca. 10 experts), Copenhagen, DK, 11/06/2015 • Focus group (23 pers), London, UK, 13/07/2016 • Special Session at RemTech 2016 (8 pers) Ferrara, IT, 21/09/2016
Discussion of broader factors development and deriving recommendations for interventions	11/2016-07/2017	Discussion of interim results and gaining review / feedback of conclusions in online consultation / questionnaire and with experts at AquaConSoil 2017 Lyon, FR, 27/06/2017

3 Results

3.1 Establishing the Baseline for Scenario Development

In order to conclude on a first set of factors that potentially determine the nanoremediation market evolution, a literature review was conducted by Bardos et al. (2014) providing a risk-benefit appraisal of nZVI for remediation. To further understand the status quo of the nanoremediation technology and reveal market prospects, this review was complemented by a workshop with experts having backgrounds in science, industry and economics. This preliminary research helped establishing a variety of external determinants from economy, technology development, politics and society.

A first list of about thirty factors was further substantiated in key-informant interviews with three experts (a European level policy maker in contaminated land regulation, a scientist working on NP development for remediation and a researcher working on societal perception and health risks of MPs in general). The purpose of the interviews was i) to deliver a practitioners' check and extension of the literature results, and ii) to identify specific stakeholder/ market needs and interests regarding nanoremediation. The interviews were complemented by questionnaires.

The result of the step was the collection of a *first list of factors that potentially influence the nanoremediation market*. Key informant interviews were also utilised to establish the most worthwhile timeframe for the scenario approach. The consensus was that evolution of the market up to 2025 was the most appropriate scope. It was felt that a long-term assessment would be impossible due to the significance of unknown and uncertain potential developments. A shorter outlook, would have been too close to allow for making adjustments in business or regulation based on exploitation/intervention recommendations. After the literature and interview scoping phase, a condensed list of 22 potential factors was established.

3.2 Systematising Market Development Factors

To aid step two of the scenario design, an expert workshop was held in December 2014 and a web-consultation process was held.

The workshop involved 36 participants from nine different countries, including land managers, consultants, technology contractors, planners, regulators and other experts, with various background and interests. In order to further condense the list of factors determined in the preliminary research stage, workshop participants were asked to provide an assessment in preparation of the workshop on how important they perceived each factor to be for the development of the EU nanoremediation market by 2025. Participants scored each factor's relevance from 0 = negligible via 1 = minor, 2 = considerable to 3 = key relevance to push or pull the nanoremediation market's development. In total 20 responses were collated and the arithmetic mean was calculated for each factor.

Table 2 presents the list of factors (column 1) in descending order of obtained scores (column 3). At first glance the scores allow to conclude: 1) there is no "key factor" (average scoring >2.50) alone pushing or pulling the nanoremediation market. 2) A wider set of considerably important factors influences the market. 3) Factors indicating *Megatrends* and some related to *Economy* and *Society* have only minor relevance. 4) Market development depends not only on technology, but also on political (dis)incentives, societal preferences or the attitude of the industry. Several driving factors are difficult to predict and to influence, such as public perception of NPs in general or environmental protection policies. Interdependencies with other fields, such as finance and regional development, technology and nature protection, are ample. Some of the scorings, e.g. the ability to treat emerging contaminants with NPs, appear to be surprising and may indicate either bias or epistemic issues in the mind of the responders.

Table 2: Factors, definitions, their perceived importance with regards to influencing nanoremediation market development in the EU up to 2025 and categorization

Factor	*Factor description*	*Score*	*Category*
Most important factors (≥2.00):			
Innovation on treatment of known contaminants with NPs	NPs are effective in treating a range of contaminants. They may be superior to existing remediation approaches (being quicker or cheaper to apply or offering another added value) on a site specific basis.	2.48	Technology
Regulation of nanoparticles	While moratoria against use of NPs for remediation still exist in a few instances, the emerging trend is that NPs can be deployed using existing regulatory regimes. Uncertainties are those experienced in general for the injection of "new" types of material into the subsurface.	2.45	Policy / Regulation
Validated information on NP application potential	'Information' dimension describing the quality of available information for decision-making. Information quality can range from a level with great uncertainty with regards to the potential developments of the market and the set of factors driving the market, to a situation where information about nanoremediation is readily available, well tested, and broadly accepted (i.e. "validated").	2.40	Communication

Costs of competing technologies	There are already competitive nanoremediation technology solutions, but their international market penetration is low and they face strong competition from more established in situ technologies. Cost effectiveness is highly site specific	2.35	Economy
Standardisation for nanoparticles	- excluded from further analysis - *	2.20	Policy / Regulation
Innovations along NP production chain	The production of NPs could be boosted by improved efficiency based on increasing knowledge and economies of scale, making NPs cheaper.	2.18	Technology
Environment (especially soil) protection policies	There is policy uncertainty at a European level for remediation drivers in general (e.g., withdrawal of Soil Framework Directive versus increasing concerns over 'emerging contaminants'). Specific to nanoremediation: 'moratoria' against use exist in some countries/regions, but these may be reconsidered, particularly as a result of current research work.	2.10	Policy / Regulation
Synergies with other technologies	NPs can be applied in remediation integrated with other approaches, e.g. bioremediation.	2.05	Technology
Public stakeholder dialogue	Refers to communication with general public. Risks, uncertainties and benefits should be communicated in targeted formats with relevant public stakeholders. (Dialogue work currently being conducted in the UK may indicate increasing acceptability of nanotechnology use in remediation.)	2.00	Communication
Less important factors (>1.50 and <2.00)			
NP treatment of emerging contaminants	NPs are may be effective in remediating various emerging contamination problems, but research and practical experience are fairly limited at present.	1.95	Technology
Public perception of NPs in general – What people think of "nano"	Public perception of NPs is patchy with low consumer knowledge and ambiguity in risk perception. The increasing use of 'nano-products' implies increasing levels of public acceptance for the technology in general, although concerns over some specific potential pollutants such as nano-silver remain.	1.93	Society
Science-Policy-Interface – Communication with others	Broadly understood as 'Dialogue' process by which stakeholder groups (in particular those from science, policy and regulation) have informal/formal discussions, consultations and other forms of engagement in order to ascertain the potential application of nanoremediation (in general or in specific cases).	1.93	Communication
Technology and research policies	European and national policies fund R&D into innovative technologies, generating new knowledge, including a range of nanoremediation R&D and demonstration work (such as NanoRem).	1.75	Policy
Growing number of nanoparticles suppliers	More producers are entering the market. Suppliers are typically remediation service providers, such as consultancies. More suppliers are considering nanoremediation, although the number investing in expertise, capacities and credibility to provide nanoremediation remains relatively small at present.	1.73	Economy
Real estate market development	The property market has begun to recover since the financial crash increasing the demand for suitable areas for development – which in turn influences the demand for the remediation of contaminated land.	1.68	Economy
Innovation attitude	There is an increasing openness in the remediation sector towards innovation paired with willingness to invest in inventions and knowledge creation along with greater readiness to apply innovative technologies.	1.60	Society
Environmental awareness	There is increasing support for ensuring a more sustainable approach to contaminated land management, and this will increasingly affect remediation decision-making. This is a highly site specific consideration.	1.55	Society
Minor relevant factors (≤1.50)			
EU economic development	- excluded from further analysis - **	1.50	Economy
Globalisation	- excluded from further analysis - **	1.20	Megatrend

Industrial and military land use	- excluded from further analysis - **	1.00	Society
Climate change	- excluded from further analysis - **	0.70	Megatrend
Demographic change	- excluded from further analysis - **	0.60	Megatrend

* Consulted regulation and policy making experts rejected this category as not meaningful (as NPs are considered in existing regulation, such as REACH). Therefore it was omitted.

** Consulted experts agreed to omit all factors with a score of < 1.5 from further assessment.

At the workshop itself, participants were introduced to the state-of-the-art of nanoremediation technology, a sustainability assessment exercise and the general scenario approach. Based on presentation of the factor list and average assessment scores (Table 2, column 3), experts agreed to omitted all factors with a score of < 1.5 from further assessment. Also, no expert claimed that a specific factor was missing, confirming completeness of a list of 17 important factors. To assess interdependencies of these, participants were divided into equally large groups based on their field of expertise matching with a categorisation of factors (Table 2, column 4): Factors related to/Experts for *Technology*, *Communication*, *Economy*, *Society* and *Regulators & Policy makers*.

First, groups reviewed and revised the draft definition provided for each factor in their domain. There was an overall intense discussion in all groups. First descriptions of factors were perceived as not specific enough. All determinants were specified with the exception of “Standardisation” – this factor was rejected and finally deleted from the list for reasons of ambiguity and regulators’ emphasis that NP fall under existing regulation and standards, such as REACH. The revised descriptions obtained are presented in column 2 of Table 2.

Second, groups were asked to discuss and score the interrelations of the development of each of their factors on the full list of factors – thereby establishing a part of the interaction matrix. Considering the European Union in 2025, the impact of the development of each factor in a row (expert groups factor) on the development of the factor in each column (complete list of factors) was judged on a four-part scale from “No impact” to “Strong / direct impact”. Next, applying the World Café format (Schieffer et al. 2004), expert groups reviewed one-by one the assessments of each of the other groups, indicating consent or disagreement with the respective assessments. Finally, assessments were revised considering the feedback process. At the end of the session, the annotated posters and notes of facilitators were collected and interpreted.

After the workshop, the information and scores from the group sessions were collated into an interaction matrix (Table 3). This allows identification of the factors that are more “active” in influencing other factors (highest sum in a row), as well as those that are more driven by the active ones (highest sum in the column).

Table 3: Interaction matrix identifying degree of influence of each factor (determining the development of the nanoremediation market in Europe by 2025) on each of all other factors

Interaction matrix *Scoring of influence of factors in a row on factor in a column:* ***0 = No impact*** ***1 = weak and delayed impact*** ***2 = medium impact*** ***3 = strong and direct impact***	Innovation on treatment of known contaminants with NPs	Regulation of nanoparticles	Validated information on NP application potential	Costs of competing technologies	Standardisation for nanoparticles	Innovations along NP production chain	Environment (especially soil) protection policies	Synergies with other technologies	Public stakeholder dialogue	NP treatment of emerging contaminants	Public perception of NPs – What people think of "nano"	Science-Policy-Interface – Communication with others	Technology and research policies	Growing number of nanoparticles suppliers	Real estate market development	Innovation attitude	Environmental awareness	**Active sum***
Innovation on treatment of known contaminants with NPs		*0*	*0*	*3*	*2*	*2*	*0*	*2*	*1*	*1*	*1*	*0*	*2*	*3*	*1*	*3*	*1*	**22**
Regulation of nanoparticles	*3*		*3*	*0*		*0*	*3*	*0*	*2*	*3*	*1*	*3*	*3*	*2*	*0*	*0*	*0*	**23**
Validated information on NP application potential	*3*	*3*		*2*	*2*	*2*	*3*	*3*	*3*	*2*	*3*	*3*	*1*	*1*	*1*	*1*	*3*	**36**
Costs of competing technologies	*3*	*2*	*2*		*2*	*3*	*0*	*3*	*0*	*1*	*0*	*2*	*1*	*3*	*0*	*2*	*0*	**24**
Standardisation for nanoparticles																		**0**
Innovations along NP production chain	*2*	*0*	*0*	*3*	*3*		*0*	*2*	*0*	*3*	*0*	*0*	*2*	*3*	*1*	*3*	*2*	**24**
Environment (especially soil) protection policies	*3*	*3*	*3*	*0*		*0*		*0*	*3*	*3*	*1*	*3*	*3*	*2*	*0*	*0*	*1*	**25**
Synergies with other technologies	*3*	*0*	*0*	*3*	*2*	*2*	*0*		*1*	*2*	*1*	*0*	*2*	*3*	*1*	*3*	*1*	**24**
Public stakeholder dialogue	*1*	*3*	*3*	*1*	*1*	*0*	*3*	*0*		*0*	*3*	*3*	*2*	*1*	*1*	*0*	*3*	**25**
NP treatment of emerging contaminants	*0*	*0*	*0*	*2*	*1*	*2*	*0*	*1*	*0*		*2*	*0*	*3*	*3*	*1*	*3*	*1*	**19**
Public perception of NPs – What people think of "nano"	*0*	*1*	*0,5*	*0*	*0,5*	*0*	*1*	*0*	*3*	*0*		*2*	*1*	*2*	*0*	*2*	*1*	**14**
Science-Policy-Interface – Communication with others	*3*	*3*	*3*	*2*	*2*	*1*	*3*	*2*	*3*	*3*	*3*		*2*	*2*	*1*	*2*	*3*	**38**
Technology and research policies	*3*	*0*	*2*	*1*		*2*	*2*	*1*	*1*	*3*	*1*	*3*		*1*	*0*	*2*	*1*	**23**
Growing number of nanoparticles suppliers	*2*	*2*	*2*	*3*	*2*	*3*	*0*	*2*	*1*	*2*	*1*	*1*	*1*		*0*	*1*	*1*	**24**
Real estate market development	*1*	*0*	*1*	*3*	*1*	*0*	*0*	*1*	*2*	*0*	*0*	*1*	*0,5*	*1,5*		*0*	*1*	**11,5**
Innovation attitude	*1,5*	*0*	*0*	*1*	*0*	*2*	*0*	*2*	*0*	*2*	*2*	*2*	*2*	*2*	*0*		*0*	**16,5**
Environmental awareness	*1*	*2*	*1,5*	*0*	*0,5*	*2*	*2*	*1*	*1,5*	*1*	*2*	*3*	*2*	*0*	*1*	*2*		**21**
Passive sum*	**29,5**	**19**	**21**	**24**	**19**	**21**	**17**	**20**	**20**	**26**	**21**	**26**	**27,5**	**28**	**8**	**24**	**19**	

*Active and passive sums had a maximum potential value of 48 (i.e. a scoring of 3 for each pair-wise assessment with the 16 other factors). The closer the active sum for a factor is to 48, the more influential that factor is. Conversely if the passive sum for a factor is close to 48, it is likely to be highly influenced by changes in other factors. Assessments are based on workshop with 36 experts from diverse backgrounds in Dec. 2014.

The key conclusion from the interaction matrix (Table 3) is, that the factors "Science-Policy-Interface" and "Validated information on NP application potential" are by far the two most active drivers and, hence, most crucial in determining the development of all factors which influence the evolution of the nanoremediation market. Looking at the passive sums, the factors are less pronounced distinguishable. The three factors most heavily being influenced in their development by the other determinants are "Innovations in treatment of known contaminants with NP", "Growing number of nanoparticles suppliers" and "Technology and research policies".

To add the range of engaged experts, the knowledge base was complemented by an online consultation, which was made available between April – July 2015 (see Bardos et al. 2016). Experts were invited to specify a list of factors, which were clustered from the full list of factors in Table 3.

In general, the feedback of the online consultation is found to be in line with the discussions at the expert engagement events. Experts expect improvements of nanoremediation competiveness as costs are likely to remain the same or improve against other competing technologies. The majority of experts also identified that by 2025 relative effectiveness of nanoremediation would stay the same or improve.

3.3 Projection of Factor Development and Establishing Consistent Scenarios

A series of focus group style events between March 2015 and September 2016 engaged in total 55 experts (cf. Table 1) from across Europe. Basically, all events were to follow the same agenda: first, participants were introduced to the state-of-the-art regarding the NP remediation technology and, second, to the scenario approach. The technology had a focus on nZVI as most commonly documented NP so far in remediation. Yet, it also accounts both for new information and a slightly wider range of NPs was included. Third, the development of market factors was discussed. The events were held in different countries (in particular Germany, UK, Italy) across Europe to collate expert knowledge in the different settings.

In the first event, experts were shown that the two most "active" of the key factors were identified as: "Science-Policy-Interface" and "Validated information on NP application potential" (see Table 3). Experts agreed that these factors are likely most crucial in determining the development of the nanoremediation market. These two factors were suggested to develop framing elements for a conceptual scheme of scenario future states, which are understood as possible futures. The participants discussed the meaning of these factors and defined them as follows:

- **Science-Policy-Interface** is part of a broader '**Dialogue**', which is the process by which stakeholder groups (in particular those from science, policy and regulation) have informal/formal discussions, consultations and other forms of engagement in order to ascertain the potential application of nanoremediation (in general or in specific cases).
- **Validated information on NP application potential** is an '**Information**' dimension, which describes the quality of available information for decision-making. Information can range from a level of great uncertainty with regards to the potential developments of the market and the set of factors driving the market, to a situation where information about nanoremediation is

readily available, well tested, and broadly accepted (i.e. “validated”). “Validated information” gives credence to a decision regarding its applicability.

In all following expert events, this selection of framing factors and their definitions were confirmed. These factors form the conceptual frames for the scenario states describing four possible futures of the nanoremediation market in Europe in 2025 (Figure 2, clock-wise in each quadrant of the matrix):

- Scenario I “Knowledge exchange”: Validated information is broadly available AND there is comprehensive dialogue between stakeholders, in particular those from science, policy and regulation.
- Scenario II “Dialogue under uncertainty”: Validated information is lacking and uncertainty is still significant BUT there is comprehensive dialogue between stakeholders, in particular those from science, policy and regulation.
- Scenario III “Isolation in uncertainty”: Validated information is lacking and uncertainty is still significant AND there is no or only minimum dialogue between stakeholders, in particular those from science, policy and regulation.
- Scenario IV “Isolated knowledge”: Validated information is broadly available BUT there is no or only minimum dialogue between stakeholders, in particular those from science, policy and regulation.

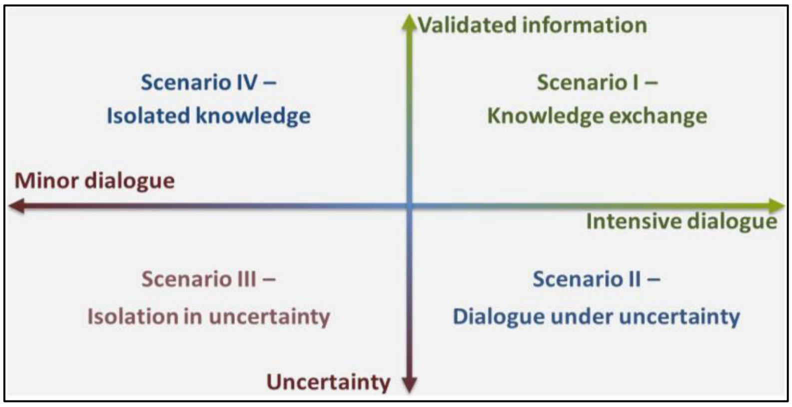

Fig. 2: Scenario states describing four possible futures of the nanoremediation market in Europe in 2025

This framework has been the basis to discuss in various formats in the workshops the plausible developments of factors. The aim was to identify in these discussions the disruptive events and decision points in order to deduce recommendations for the exploitation of nanoremediation.

The German focus group in March 2015 was a meeting of practitioners, regulators and academics dealing with NPs and/or remediation. The meeting confirmed the importance of the key factors “availability of valid information” and “dialogue between stakeholders” as meaningful framing variables of plausible future states of the market. The group strived for a joint understanding a concretisation of these two factors which were hence used and confirmed in the following engagement activities. Moreover, the groups draw some key conclusions on the potential market development for nanoremediation. Consultant, market and industry representatives emphasised the need for more documented applications and success stories of the technology's application. The role of trustworthy communicators and knowledge arenas (such as AquaConSoil, DECHEMA or Battelle) was highlighted. The necessary recognition of the site specificity was pointed out in this respect, too. Research funding could support closing the knowledge gap, in particular related to risk understanding with public research and for elucidating the innovative potential with research driven by market interested industry and consultants. Overall, a concentrated dialogue of problem owners, consultants, researchers and regulators was stressed to be essential.

The UK focus group in July 2016 also confirmed the key market determinants being available validated information and dialogue of stakeholders. Existing knowledge gaps need to be addressed. It has been emphasised that nanoremediation is a site specific technology, so there is need to demonstrate in the UK with its specific conditions its applicability to understand the performance envelope of the technology. A specific need has been stated to clearly understand the human health risks. Also a better understanding and documentation of the fate and transport of NPs is vital for market development. In the specific context of the UK, the voluntary moratorium on environmental release of NPs was a main topic of the focus group. It is understood to be a significant market determinant in the country. Some UK workshop participants expressed hope that Defra will review this in the light of emerging validated information availability. However, it was emphasised that the moratorium does not prevent the regulator agreeing to pilot deployments of nanoremediation in the field, which would support the creation of further validated information and exchange of actors, and could ultimately support a case for the moratorium's removal. Last not least as summary, opportunities are seen in the UK for nanoremediation.

The expert engagement at AquaConSoil 2015 and Remtech 2016 conferences confirmed the results.

3.4 General Findings on Market Drivers

A number of issues were identified in the interviews, workshops and survey. These related to strengths of nanoremediation related to its *relative effectiveness* due to rapid contaminant treatment where nano-activity is taking place as well as promising laboratory investigations indicating for many contaminants that there is a complete destruction effect for chlorinated solvents and, moreover, a wider treatable range of contaminants. Additionally, it was stated that NP deployments tend to facilitate in situ dehalorespiration (a specific form of bioremediation). Nanoremediation offers clear opportunities in its abilities to treat contaminants in the vadose zone, potential for treatment of source terms, that integrated approaches (e.g. combining nano and micro scale ZVI) may improve effectiveness and reduce costs (also opportunities with electro-remediation and bioremediation approaches) and inclusion of nanoremediation in *in situ* integrated treatment approaches.

Although most experts appreciated the increasing documented knowledge about nanoremediation, there was at large concern that public domain publications of field scale deployments remain relatively scarce and that examples are lacking of field deployments with comprehensive sustainability assessment. Also, field scale deployments remain rather limited in the number of contaminant types targeted. Similarly, public domain and validated reports of commercial deployments are lacking. Limited availability of know-how for field based NP monitoring techniques causes relative risks related to NPs next to handling risks. It was also stated that numerous coatings, modifiers, catalysts could make establishing risks complicated. On the other hand, experts pointed to studies indicating that ecotoxicological impacts of NPs would be limited in scale and duration. The limited longevity of NP activity may reduce environmental risks and allow more targeted applications. Yet, the limited migration in the subsurface may also require additional injection points. Also, deployment retains a need for fairly specialised experience and know-how. The development of more convenient deployment systems and information extending the range of potential service providers able to deploy nanoremediation is considered being a challenge and opportunity.

An improved understanding based on more available knowledge could lead to reduced public and regulatory fears. However, potentially significant public concern about nanotechnology being inherently risky might remain as a threat to the market development.

As a summary, the existence of validated data on case studies is critical for market development – in particular if this information can be told as success stories. In addition, dialogue between the stakeholders (science – industry – policy – general public) is crucial. An open debate is the question: Who is best to initiate the communication: Is scientific knowledge transferred to consultants and then to regulators? – No answer was provided, but it became clear that those interested in the promotion should invest, i.e. politics should support research in innovative NP to tackle emerging contaminants and prevent risks to society; researchers should communicate their results in a way that is understood by the market and regulators; consultants should invest in nanotechnologies to gain from early mover advantages; and so forth. Regarding the key drivers identified in the scenario process, the consultation results indicate the following: Related to “dialogue”, experts stated that there was a low level of dialogue between most, including the scientific community, industry, and regulators. Experts provided suggestions on how to improve the dialogue by “Independent scientists – consultant who has no conflict of interest should be approached for an opinion – in order to have a better understanding of all pros and against" and "there is nothing comparable to true success stories written in an understandable manner".

These success stories also link to the availability of "information". Indeed, field scale experience was identified as an important or very important by all experts. Related to this, the majority of experts identified that the risk perception and technology dread were important factors related to available information. Both are assumed to being likely to rather improve over the next ten years, stating "at the moment, there is more risks assumed and feared than really shown to exist. This will change with better knowledge basis." All experts identified that current knowledge improvements was important or very important if nanotechnology was to improve its use in the next ten years. The majority expects that knowledge will improve in the next ten years.

The majority of involved experts expect that knowledge will improve in the next ten years by some explaining their reasoning with "more complex information will be available" and "once seen as tried and tested, practitioners will be more likely to apply it". If it will be documented in a plausible way and involved actors will speak about the outcomes, it will be far more likely to foster nanoremediation and exploit the market for it. The experts provided suggestions how to improve dialogue, e.g. by "Independent scientists - consultant who have no conflict of interest should be approached for an opinion - in order to have a better understanding of all pros and against" and "there is nothing comparable to true success stories written in an understandable manner".

4 Conclusions for Interventions

The scenario assessment approach yielded a wealth of insights into the diversity of factors influencing the potential market emergence of nanoremediation. In the focus groups and workshops, several trends were identified as affecting the nanoremediation market. Table 4 suggests a series of measures, that are readily achievable that could impact these trends to benefit strengths and opportunities for nanoremediation, whilst mitigating for weaknesses and threats. These suggestions are based on the focus group and expert discussions, as well as taking into account the existing pattern of deployment summarised in the literature (e.g. Bardos et al. 2015). The analysis provides an initial, and tentative, view on how time sensitive these may be and state, if they will change over time; what the authors can say now about likely changes; and how certain these are.

Table 4: Readily achievable interventions to enhance nanoremediation deployment

Item	Possible trends to 2025	Certainty of development	Interventions

Item	Possible trends to 2025	Certainty of development	Interventions
Relative costs	Economies of scale lead to cost reductions related to: a) production of NPs b) application of NPs Combined / integrated approaches bring costs down to competing options such as *in situ* bioremediation	Highly likely, scaled up production (early adoption) already occurring - and field deployments of engineered combined approaches already taking place.	Transfer of more readily usable nanoremediation systems to commercial scale manufacture of NPs and productising deployment applications and guidance. Effectively validated field scale deployments of combined / integrated approaches with release of reliable cost and performance data.
Field scale experience	Additional field trials including a wider range of contaminants could strengthen the evidence base for nanoremediation effectiveness and reduce public concerns associated with deployment safety	Highly likely. This has been a objective of recent research projects.	Replication of nanoremediation application via early adopters who might gain market edge in know-how / service delivery is facilitated by NanoRem outputs and guidance.
Relative effectiveness	a) Research funding to address difficult contaminants and develop novel NPs b) Vadose zone treatment could solve difficult / untreatable problems, such as highly recalcitrant contaminant classes c) Development of coatings to improve persistence and mobility	a) Highly likely – There are a number of research projects taking place across Europe b) Likely - Currently vadose zone treatment has not been well investigated, but exploiting NPs for this use may be possible c) Highly likely - Relatively certain, research being carried out	A range of related research projects are underway or at the proposal stage and the number of publications grows right across the academic community.
Relative risks	Additional risk due to development of coatings to improve persistence and mobility	Highly likely	A range of related research projects are underway or at the proposal stage.
Ease of use	Improvement and productising of nanoremediation deployment	Highly likely, research being carried out	Include productising as a key feature of field scale deployment projects.
Technology dread / scepticism	Gradually diminishing as an issue as research outcomes and information become more widely available.	More likely than not, however, unforeseen events are to be considered that might increase the dread, e.g. news about inefficient use and even contaminations (e.g. – and nonetheless if – caused by inappropriate use).	Improvement of overall information availability – in different formats for easy dialogue between different stakeholder groups – and simple information relating to appropriate use.
Current knowledge	Knowledge expansion leading, improved certainty of effectiveness, increased uptake of the technology, and more straightforward deployment and permitting.	Likely, scientific research projects as a major contribution towards this development, however, a mayor challenge is awareness amongst decision makers.	Improvement of overall information availability from multiple platforms to achieve a scenario where there is extensive exchange of well validated information.

The paper presented the individual steps and results of a deliberate scenario process to gain information on key factors that foster or inhibit the evolution of the nanoremediation market in

Europe by 2025 based on the application. A key motivation was ensuring that research addresses real market and regulatory interests. The analysis highlighted that the existence of validated data on case studies is critical for market development – in particular if this information can be told as success stories. Furthermore, stakeholder dialogue is crucial.

Any new technology has to prove that it is complementing or improving existing technologies at an appropriate economic cost and acceptable risks. There are no absolute blocks to an uptake of nanoremediation in the markets, but documented, validated case studies and understanding the "operational window" of nanoremediation are found to be extremely significant. Research is seen by experts as a disruptive element as results can help to deliver the required validated information – however, academics must communicate these in an appropriate way to business and regulation.

Overall, the scenario process has significantly increased the availability of evidence for the applicability of NPs enhanced remediation techniques – if these will be taken up broadly by the market will however depend on the degree to which these information will be used by the stakeholders and to which the stakeholders, in particular from academics, regulation and business, continue and extend their dialogue.

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