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Sustainable Remediation Methodology for Assessment

Environmental project No. 2209

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Content

Preface

This project is financed through the Technology Development Programme by the Danish Environmental Protection Agency (Miljøstyrelsen), with a contribution from the Capital Region and co-financed by Ramboll's Knowledge & Innovation fund.

An advisory group has followed the project. The members of the advisory group are:

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Dansk sammenfatning

Denne rapport præsenterer en metode til vurdering af den relative bæredygtighed af forskellige afværgealternativer for en forurenet lokalitet.

Metodikken følger principperne i ISO-standarden for bæredygtig afværge (ISO, 2017), hvor bæredygtig afværge defineres som "afværge, der eliminerer og/eller kontrollerer uacceptable risici på en sikker og rettidig måde, mens den miljømæssige, sociale og økonomiske værdi af arbejdet optimeres". Evalueringen af bæredygtig afværge dækker således over vurderingen af miljømæssige såvel som sociale og økonomiske bæredygtighedsindikatorer.

I projektet er der udviklet to sæt af bæredygtighedsindikatorer:

- **Den fulde liste med bæredygtighedsindikatorer**: Denne liste dækker i alt 49 indikatorer fordelt på 19 miljømæssige indikatorer, 12 sociale indikatorer og 18 økonomiske indikatorer. Ikke alle indikatorer er nødvendigvis relevante for hvert afværgeprojekt. Listen kan anskues som en bruttoliste, hvorfra de relevante indikatorer kan vælges.
- **Den simple liste med bæredygtighedsindikatorer**: Denne liste dækker i alt 21 indikatorer, der er opdelt i 9 miljømæssige indikatorer, 6 sociale indikatorer og 6 økonomiske indikatorer. Dette udvalg af indikatorer anbefales at være udgangspunktet for indledende bæredygtighedsvurdering.

Det anbefales, at bæredygtighedsvurderingen følger en trinvis tilgang, som illustreret i Figur 1. **Trin 1 vurderingen** er en indledende vurdering, der typisk foretages på et tidligt stadie i processen omkring valg af afværgeløsning, hvor flere løsninger er i spil. Denne vurdering kan udføres under anvendelse af begrænsede ressourcer og tid, og kan anvendes for alle størrelser af afværgeprojekter. Den indledende bæredygtighedsvurdering vil f.eks. være relevant at inddrage i forbindelse med den indledende teknologiscreening, der allerede finder sted i regionernes afværgeprogrammer. På Trin 1 udføres vurderingerne af bæredygtighedindikatorerne hovedsageligt ved kvalitative vurderinger, der oversættes til scorer fra 1-5 for at give mulighed for en semikvalitativ vurdering, og beregning af en samlet bæredygtighedsscore. En score på 1 er den bedst mulige score, og en score på 5 er den dårligst mulige score. Hver indikator kan tildeles en vægt fra 1-5 afhængigt af deres relative vigtighed. Det anbefales, at der gives en lige vægtning af hver af de tre bæredygtighedsdimensioner miljø, samfund og økonomi.

Trin 2 vurderingen repræsenterer en mere detaljeret vurdering, som hovedsageligt er relevant for større og/eller komplekst forurenede lokaliteter. Her understøttes scoringen af bæredygtighedsindikatorer ved hjælp af kvantitative vurderinger, såsom livscyklusvurderinger og cost-benefit analyser. Livscyklusvurdering kan hovedsageligt give input til specifikke miljøindikatorer, f.eks. de forskellige luftemissionsindikatorer, anvendelse af råmaterialer og affaldsproduktion. Elementer fra cost-benefit-analyse kan bruges til at vurdere nogle af indikatorerne i den økonomiske dimension, såsom ændringer i ejendomsværdi, påvirkning af lokalområdets forretningsliv mv.

På det detaljerede vurderingsniveau (Trin 2) anbefales det at inkludere en bred interessentgruppe, der kan give input til vurderingen af især sociale indikatorer. Ved at inkludere interessenters meninger og synspunkter, øges kvaliteten af bæredygtighedsvurderingen. Litteraturen viser også, at en tidlig inddragelse af interessenter kan hjælpe med at fokusere beslutningsprocessen, da nogle afværgealternativer kan være uacceptable set fra et interessentperspektiv.

Tidlig involvering af interessenter kan derfor bidrage til at identificere sådanne uacceptable løsninger, således at afværgealternativer, der anses som uacceptable, kan tilpasses/ændres på et tidligt stadie, såfremt det er nødvendigt.

Begge vurderinger resulterer i beregningen af et samlet bæredygtighedsscore beregnet som den vægtede sum af de individuelle scorer. Den samlede bæredygtighedsscore kan anvendes til at vurdere den relative bæredygtighed mellem de sammenlignede afværgealternativer. Evalueringen fører endvidere til en score, der beskriver effekten på FN's verdensmål for bæredygtig udvikling baseret på en kobling mellem indikatorresultater og de relevante verdensmål.

Afslutningsvis understreges det, at selv om metoden giver mulighed for beregning af en samlet bæredygtighedsscore, der kan sammenlignes på tværs af de vurderede afværgealternativer, er metodens vigtigste styrke, at den på baggrund af de fastsatte indikatorer, der omfatter miljømæssige, sociale og økonomiske aspekter udgør et værktøj til forbedret dialog om bæredygtighed. Dette bidrager til at kvalificere diskussionen om bæredygtig afværge, og til forbedre kommunikationen mellem interessenter.

Summary

This report presents a methodology for assessment of the relative sustainability of different remediation options for a contaminated site.

The methodology follows the principles in the ISO standard for sustainable remediation (ISO, 2017) where sustainable remediation is defined as “remediation that eliminates and/or controls unacceptable risks in a safe and timely manner whilst optimizing the environmental, social and economic value of the work”. Thus, the assessment of sustainable remediation covers the assessment of environmental as well as social and economic sustainability indicators.

During the project two sets of sustainability indicators have been developed:

- **The full list of sustainability indicators**: This list covers a total of 49 indicators divided into 19 environmental,12 social and 18 economic indicators. Not all indicators may be relevant for each remediation project. The list can be used as a gross list from which the relevant indicators can be chosen.
- **The simple list of sustainability indicators**: This list covers a total of 21 indicators divided into 9 environmental, 6 social and 6 economic indicators. This preselection of indicators are recommended to be the starting point for an early stage sustainability assessment.

It is recommended that the sustainability assessment follows a tiered approach as illustrated in FIGURE 1. **The Tier 1 assessment** is an initial early stage assessment. This assessment can be carried out using limited resources and time and is applicable for all sizes of remediation projects. The sustainability assessment can thus be added to the first screening of applicable remediation alternatives for a site (“afværgeprogram” by the Danish regions). In Tier 1 the assessment of indicator scores is done mainly by qualitative assessments that are translated into scores from 1-5 to allow for a semi-qualitative assessment and calculation of a total sustainability score. A score of 1 is the best possible score and a score of 5 is the worst possible score. Each indicator can be given a weight from 1-5 depending on their relative importance for the specific site. However, it is recommended that an equal weighting is given to each of the three sustainability dimensions of environment, society and economy.

The Tier 2 assessment represents a more detailed assessment, which is mainly relevant for larger and/or complex contaminated sites. Here the scoring of sustainability indicators is backed up by the use of quantitative assessments, such as life cycle assessment and cost-benefit analysis. Life cycle assessment can mainly give input to specific environmental indicators, e.g. the different air emission indicators, raw material use and waste production. Elements from cost-benefit analysis can be used to assess some of the indicators in the economic dimension such as changes in property values, uplift to local business etc. It is furthermore recommended that the Tier 2 assessment process includes a broad stakeholder group that can give input to the assessment of especially social indicators. Taking stakeholder opinions and views into account will enhance the quality of the sustainability assessment. The literature also indicate that early inclusion of stakeholders can help focus the decision support process, since some remediation options may be unacceptable from a stakeholder point-of-view. The early inclusion of stakeholders can help identify such unacceptable solutions at an early stage and adapt them accordingly.

Both assessments results in the calculation of an overall sustainability score calculated as the weighted sum of the individual scores. This score is used to assess the relative sustainability

between the compared remediation options. Additionally, the assessment leads to scoring of the effect on the UN sustainable development goals (SDGs) based on a coupling between indicator scores and the relevant SDGs.

In conclusion, it is emphasized that although the methodology allows for a calculation of an overall sustainability score that can be compared across the assessed remediation alternatives, the main strength of the methodology is that, based on the established indicators comprising environmental, social and economic aspects, it provides a tool for enhanced sustainability dialoque. This helps to qualify the discussion on sustainable remediation and to improve communication between stakeholders.

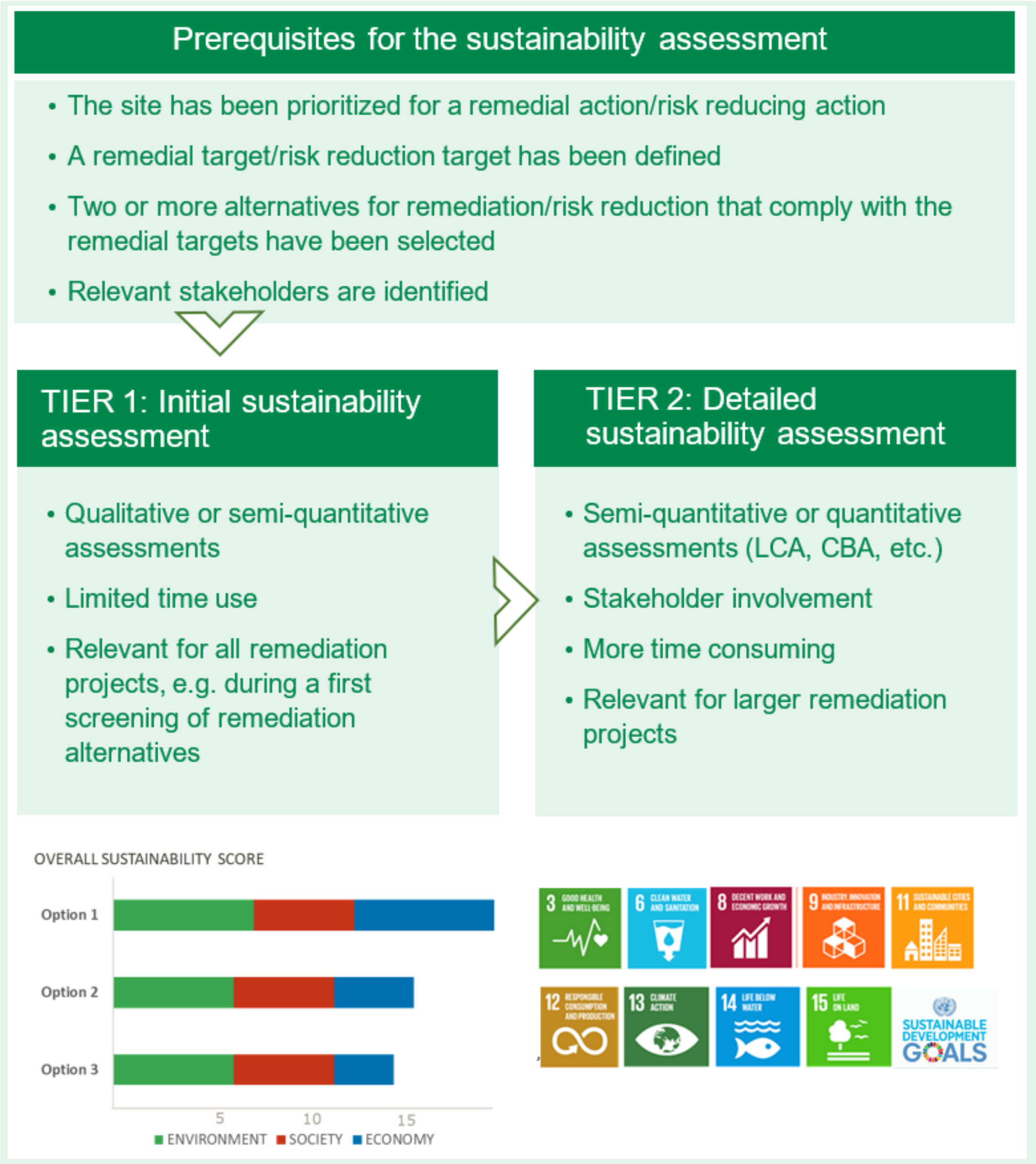

FIGURE 1: Sustainability assessment concept.

1. Introduction

1.1 Background

Remediation of contaminated sites removes or reduces a local environmental problem, which poses a risk to groundwater, surface water and/or humans. At the same time, remediation requires the use of energy and materials, impacts the surrounding society and is costly to undertake. It is therefore widely recognized that remediation while removing a local problem, may cause other local, regional and global impacts on the environment, society, and economy.

During recent years there is an increasing focus on sustainability also within the remediation industry. Several countries including the UK, US, Canada, Australia and New Zealand, Netherlands, Italy, Brazil and Japan have established Sustainable Remediation Forums (SuRFs) that are committed to the development and promotion of sustainable remediation practices. In 2017 an ISO standard on Sustainable remediation was published (ISO 2017). The ISO standard defines sustainable remediation as “elimination and/or control of unacceptable risks in a safe and timely manner whilst optimizing the environmental, social and economic value of the work”. The ISO standard provides a framework and a common terminology on the topic of sustainable remediation but it does not provide a set methodology for the assessment.

Traditionally the key criteria for choosing a remediation technology for a contaminated site have been 1) effective risk reduction, 2) technical practicability and 3) cost-efficiency. However, the increased focus on sustainability within the remediation sector has created a need for a tailor-sized tool that enables the assessment of all aspects of sustainability when remediation technologies are selected. When introducing new remediation methods or optimizing already existing methods, it is furthermore important that the methods are more sustainable than existing methods.

1.2 Project objectives

The goal of this project is to develop a methodology for sustainability appraisal of remediation options for contaminated sites. The methodology will be of a general character that can be applied to compare all types of remediation options.

The developed methodology should allow for an initial simple assessment, which should be faster to carry out and be relevant during the first screening of applicable remediation options for a contaminated site. In Denmark, this first screening is usually carried out in the remediation programme (“afværgeprogram”) for the site.

In addition, the methodology should allow for a more detailed sustainability assessment, which is relevant in a later stage of the remediation project or for larger and more complex contaminated sites, where the societal interest in the site is also larger.

The assessment on both the initial and the detailed level should be coupled to an assessment of the effect of the remediation project on the UN sustainability goals (SDGs) set in 2015 by the United Nations General Assembly.

During the development of the methodology, the advisory group consisting of representatives from three Danish regions, the Danish Regions’ Knowledge Centre for Environment and Resources and the EPA, were actively involved in discussions and the selection of relevant sustainability indicators to be used for the initial sustainability assessment. Furthermore, a workshop was arranged, where the advisory group and a wider group of representatives from the regions tested the methodology by applying it to a case site. Based on that, the group provided valuable input to the further development and refinement of the methodology with special focus on the initial sustainability assessment.

2. Sustainable remediation

Sustainable development was first described in the Brundtland Report “Our common future”, UN (1987), that defined sustainable development as a development ”that meets the needs of the present without compromising the ability of future generations to meet their own needs” and talks about “a new era of economic growth - growth that is forceful and at the same time socially and environmentally sustainable”.

The increased focus on sustainability within the remediation sector has led to the preparation and publication of an ISO standard (ISO 2017) which provides a standard methodology and terminology and information about the key components and aspects of sustainable remediation assessment. The ISO standard provides an overall framework for an assessment of sustainable remediation; however, it does not provide a set methodology or tool for the assessment.

The methodology for sustainable remediation assessment developed in this project is based on the definitions and the framework provided in the ISO standard. Key definitions and the tiered framework approach in the ISO standard are described below and form the basis of the developed methodology.

2.1 ISO standard

The ISO standard defines sustainable remediation as “elimination and/or control of unacceptable risks in a safe and timely manner whilst optimizing the environmental, social and economic value of the work”.

The assessment of sustainable remediation is based on a set of **indicators**, which each represents a sustainability effect, whether a positive or a negative impact, which may be compared across alternative remediation strategies, comprising one or more remediation techniques and/or institutional controls, to evaluate their relative performance.

The included indicators should, according to ISO, represent a holistic indicator set that reflects all three dimensions of sustainability: environment, society and economy. An example of a holistic set of indicator headings are presented in the ISO standard based on work by Sustainable Remediation Forum UK (SuRF-UK) and is seen in TABLE 1. Note that these are only indicator headings and not specific indicators. An example of a specific indicator under the Air heading in the Environment dimension could for example be greenhouse gas emission measured as tonnes of CO_2-equivalents.

TABLE 1. Example of sustainable remediation indicator categories based on SuRF-UK (2011)

Economy	Society	Environment
Direct economic costs and benefits	Human health and safety	Air
Indirect economic costs and benefits	Ethics and equality	Soil and ground conditions
Employment and employment capital	Neighbourhood and locality	Groundwater and surface water
Induced economic costs and benefits	Communities and community involvement	Ecology
Project lifespan and flexibility	Uncertainty and evidence	Natural resources and waste

2.1.1 Tiered assessment, assessment types and process

The ISO standard recommends that a tiered approach to sustainable remediation assessment is applied. This implies that simple and more qualitative approaches are the default and most commonly used assessments at the first tiers. Thus the assessment should start out as simple as possible and increase in detail if necessary. The tiered approach is also supported by SuRF-UK as presented in FIGURE 2.

According to the SuRF-UK approach, the entry level assessment should be qualitative. If this does not lead to a clear finding that can be used as decision support, a semi-quantitative assessment is applied in the next tier. In the few cases, where this will not lead to a clear finding of the most sustainable option, a quantitative assessment can be applied in Tier 3. Box 1 includes a description of what is meant by a qualitative, a semi-quantitative and a fully quantitative assessment.

Underlying all tiers, is the general application of good and sustainable management practice, such as maximising the use of renewable energy, minimizing transport distances, identifying re-use options e.g. for treated soil or "grey" water and to set up effective communication with stakeholders.

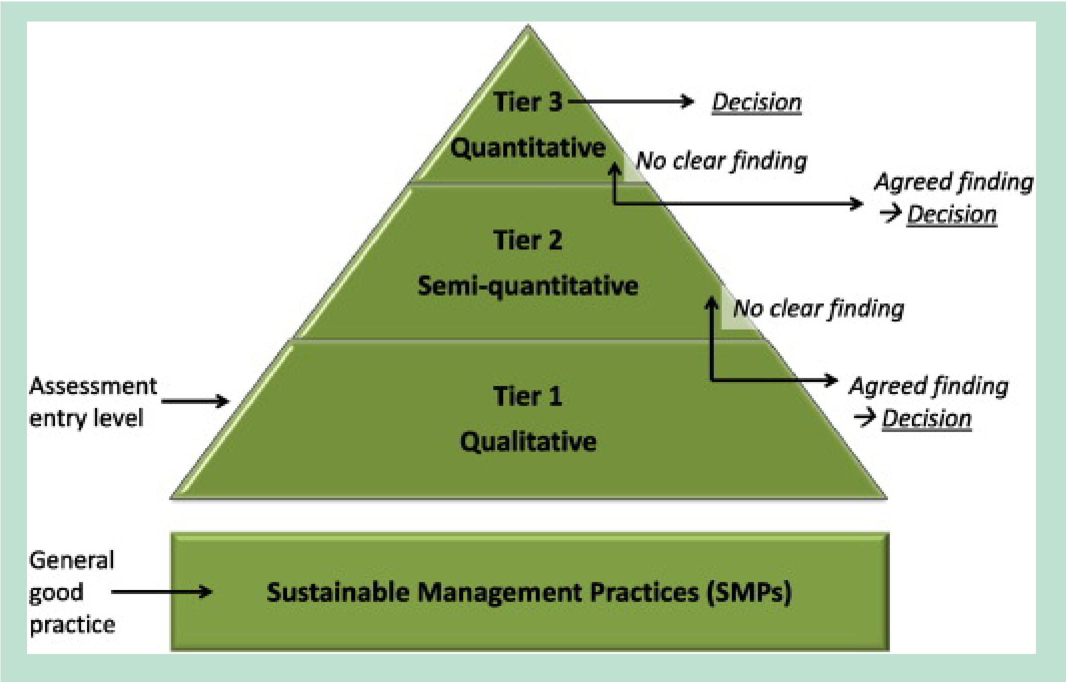

FIGURE 2. Tiered approach to sustainability assessment as represented by SuRF-UK (Bardos et al. 2016).

BOX 1: Short description of different assessment techniques for indicator assessment

Qualitative assessment
Assessment of indicators based on qualitative statements, for instance "better", "neutral" and "worse". No values/scores are assigned to the indicators.

Semi-quantitative assessment
Assessment of indicators is done by assigning a relative score to each remediation strategy without carrying out detailed quantification or monetization of every aspect.

Quantitative assessment
Seeks to carry out a detailed quantification of indicators, for instance by using cost-benefit analysis (CBA), life cycle assessment (LCA) or other methods to quantify impacts in monetary or physical units.

2.1.2 Stakeholder engagement

It is generally accepted that stakeholder engagement is an important part of the process of assessing the sustainability of remediation (ISO 2017, SuRF-UK, 2011, Nicole 2010). Taking stakeholder opinions and perspectives into account will enhance the quality of sustainability assessment of remediation alternatives, since it will incorporate the stakeholders' views of the different remediation options, ensuring that the relevant aspects of community and societal interests are represented.

A stakeholder can be defined as individuals, groups, authorities or organisations that can directly or indirectly affect a project or be affected by a project (Freeman, 1984). Examples of stakeholders that can be directly involved in the decision making are:

- Site owner/problem owner
- Local authorities
- Environmental protection agency

Examples of stakeholders that can indirectly affect or be affected by a project are

- Neighbours
- Local community
- Local business
- Interests groups

The ISO standard (ISO 2017) recommends that stakeholders are involved in assessments of sustainable remediation where it is practical to do so, since stakeholder views and perspectives will improve the sustainability assessment. The larger and more complex and controversial the project is, the more relevant it is to engage stakeholders.

In the case of smaller and more simple projects, according to ISO (2017), a more limited stakeholder group consisting of the site owner, their professional representatives and local authorities are relevant to involve in the project. In the case of lager and more controversial remediation projects that attract a wide community and/or societal interest, it is relevant to expand the stakeholder group to represent also the local community and other societal interest e.g. through non-governmental organisations representing different society interests that may be affected by the project.

3. Sustainability assessment methodology

This chapter presents the sustainability assessment methodology for remediation options developed within this project. The methodology builds on the principles for sustainable remediation defined by the ISO standard.

FIGURE 3 illustrates the concept of the sustainability assessment and the two tiers for assessment. Tier 1 is the initial assessment relevant for all types of sites. The Tier 1 assessment represents a relatively fast and qualitative assessment, which can be done in a few hours. The Tier 2 assessment represents a more detailed and quantitative assessment applying life cycle assessment and/or cost benefit analysis to provide a better assessment of sustainability indicators. Such analyses are more time-consuming and therefore more relevant for larger and/or complex remediation projects.

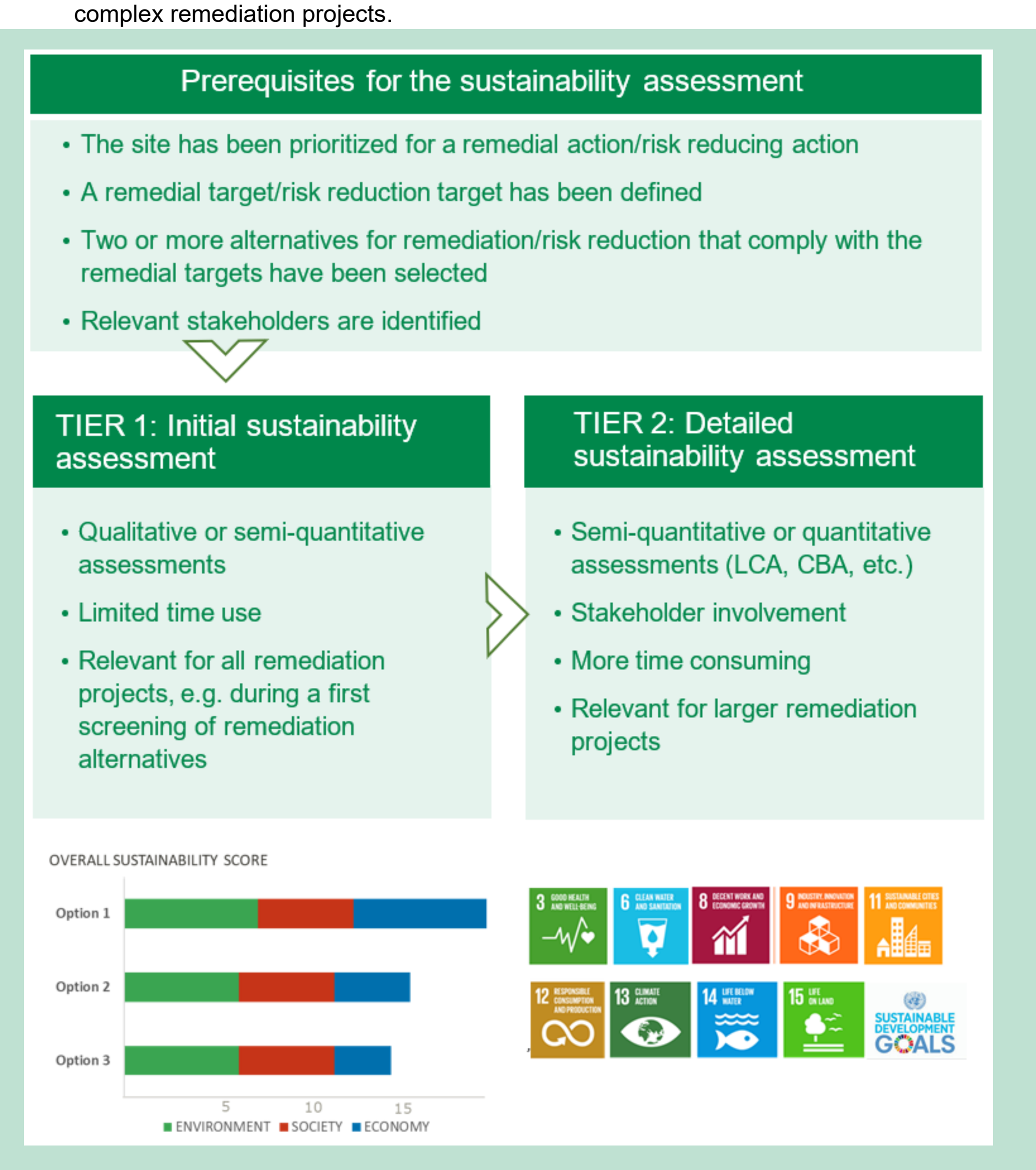

FIGURE 3. Sustainability assessment concept

As a starting point for any sustainability assessment, whether it be a Tier 1 or a Tier 2 assessment, the following prerequisites should be fulfilled before an assessment is initiated:

- The site poses a significant risk to humans and/or the environment. Therefore, there is a need for risk management, either in the form of remediation or other protective measures
- A remedial objective for the site has been defined, for instance in the form of a target concentration for the relevant contaminated compartments.
- A number of remediation strategies/protective measures that are able to comply with the defined remedial objectives have been identified.
- Relevant stakeholders have been identified cf. section 2.1.2

The assessment is done based on a relative scoring of the sustainability indicators presented in this chapter. In addition to the scoring, a weighting of the indicators is made. The scoring and weighting of indicators is presented at the end of this chapter.

This chapter presents two lists of sustainability indicators (simple list and full list), that can be used depending on the Tier and the goal of the assessment, see Box 2.

BOX 2: Recommended sustainability indicator lists for Tier 1 and Tier 2 assessments

Tier 1: Initial assessment
The ***simple list*** (TABLE 5) is the recommended indicator list to use within the scope of a remediation program ("afværgeprogram").

Alternatively, the assessment in Tier 1 can start out using the ***full list*** (TABLE 2, TABLE 3 and TABLE 4) and selecting relevant indicators from this list.

Tier 2: Detailed assessment
In the detailed assessment it is recommended to use the full list (TABLE 2, TABLE 3 and TABLE 4). Depending on the site, some indicators may be irrelevant and can be left out.

Chapter 4 presents in more detail the assessment criteria to consider during the indicator scoring, as well as present methods for more detailed assessments in Tier 2.

3.1 Sustainability indicators

Two lists of sustainability indicators have been developed within this project, a full list and a simple list respectively. Box 2 outlines when to make use of the different lists.

The indicator lists are divided into environmental, social and economic indicators. The starting point for the development of the lists has been the ISO framework and the indicator headings defined by SuRF-UK (TABLE 1). In addition, the advisory group has provided valuable input to the selection of specific indicators representing these headings, and especially to the choice of indicators representing the simple list, relevant for an early stage remediation screening carried out by the Danish regions or others.

The full indicator list covers all aspects of sustainability as represented in the criteria headings by SuRF-UK (see TABLE 1). The simplified list covers a subset of the indicators from the full list and it represents the minimum number of indicators recommended for a first assessment e.g. in a remediation program ("afværgeprogram") done by the Danish regions as a first screening of the technically feasible remediation strategies for a site, which is to be remediated.

3.1.1 Full indicator list

The full indicator list is shown in TABLE 2 (Environmental indicators), TABLE 3 (Social indicators) and TABLE 4 (Economic indicators). A short indicator description as well as indicator lists both in English and Danish are included in Appendix 1.

The full list should be seen as a gross list of indicators, from which the assessment team can choose the indicators that are relevant for the specific site. For some indicators, it may be difficult to carry out a scoring at a specific site. It might also be the case, that the indicators will be equally impacted by the different assessed remediation strategies.

3.1.1.1 Indicators related to the contamination level after remediation

There are three different indicators related to the clean-up efficiency of the assessed remediation alternatives. These are:

- **ENV 2.1** Residual soil contamination
- **ENV 3.1** Residual groundwater contamination
- **SOC 1.1** Reduction in health risks

As specified previously, all compared alternatives must comply with a defined remediation objective which represents an acceptable risk reduction. However, it might be the case, that some of the alternatives reduce the contaminant levels even more than what is specified in the remediation objective. In this case, the quality difference may be assessed using one or more of the three sustainability indicators below depending on the actual aim of the remedial action. If the aim is to remediate soil, indicator ENV 2.1 is assessed, if ground- or surface water remediation is the aim, then indicator ENV 3.1 is assessed. Finally, if reduction of human health impacts through indoor air contamination or soil contact is the aim, the indicator SOC 1.1 is assessed.

3.1.1.2 Environmental indicators

The environmental sustainability indicators are divided under the six headings Air, Soil and ground conditions, Groundwater and surface water, Nature, Raw materials and Waste. Under each heading there are 3-4 indicators as seen in TABLE 2.

- **Air:** Cover emissions to air divided into 3 indicators covering 1) greenhouse gas emission, 2) emission affecting the local air quality (NO_x, VOCs and particulate matter) and 3) acidifying emissions.

- **Soil and ground conditions:** Cover impacts related to the upper part of the soil such as topsoil degradation and consumption, impact on ecosystem services and changes in geotechnical properties.
- **Groundwater and surface water:** Cover impacts on groundwater quality and quantity such as mobilization of contaminants, changes in hydrology and changes in chemical properties such as pH, redox conditions, oxygen content, dissolved metals or nutrients. It also covers the impact to water abstraction and recreational water use.
- **Nature:** Cover the impacts on plants and animals at the site. It also covers ecological and ecosystem effects such as changes in habitats, populations or food webs and the effect on landscape.
- **Raw materials:** Cover the use of 1) Virgin raw materials, e.g. sand, gravel, water and metals; 2) Fossil energy resources such as coal, oil and gas, and 3) Reused or recycled materials for instance crushed concrete.
- **Waste:** Cover the production of 1) non-hazardous waste and 2) hazardous waste. Hazardous waste also covers contaminated soil for disposal.

Refer to Appendix 1 for a description of each indicator.

TABLE 2. Environmental sustainability indicators (full list). A short description of each indicator is available in Appendix 1.

ENVIRONMENTAL INDICATORS		
Indicator heading	**Indicator ID**	**Indicator**
Air	ENV.1.1	Greenhouse gas emissions
	ENV 1.2	Local air pollution
	ENV 1.3	Acidifying emissions
Soil and ground conditions	ENV.2.1	Residual soil contamination
	ENV 2.2	Topsoil degradation and consumption
	ENV 2.3	Effects on ecosystem services
	ENV 2.4	Changes in geotechnical properties
Groundwater and surface water	ENV 3.1	Residual groundwater contamination
	ENV 3.2	Contaminant mobilization and movement
	ENV 3.3	Ground- and surface water quality
	ENV 3.4	Water abstraction and recreational use
Nature	ENV 4.1	Effects on biota
	ENV 4.2	Changes in ecology and ecosystems
	ENV 4.3	Landscape effects
Raw materials	ENV 5.1	Virgin raw material use
	ENV 5.2	Fossil energy resources
	ENV 5.3	Reused and -cycled materials
Waste	ENV 6.1	Non-hazardous waste
	ENV 6.2	Hazardous waste

3.1.1.3 Social indicators

The social indicators cover a variety of impacts due to remediation as experienced by the surrounding society. The social indicators are grouped under four indicator headings being Health and Safety, Ethics and equality, Neighbourhood and Community. Each heading has between 2-4 indicators as seen in TABLE 3.

- **Health and safety:** Cover the local health impacts related to emissions and dust from remediation work on the site. It also covers occupational risks related to remediation workers on site, or occupational risks related to the handling of contaminated materials and chemicals off site. Finally, it covers risks to the public due to remediation. This could for example be due to traffic and chemical storage at the site.
- **Ethics and equality:** Cover considerations of whether the impacts and benefits are disproportionately distributed between affected stakeholders or between generations (intragenerational equity) It also covers considerations of whether there are unethical issues related to any of the remediation options.
- **Neighbourhood:** This heading covers changes experienced by the neighbourhood, e.g. changes in site usage, changes in the built environment and the level of general nuisance due to remediation activities as experienced by people living at or near the site.
- **Community:** Cover considerations of whether the remediation options allow for realisation of local stakeholder views, and whether the remediation options support the local spatial planning objectives and plans.

Refer to Appendix 1 for a description of each indicator.

TABLE 3. Social sustainability indicators (full list). A short description of each indicator is available in Appendix 1.

SOCIAL INDICATORS		
Indicator heading	**Indicator ID**	**Indicator**
Health and safety	SOC 1.1	Health risk reduction
	SOC 1.2	Local health impacts
	SOC 1.3	Working environment risks
	SOC 1.4	Risks to public
Ethics and equality	SOC 2.1	Distribution of responsibilities
	SOC 2.2	Distribution of impacts
	SOC 2.3	Ethical concerns
Neighbourhood	SOC 3.1	Changes in site usage
	SOC 3.2	Changes in the built environment
	SOC 3.3	Nuisance due to remediation
Community	SOC 4.1	Involvement and transparency of decision making
	SOC 4.2	Local spatial planning objectives

3.1.1.4 Economic indicators

The economic indicators are grouped under six headings: Direct economic costs and benefits, Indirect economic costs and benefits, Induced economic costs and benefits, Employment and employment capital, Lifespan and flexibility, and Uncertainty and evidence. Each heading has between 2-4 indicators as seen in TABLE 4.

- **Direct economic costs and benefits:** Cover the direct costs of remediation, operation and monitoring associated with each remediation option, and the possible benefit associated with the increasing property value after remediation.
- **Indirect economic costs and benefits:** Cover indirect costs associated with potential residual liabilities, and indirect benefits associated with changes in neighbourhood reputation, as well as indirect impact to local businesses whether positive or negative.
- **Induced economic costs and benefits:** Cover economic effects on other projects and investments caused by the remediation project.

- **Employment and employment capital:** Cover effects from the remediation project such as creation of new jobs, increase of skill levels for people involved in the remediation project, and the possibility for boosting innovation.
- **Lifespan and flexibility:** Cover differences related to lifespan (for how long is the risk management effective?), the need for institutional controls, and flexibility, i.e. how resilient is the remediation option to changing conditions such as heterogeneities in contamination or geology, climate changes and budget changes?
- **Uncertainty and evidence:** This cover assessments of the degree of uncertainty related to the performance of the specific remediation technology, and of the quality of available information for each technology and the need of additional data.

Refer to Appendix 1 for a description of each indicator.

TABLE 4. Economic sustainability indicators (full list). A short description of each indicator is available in Appendix 1.

ECONOMIC INDICATORS		
Indicator heading	**Indicator ID**	**Indicator**
Direct economic costs and benefits	ECON 1.1	Cost of remediation
	ECON 1.2	Cost of operation and maintenance
	ECON 1.3	Other associated (third party) costs
	ECON 1.4	Changes in property values
Indirect economic costs and benefits	ECON 2.1	Risk of damages
	ECON 2.2	Impact on neighborhood reputation
	ECON 2.3	Uplift to local business
Induced economic costs and benefits	ECON 3.1	Use of funding schemes
	ECON 3.2	Effect on other projects/investments
Employment and employment capital	ECON 4.1	Job creation
	ECON 4.2	Competency levels before and after project
	ECON 4.3	Innovation potential
Lifespan and flexibility	ECON 5.1	Lifespan of remediation technology
	ECON 5.2	Need for institutional controls
	ECON 5.3	Flexibility of remediation alternative
Uncertainty and evidence	ECON 6.1	Uncertainty of technology performance
	ECON 6.2	Quality of available information
	ECON 6.3	Quality of sustainability assessment

3.1.2 Simple indicator list

The simple indicator list (see TABLE 5) represents a subset of indicators in the full list and a few indicators which represent combinations of two indicators in the full list. Combined indicators include the letter S in the indicator ID, for instance indicator ENV 4.S (Effects on biota and ecosystems), which is a combination of ENV 4.1(Effects on biota) and ENV 4.2 (Changes in ecology and ecosystems) in the full list.

The simple list of indicators represents the recommended indicators to be included in an initial sustainability assessment, e.g. in the remediation program ("afværgeprogram"), and were selected in dialogue with the advisory group.

TABLE 5. Simple indicator list for a first sustainability screening. A description of each indicator is found in Appendix 1. Criteria for assessment of each indicators are found in Appendix 2.

ENVIRONMENTAL INDICATORS		
Indicator heading	**Indicator ID**	**Indicator**
Air	ENV.1.1	Greenhouse gas emissions (CO2-eq.)
Soil and ground conditions	ENV.2.1	Residual soil contamination
	ENV 2.2	Topsoil degradation and consumption
	ENV 2.3	Changes in geotechnical properties
Groundwater and surface water	ENV 3.1	Residual groundwater contamination
	ENV 3.S	Ground- and surface water quality
Nature	ENV 4.S	Effects on biota and ecosystems
Raw materials	ENV 5.1	Virgin raw material use
Waste	ENV 6.2	Hazardous waste

SOCIAL INDICATORS		
Indicator heading	**Indicator ID**	**Indicator**
Health and safety	SOC 1.1	Reduction in health risks
	SOC 1.2	Local health impacts
	SOC 1.3	Working environment risks
Ethics and equality	SOC 2.1	Distribution of impacts
	SOC 2.2	Ethical concerns
Neighbourhood	SOC 3.2	Nuisance due to remediation

ECONOMIC INDICATORS		
Indicator heading	**Indicator ID**	**Indicator**
Direct economic costs	ECON 1.S	Total cost of remediation
Lifespan and flexibility	ECON 5.1	Lifespan of remediation technology
	ECON 5.2	Need for institutional controls
	ECON 5.3	Flexibility of remediation alternative
Uncertainty and evidence	ECON 6.1	Uncertainty of technology performance
	ECON 6.2	Quality of available information

3.2 Scoring, weighting and total sustainability score

3.2.1 Scoring of indicators

The scoring of the indicators is done on a relative basis by applying a 1 to 5 scale, where 1 represents the best score and 5 represents the worst score. Thus high scores represents the most negative impact or least positive impact, and the lowest score represents the least negative score or the most positive score, depending on the indicator.

Therefore, the best score can both represent the most positive impact of an indicator, e.g. the lowest amount of residual soil contamination (indicator ENV 2.1), or it can represent the least negative impact, e.g. the lowest greenhouse gas emission (indicator ENV 1.1) of the compared remediation strategies depending on the indicator being assessed.

It is noted that it may not always be necessary to use the entire scale from 1 to 5 to score the remediation options. If all compared options are relatively simple, for instance different versions of source excavation projects, they may all have relatively high scores in greenhouse gas emission, since excavation is an energy-intensive remediation method in any case.

Chapter 4 (4.1.1) and Appendix 2 provide further guidelines to the scoring of the specific indicators.

3.2.2 Weighting of indicators

Each indicator is given a weight from 1 to 5. The weights represent the importance of the specific criteria, with 1 representing the lowest importance and 5 representing the highest importance. If a criterion is not relevant for the specific case, a weight of zero can be given to leave the indicator out.

It is recommended to use an equal weighting of the three domains (environment, society and economy) in the Tier 1 assessment. This can for instance be done by giving a fixed number of weighting points in each domain (e.g. 12 points). In that way, the weights of the individual indicators can be differentiated ensuring that the total weighting of each domain is the same. Note that decimal number (e.g. 1.20) can be used as weights. This makes it possible to assign an equal weight to each indicator within a given domain. Refer to the case study in section 5 to see an example of weighting of indicators.

3.2.3 Total sustainability score

A total sustainability score is calculated for each compared remediation option. The total sustainability score *S* is calculated as a weighted sum of the assigned scores s_i and weights w_i of each indicator *I* across all *n* indicators:

EQUATION 1

$$S = \sum_{i=1}^{n} w_i \cdot s_i$$

3.3 Coupling to the UN Sustainable Development Goals

The indicator scoring is coupled to an assessment of the impact to the UN Sustainable Development Goals (SDGs). The relevant SDGs and the coupling to specific indicator headings are seen in TABLE 6. The coupling is either defined as a strong or a weak link as indicated in TABLE 6.

The total score given to the indicators coupled to each SDG is calculated. The higher the calculated score, the worse the remediation strategy impacts the SDG:

- A score of below 5 represents a “low impact”
- A score of 5-15 represents a “medium impact”
- A score of above 15 represents a “high impact”

For weak links, only 1/3 of the score is coupled to the SDG.

TABLE 6. Sustainability indicator headings coupled to SDGs.

SDG	Indicators coupled to SDG	Strong link	Weak link
3 GOOD HEALTH AND WELL-BEING	SOC 1: Health and safety	X	
	SOC 3: Neighbourhood	X	
6 CLEAN WATER AND SANITATION	ENV 3: Ground- and surface water	X	
8 DECENT WORK AND ECONOMIC GROWTH	ECON 1: Direct costs and benefits	X	
	ECON 2: Indirect costs and benefits	X	
	ECON 3: Induced costs and benefits	X	
	ECON 4: Employment and employment capital	X	
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	ECON 3: Induced costs and benefits	X	
	ECON 4: Employment and employment capital	X	
11 SUSTAINABLE CITIES AND COMMUNITIES	ENV 1: Air		X
	SOC 1: Health and safety		X
	SOC 3: Neighbourhood	X	
	SOC 4: Community	X	
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	ENV 1: Air	X	
	ENV 5: Raw materials	X	
	ENV 6: Waste	X	
	SOC 1: Health and safety	X	
13 CLIMATE ACTION	ENV 1: Air	X	
	ENV 5: Raw materials (5,2: Energy resources)		X
14 LIFE BELOW WATER	ENV 3: Ground- and surface water	X	
15 LIFE ON LAND	ENV 2: Soil and ground conditions	X	
	ENV 4: Nature	X	

4. Assessment of sustainable remediation

This chapter provides further guidance on the scoring of specific indicators. It also provides guidance to tools and methodologies that can be applied in Tier 2 “Detailed sustainability assessment”.

4.1 Tier 1 assessment

The tier 1 assessment involves the assessment of the sustainability indicators on a scale from 1-5, where 1 represents the best score and 5 represents the worst score.

There are two sets of sustainability indicators, the full and the simplified list.

The simplified list is targeted for use in the initial screening of remediation alternatives as carried out by the Danish regions during a remediation program “afværgeprogram”.

The full list represents a larger number of indicators. The Tier 1 assessment may also be carried out starting from the full list and selecting the indicators relevant for the specific site. Irrelevant criteria can be disregarded by assigning them a weight of zero. In that case, they will not contribute to the total sustainability score as calculated by Equation 1. A description and examples of the indicator criteria are given in the following sections.

4.1.1 Criteria for indicator assessment (Environmental indicators)

TABLE 25 in Appendix 2 covers descriptions of which criteria the assessment of environmental indicators in the simple list may be based on. These criteria descriptions can aid the assessor in the assessment of criteria scores.

Examples of these criteria are given below for the indicators ENV 1.1 Greenhouse gas emission and ENV 5.1 Virgin raw material use.

4.1.1.1 Assessment criteria for ENV 1.1: Greenhouse gas emission

Assessment of Tier 1 greenhouse gas (GHG) emissions should as a minimum include a qualitative estimation of the emissions from direct site remediation activities. Based on results from life cycle assessments carried out for remediation options in the literature (Cadotte et al. 2007, Bayer et al. 2006, Lemming, 2010, Lemming et al. 2010, Lemming et al. 2012, Søndergaard et al. 2018), it is identified that the following processes and material uses will contribute the most to the GHG emission:

- Excavation and transportation of soil and backfill
- On-site energy use, e.g. for heating or continued pumping
- Use of large amounts of consumables, e.g. concrete, metals, activated carbon, chemicals or other remedial amendments

A more thorough tier 2 assessment should also include a quantitative full life-cycle assessment of the global warming potential including all main processes of the remediation system including upstream production processes and downstream end-of-life processes, cf. to section 4.2.1.

In TABLE 7, a generalized relative scoring of the indicator greenhouse gas emissions of a number of common remediation technologies are presented. The scoring is based on life cycle assessments carried out in the literature. The scores can be used for inspiration, but it should be kept in mind that generalized scores should always be used with care. The implementation of remediation techniques vary from site to site. Furthermore, the greenhouse gas emission related to production processes for materials and electricity depends on the production place. The production of electricity used on site is particularly dependent on the geographical location of the remediation project as the share of renewable energy varies greatly between countries. The greenhouse gas emission related to the use of 1 kWh of electricity is therefore very different in a country like Norway, where electricity is mainly produced by hydro energy and in Denmark, where the production is based on mixed sources of renewable and non-renewable energy sources. The generalized scores in TABLE 7 are mainly based on remediation projects taking place in Denmark.

TABLE 7. Generalized relative indicator scores for ENV1.1 Greenhouse gas emissions based on literature (Cadotte et al. 2007, Bayer et al. 2006, Lemming, 2010, Lemming et al. 2010, Lemming et al. 2012, Søndergaard et al. 2018).

Remediation technology	Greenhouse gas emission Score 1-5
Excavation	4-5
In situ thermal remediation	4-5
In situ chemical oxidation	2-3
In situ biological remediation	1-2
Pump-and-treat	Timeframe dependent
Permeable reactive barrier	Dependent on reactive media and timeframe
Monitored natural attenuation	1
Phytoremediation	1

4.1.1.2 Assessment criteria for ENV 5.1: Virgin raw material use

Assessment of Tier 1 virgin raw material use should include an assessment of the relative amounts of consumed virgin materials for each remediation option. Virgin materials include:

- Virgin materials used on site during remediation. This could include virgin mineral resources for backfill after excavation.
- Use of water, either abstracted from the groundwater or surface water on site, or tap water
- Virgin materials used on site for landscaping after remediation
- Metal installations such as sheet piles or pipes
- Virgin materials used upstream for production of consumables e.g. activated carbon or concrete

Remediation options including excavation will generally have a high impact on virgin raw material use if virgin material is used as backfill after excavation. Excavation might also require large amounts of steel for sheet piling.

4.1.1.3 Assessment criteria for other environmental indicators

The assessment criteria for the remaining environmental indicators are presented in TABLE 25 in Appendix 2 as mentioned previously.

Below, some general issues related to specific remediation technologies that can impact the indicator assessments are summarized:

Excavation will generally have a high impact on virgin raw material use, if virgin material is used as backfill after excavation. Excavation can also lead to large amounts of hazardous waste if contaminated soil needs to be disposed of after excavation.

In situ thermal remediation (Ding et al. 2019)

- Will typically have a positive impact on the geotechnical properties of the soil, since it may increase the stability, bearing capacity and compressive strength
- A negative impact on soil ecology, since heating reduces microorganism biomass. Heated soil can be recolonized by soil microorganisms, however the recovery is poor for fungi-enriched communities
- Heating at high temperatures (above 250 °C) reduces soil organic matter and clay content. This will have a negative impact on cation exchange capacity and water holding capacity, which reduce soil fertility and inhibit microbial recovery. Most often heating is done up to around 100 °C. Heating above 100 °C is only relevant for thermal conduction heating and smoldering.

Chemical oxidation may lead to increased metal mobility (Villa et al., 2008), degradation of soil organic content (Villa et al., 2008) and reduced microbial density, diversity and activity (Liao et al. 2019, Polli et al. 2018).

Enhanced reductive dechlorination of chlorinated ethenes can lead to accumulation of degradation products, especially vinyl chloride is problematic, since it is more toxic and carcinogenic than the mother products. It will also lead to a shift in the microbial community in favour of the specific degraders that degrade the chlorinated ethenes.

4.1.2 Criteria for indicator assessment (Social indicators)

TABLE 26 in Appendix 2 cover descriptions of which criteria the assessment of social indicators in the simple list may be based on. These criteria descriptions can aid the assessor in the assessment of criteria scores.

Examples of these criteria are given below for the indicators SOC 1.2 Local health imnpacts and SOC 3.3 Nuisance due to remediation.

4.1.2.1 Assessment criteria for SOC 1.2: Local health impacts

The health impacts to local inhabitants should as minimum include an assessment of

- The level of exhaust emissions due to increased traffic and heavy machinery experienced by local inhabitants due to remediation
- The level of dust caused by soil excavation or other soil works

4.1.2.2 Assessment criteria for SOC 3.3: Nuisance due to remediation

The assessment of the level of nuisance experienced by residents and neighbors due to the remediation should cover a broad range of possible nuisances such as

- Operating hours at the site (per day and days in total)
- Noise, vibrations, light and odor from the remediation activities
- Aesthetic/visual pollution due to installations at the site, e.g. containers
- Restrictions to site use during remediation, e.g. due to restricted access to certain areas
- Increased traffic to/from site

4.1.2.3 Assessment criteria for other social indicators

Assessment criteria for the remaining social indicators are presented in TABLE 26 in Appendix 2 as mentioned above.

Each remediation project is site-specific, and therefore beneficial and/or undesirable impacts depend on the unique community characteristics and the context of the project (Harclerode et al. 2015). Therefore, it is difficult to provide advice for general scorings in the Tier 1 assessment. An Australian study (Huynh et al. 2018) investigated residents' acceptability of different remediation technologies using a sample of 944 residents in New South Wales, Australia. Given that all compared technologies have the same remediation efficiency, the study showed that residents preferred monitored natural attenuation and bioremediation to other technologies, and that there was a willingness to pay an increase in yearly taxes to implement these instead of chemical remediation, which was the least preferred technology. Physical remediation (e.g. excavation) and thermal remediation were in between in terms of acceptability among residents. The same result was found by Prior and Rai (2017) who, based on a telephone survey of 2009 residents living close to 13 contaminated sites in Australia, found that bioremediation technologies generally were perceived as less risky and more beneficial than chemical, thermal and physical technologies.

Norrman et al. (2020) and Søndergaard et al. (2018) who performed sustainability assessments of remediation options for large contaminated sites in Sweden and Denmark respectively, experienced that stakeholders, especially local residents tend to prefer alternatives with a high degree of contaminant removal, if this parameter varies between the assessed remediation options. Thus, in both studies excavation was preferred over containment options and less effective in situ options.

4.1.3 Criteria for indicator assessment (Economic indicators)

TABLE 27 in Appendix 2 cover descriptions of which criteria the assessment of social indicators in the simple list may be based on. These criteria descriptions can aid the assessor in the assessment of criteria scores.

Examples of these criteria are given below for the indicators ECON 1.S Total cost of remediation and ECON 6.1 Uncertainty of technology performance.

4.1.3.1 Assessment criteria for ECON 1.S: Total cost of remediation

The assessment should include an estimation of the total investment cost for the remediation, the cost for operation, including consumables e.g. electricity, activated carbon or chemicals, and the cost of monitoring. The costs should be estimated for the whole project lifecycle in order to be comparable between the assessed remediation options.

For preliminary assessments the estimation can be made qualitatively, by assessing the relative cost of the compared remediation options using descriptive statements such as "high cost", "intermediate cost" and "low cost" and translating these to scores from 1 (lowest cost) to 5 (highest cost).

4.1.3.2 Assessment criteria for ECON 6.1: Uncertainty of technology performance

The assessment should consider the uncertainty of the remediation strategy to achieve the predefined remediation criteria in terms of time, unit costs and reduction in risk levels, i.e. this indicator includes all types of uncertainties related to the performance of each remediation option.

The assessment can be based on benchmarking similar projects and technology applications. Generally, well known methods such as excavation score better in terms of uncertainty, whereas in situ and innovative technologies tend to score worse. In situ remediation techniques, such as in situ bioremediation or chemical oxidation rely on establishing the right redox conditions as well as contact between contaminants and different types of amendments injected to the subsurface. This creates a larger uncertainty related to performance of the technology and may result in a need for further injections of remedial amendments, thereby increasing the operation time, and increasing the remediation cost. For this reason, the uncertainties are assessed under the economic dimension. Thus, this indicator should be assessed as a combination of all uncertainties related to the technology performance, and uncertain issues should therefore not be addressed under the environmental or social dimensions in order to avoid double counting.

4.1.3.3 Assessment criteria for other environmental indicators

Assessment criteria for the remaining economic indicators are presented in TABLE 27 in Appendix 2 as mentioned above.

4.2 Tier 2 assessment

The Tier 2 assessment represents a later stage assessment than the Tier 1 assessment. In Tier 2, indicators are to a larger extent assessed using quantitative assessments such as life cycle assessment or cost-benefit analysis. This more detailed assessment is generally mostly applicable for larger and/or complex contaminated sites were remediation is more costly. The more detailed assessment of sustainability indicators gives a more accurate comparison of remediation options. In the Tier 2 assessment it is also recommended to include stakeholder views in the sustainability assessment f.ex. in the weighting of indicators. This may also be done in Tier 1 if relevant for the specific site.

The starting point for a Tier 2 assessment is the full list of indicators as mentioned in Box 2. The relevant indicators can then be selected based on this list. The assessment of the indicators is, as in Tier 1, done on a scale from 1 to 5. However, the scores are backed up by more detailed calculations and assessments as presented in the following.

4.2.1 Life cycle assessment (LCA)

Life cycle assessment (LCA) is a method for comparing environmental impacts related to obtaining a certain function, which could be the remediation of a contaminated site.

Use of resources and emissions are tracked in all life stages “from cradle to grave”, i.e. including the extraction of raw materials, the production stages, use stages and end-of-life stages for all relevant processes and material uses related to the remedial actions compared. The emissions are aggregated depending on type and translated into a number of potential environmental impacts.

The relevant impact indicators in LCA, which can be used for the scoring of the sustainability indicators in this project are listed in TABLE 8. Some of the environmental impacts quantified in LCA can be directly used for assessing specific sustainability indicators. These are:

- **Global warming potential:** Cover the greenhouse gas emission in kg of CO_2-equivalents through the entire lifecycle of the remediation and can be directly used to score ENV 1.1: Greenhouse gas emission
- **Acidification potential:** Cover all acidifying emissions throughout the remediation lifecycle and be directly used to score ENV 1.3: Acidifying emissions

Other environmental impacts in LCA represent a less direct link

- **Photochemical ozone formation:** Cover emissions of nitrous oxides (NOx) and volatile organic compounds (VOC) throughout the remediation lifecycle. These are emissions that impact local air pollution were emitted and can be used to score ENV 1.2: Local air pollution
- **Particulate matter:** Cover emissions of particulate matter in PM2.5-equivalents through the remediation lifecycle, and can be used to score ENV 1.2: Local air pollution
- **Human toxicity, air:** Cover human toxic emissions to air and may be used to score the SOC 1.2: Local health impacts. It should however be kept in mind, that the human health impact quantified in LCA cover emissions on all geographic locations and are not only related to on-site emissions due to the remediation itself.

In addition, metal consumption, water depletion, fossil energy use, if assessed in the LCA, may be used in the assessment of ENV 5.1: Virgin raw materials. It should be noted, however, that the use of mineral resources such as sand, gravel etc. are not typically assessed in LCA.

A few LCA methods include quantification of different waste fractions, such as bulk waste, hazardous waste, radioactive waste, and slags and ashes, however this is not the standard.

A number of tools are available for life cycle assessment and can be applied to assess remediation options. These can be divided into commercial LCA software applicable to assessment of all types of products or processes, and LCA-based tools specifically tailored for the assessment of remediation technologies. The advantages and dis-advantages of these two types of tools are presented in the following sections.

TABLE 8. Relevant LCA indicators that can contribute to the assessment of sustainability indicators.

Sustainability indicator	Relevant LCA impact (example of unit in LCA)
ENV.1.1 Greenhouse gas emission	• Global warming (kg CO_2-eqiuvalents)
ENV.1.2. Local air pollution (NOx, VOC, particles)	• Photochemical ozone formation (kg NO_x-equivalents) • Particulate matter* (kg PM2.5-eqiuvalents)
ENV.1.3. Acidifying emissions	• Acidification (kg SO_2-equivalents)
ENV.5.1. Virgin raw materials	• Metal consumption, each type* (kg) • Water resource depletion* (m^3 water equivalent)
ENV.5.2. Fossil energy resources	• Non renewable resources* (MJ primary)
ENV.6.1. Non-hazardous waste	• Bulk waste* (kg)
ENV.6.2. Hazardous waste	• Hazardous waste* (kg) • Radioactive waste* (kg) • Slags/ashes* (kg)
SOC. 1.2. Local health impacts	• Human toxicity air (m^3 air)

* Not included in all LCA methods

4.2.2 General LCA software and databases

General LCA software allow the user to model any type of processes and link them to each other. The modelling software are coupled with life cycle inventory databases, which represent the backbone of the life cycle assessment. Life cycle inventory data are lists of inputs and outputs related to specific processes, e.g. electricity production and transport processes. These can be combined with the user-collected life cycle inventory data for specific processes that are not represented in the databases.

SimaPro and GaBI are the examples the most commonly used LCA software. The tools contain extensive databases with life cycle inventory data (e.g. the Ecoinvent database and the GaBi databases) and life cycle impact assessment models that convert emissions to potential environmental impacts. The price of such commercial LCA software is typically around 40.000-50.000 DKK for an annual license for one user including access to the life cycle inventory databases.

The free LCA software "OpenLCA" provided by GreenDelta is an alternative to these commercial tools. The software has the same functionality as the commercial tools, and can be used freely but only with freely available life cycle inventory data, such as the ELCD database (see section 4.2.2.1) is used. OpenLCA can also be used with the best quality databases such as Ecoinvent and GaBi, however in that case the cost for using these databases is nearly the same as the license for the commercial LCA tools.

General LCA software has the advantages of being flexible and applicable to all types of projects. Furthermore, the associated databases are continuously updated when new versions are available. The disadvantages of general LCA software is, apart from the cost, that it requires a skilled user trained in life cycle assessment to use the software. Furthermore, it can take a considerable amount of time to model the compared remediation systems. Therefore, it is typically not feasible to use such a software to carry out an LCA for smaller or medium sized remediation projects.

4.2.2.1 ELCD database

The European reference Life cycle database (ELCD database) is a freely available life cycle inventory database provided by the EU Joint Research Center. It contains EU-level data for key materials, energy carriers, transport and waste management, however the amount of included data is much smaller than for the commercial databases. The newest version of the database is version 3.2 from October 2015. As of June 2018, the database has been discontinued as will not be updated in the future.

4.2.3 LCA-based tools tailored for remediation

As alternatives to general LCA software a few LCA-based tools specifically tailored for the application to remediation projects have been developed. Examples of such tools are:

- RemS - Remediation Strategy for Soil and Groundwater Pollution (Weber et al. 2010)
- SiteWise^{TM}, Version 3.2 (NAVFAC, 2018)
- Spreadsheets for Environmental Footprint Analysis (SEPA) (US EPA, 2012)

The advantages of such tools are that they are easier to use, require less knowledge about life cycle assessment and take less time to apply, since they typically contain many default data about the included remediation technologies. The disadvantages of these tools are that they are less flexible and only can be used to assess selected remediation technologies, the background data, e.g. the life cycle inventory data are not continuously updated, and that these tools therefore rely on data from before 2009. Furthermore, the tools are developed for use in a specific geographical setting e.g. the US (SiteWise and US EPAs SEPA tool) or Denmark (RemS). Many production processes vary substantially between countries and states, e.g. the production of electricity. Therefore, the tools can only be used for the region that they are developed for. They are also limited in the number of remediation technologies that are represented in the tools. New and innovative techniques are not included and can therefore be difficult to assess with these tools.

4.2.3.1 RemS – Remediation Strategy for Soil and Groundwater Pollution

The RemS tool (Weber et al. 2010) is developed in Denmark and applicable to remediation taking place in Denmark. There is also a possibility to shift from Danish electricity to Swedish or

Norwegian electricity. The tool was issued in its first version in 2009 applying life cycle inventory data from the Ecoinvent database version 2.0 released in 2007.

RemS includes a number of remediation technologies that may also be combined for each compared remediation strategy, see Box 3. Based on the consumption of materials and energy for each remediation alternative, the tool calculates the life cycle impacts using the EDIP97 life cycle impact assessment method (Wenzel et al. 1997). Box 3 lists the remediation technologies and the life cycle impacts included in RemS.

Even though the background data in RemS has not been updated recently, it may still be applied to assess the relative size of environmental impacts associated with different remediation options. In this project it was applied to assess two different remediation options for a case site, see Section 5.3.1. One of the assessed remediation technologies is a technology based on liquid activated carbon, which is not included in the tool. Through the combination of the somewhat similar technology enhanced reductive dechlorination and the "specific consumption" choice in RemS, it was however, possible to model the most important parts of this technology. Missing processes were modelled using the OpenLCA software.

BOX 3: RemS – Remediation Strategy for Soil and Groundwater Pollution

Remediation technologies

- Excavation with off-site biological soil treatment
- Sheet pile wall
- Pumping
- Activated carbon treatment
- Passive soil vapor extraction
- Soil vapor extraction
- Dual-Phase extraction
- In situ chemical oxidation
- Enhanced reductive dechlorination
- Soil mixing with zerovalent iron
- In situ chemical oxidation
- Natural attenuation
- In situ thermal desorption
- Steam enhanced extraction
- Electrical resistivity heating

Life cycle impacts (unit)

- Global warming potential (ton CO_2-eq.)
- Acidification potential (kg SO_2-eq.)
- Photochemical ozone formation potential (kg C_2H_4-eq.)
- Eutrophication potential (kg NO_3-eq.)
- Persistent toxicity (m^3 soil or m^3 water)
- Ecotoxicity (water, acute) (m^3 water)
- Human toxicity (air) (m^3 air)

Waste

- Bulk waste (kg)
- Hazardous waste (kg)
- Radioactive waste (kg)
- Slags/ashes (kg)

Resource use

- Metal resources (kg)
- Energy resources (MJ)
- Mineral resources (sand, gravel) (kg)

4.2.4 Stakeholder engagement

As described in section 2.1.2 stakeholder engagement is an important part of valid sustainability assessment, especially in the case of larger remediation projects at sites representing a significant community and society interest.

At large sites with broad community interests, early inclusion of stakeholders can help qualify selection of appropriate remediation strategies that meet larger acceptance by stakeholders (Norrman et al., 2020). This was seen both in Sweden in relation to a sustainability assessment for remediation alternatives for a large site in southern Sweden (Norrman et al. 2020) and in a

Danish assessment comparing the sustainability of remediation alternatives for a large site in Denmark (Søndergaard et al. 2018). Both of these sites were among the largest contaminated sites in each country and well-known sites with large societal interest both at the community level and the national level.

If the compared remediation options, however, have the same efficiency towards removing contamination, two Australian studies concluded that stakeholders prefer more "natural" remediation options such as monitored natural attenuation and bioremediation over chemical, thermal and physical methods (excavation) (Huynh et al. 2018, Prior and Rai 2017).

4.2.4.1 Stakeholder involvement approaches

Before engaging stakeholders in the process, it is important 1) identify the relevant stakeholders, and 2) to clarify the goal of the stakeholder involvement.

According to English et al. (1993) the general goal of stakeholder involvement should be to develop a consensus among the stakeholder group, i.e. a shared sense of the long-term public interest for the area. The goal is not to develop a majority that will accept a proposed decision.

There are different approaches for involving stakeholders, examples of these are (English et al. 1993):

- **Small group approaches:** A smaller group of stakeholders that broadly represent the different interests related to a remediation project is identified. The group meets to discuss and reach consensus.
- **Open stakeholder meetings:** Large meetings that are open for all represent direct democracy. This format is, however, less appropriate for technical content, and discussions will often be controlled by few people in the large crowd.
- **Surveys:** Surveys in the form of questionnaires can be an easy way of investigating stakeholders (e.g. residents) opinion to certain questions. However, questions must be kept relatively simple to avoid misunderstandings. This format lacks the discussion and consensus part.
- **Multi-party mediation**: Agreement among a group of stakeholders is sought through the assistance of a trained, neutral mediator.

4.2.4.2 Relevant input from stakeholders in the Tier 2 assessment

After establishing a group of stakeholders broadly representing the interests related to the specific site (see also Section 2.1.2), a stakeholder meeting can be arranged. The stakeholder group should initially come to an agreement about:

- The objective of the remediation of the site
- The objective of the sustainability assessment
- The included sustainability criteria relevant for the specific site. These can be identified from the full list of indicators represented in TABLE 2, TABLE 3 and TABLE 4.

Following this, the stakeholder group can go into discussions about the assessment of specific indicators. The list below highlights the sustainability indicators that may benefit from assessment in a broader stakeholder group. The focus is especially on social indicators, but in addition also some of the economic indicators may be relevant to discuss in the stakeholder group depending on its composition:

- **Ethics and equality:**
  SOC 2.1: Distribution of responsibilities
  SOC 2.2: Distribution of impacts
  SOC 2.3: Ethical concerns

- **Neighbourhood:**
  SOC 3.1: Changes in site usage
  SOC 3.2: Changes in the built environment
  SOC 3.3: Nuisance due to remediation

- **Community:**
  SOC 4.1: Involvement and transparency of decision making
  SOC 4.2: Local spatial planning objectives

- **Indirect economic costs and benefits**
  ECON 2.1: Impact on neighbourhood reputation
  ECON 2.3: Uplift to local business

- **Induced economic costs and benefits**
  ECON 3.2 Effect on other projects/investments

- **Employment and employment capital**
  ECON 4.1: Job creation
  ECON 4.2: Effect on competency levels
  ECON 4.3: Innovation potential

In addition to assessing selected sustainability indicators in the stakeholder groups, stakeholders can also give input to how important the indicators are in relation to each other by establishing indicator weights.

4.2.5 Cost-benefit analysis (CBA)

Cost-benefit analysis (CBA) considers the gains and losses to society related to a project. The gains and losses (benetifts and costs) are valued in terms of a common scale – the monetary unit. The valuation can be carried out by means of different valuation methods expressing peoples preferences and willingness to pay.

Cost-benefit analysis seeks to calculate the net present value, NPV, of monetized costs and benefits over the remediation lifecycle by discouting of future costs and benefits. In practice, a full monitization of costs and benefits related to remediation of a contaminated site is difficult to carry out. However elements of cost-benefit analysis may be implemented in the assessment of selected impacts in a sustainability assessment, e.g. property value increase following remediation as well as indirect and induced impacts from a remediation project.

4.2.5.1 Remediation impact on property values

Remediation of a contaminated site can lead to increasing property values both for the remediated site and for site within the vicinity of the site. A US study has investigated the remediation effect on property values across the entire federal Brownfields Program (Haninger et al., 2017). This study indicated average increases in property values between 5-15% within 2.070 m of the remediated brownfield.

A Swedish study used a questionnaire to assess the increase in property values following the remediation of a well-known contaminated site (a former pesticide production plant) in the village of Teckomatorp (Norrman et al. 2020). The study gave a mean percentage change in property value of 14%, in the case of a full remediation with excavation of the soil followed by high temperature thermal treatment of the soil. For the containment alternative, where the contamination was contained by a physical barrier and a horizontal cover, the mean percentage change in property value as assessed by residents was 1%. For both alternatives the site would be developed to a recreational area, however with restrictions on future land use for the containment option.

5. Application to case study

5.1 Case study description

The case study site is based on an actual site, which is currently undergoing remediation in the Capital Region of Denmark. The site has hosted polystyrene production since 1962 and is located in a predominantly industrial area with several other smaller and medium-sized enterprises. A residential area is located just to the north-east of the site.

At the actual site, groundwater remediation using the innovative remediation technology "PlumeStop" is currently being tested. However, for the purpose of this report, the case study and the remediation technology design have been made more idealised than for the real case remediation design, which represents a test design with a higher degree of monitoring than would typically be carried out.

5.1.1 Site contamination

Investigations at the site showed that an underground storage tank placed in the southwest corner of the factory building has led to soil contamination with petroleum hydrocarbons in depths around 3-3,5 m below the ground.

The dominant contaminant at the site is trichloroethene (TCE) which has been found in a thin sand layer in the clay till and in the groundwater aquifer located around 8 meters below ground level. Based on pore gas investigations, the source area of TCE is expected to be located in the northern end of the factory building; however, the hotspots have not been located and characterized. A conceptual model of the TCE contamination at the site is seen in FIGURE 4.

The aquifer is regional (primary) and is located in medium-fine sand with a hydraulic conductivity of approximately 1 x 10^{-5} m/s in average. The contamination at the site constitutes a risk to the groundwater quality. The remediation effort at the site is directed towards this groundwater risk.

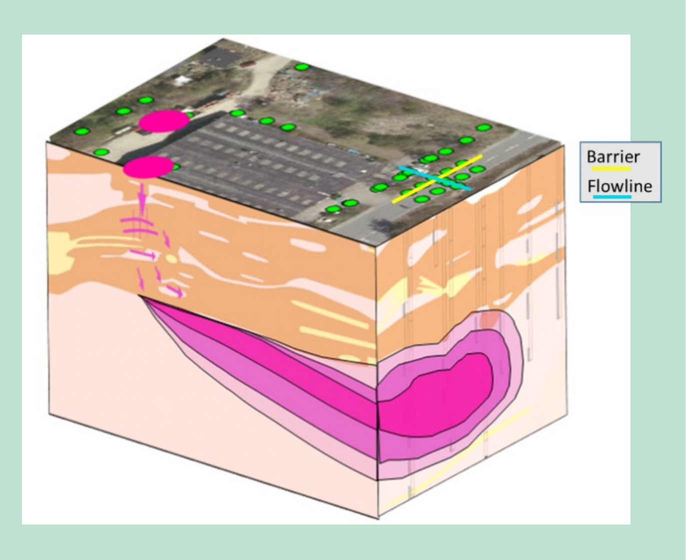

FIGURE 4. Conceptual model of the TCE contamination at the site showing the TCE-contaminated plume in pink (1-1200 µg TCE/l) and the groundwater flow direction (blue flowline).

5.1.2 Remediation alternatives

Two remediation options are compared for this site. Since the source of TCE is not identified, the focus of the remedial action is to treat the groundwater plume. Currently, concentration levels of up to 680 µg/l of TCE are found in the aquifer below the site upgradient the treatment zone.

For the purpose of using this site as a case study, a remediation objective has been defined as the containment of the contaminant groundwater plume for a period of 30 years. For this period, the maximum concentration of chlorinated ethenes accepted downgradient in the groundwater is 1 µg/L.

The two compared remediation methods are:

- **Pump-and-treat:** involves continuous pumping of groundwater from the site and on-site treatment using activated carbon. After treatment the water is reinfiltrated to the groundwater aquifer.
- **PlumeStop**: involves the injection of a liquid activated carbon (called "PlumeStop") along a transect of the plume together with an electron donor and a bacterial culture. The PlumeStop creates a barrier to which the chlorinated compounds adsorb on the surface of the fine activated carbon particles. The electron donor and bacterial culture enhances the degradation of the TCE via the reductive dechlorination pathway through cis-DCE (cis-dichloroethene) to VC (vinyl chloride) and ethene.

The PlumeStop product consists of activated carbon particles (≤ 4% weight), water (96% weight) and additives (≤ 2% weight). The electron donor is a mix of lactic acid, glycerol and glycerol tripolyacetate. The PlumeStop regenerates itself and is only injected once, whereas electron donor and bacterial culture are assumed to be reinjected after 10 years. The PlumeStop barrier will be approximately 30 m wide and 9 m deep in the direction perpendicular to the groundwater.

The pump-and-treat option will abstract water continuously from the aquifer. The water is treated on-site using activated carbon after passing through sandfilters to remove iron, manganese and organic matter. After treatment the water is reinfiltrated to the groundwater aquifer.

Key data regarding main material use, energy use, time use and cost for the two remediation alternatives are summarized in the TABLE 9 below.

TABLE 9. Overview of key data regarding the two remediation alternatives.

	Pump-and-treat	PlumeStop
Installations at site		
Material use	1 pumping well (polyethylene, PE) 5 monitoring wells (polyethylene, PE) Activated carbon treatment unit 1 reinfiltration well (polyethylene, PE)	18 injection wells (steel) (first injection round) 9-10 injection wells (following injection rounds) 7 monitoring wells (polyethylene, PE)
Energy use	Drilling of boreholes (7 pcs.)	Direct push injections using Geoprobe Drilling of monitoring wells (7 pcs)
Remediation phase		
Material use	Activated carbon (0,08 kg/m^3 of water → 125 tons in 30 years)	PlumeStop (PS): 13.000 L containing approx. 520 kg activated carbon Bacterial culture (BDI): 36 L/injection round, 108 L in total Electron donor (HRC): 2.200 kg/injection round. 6.600 kg in total Water for dilution of PS (diluted to 145.000 L)
Energy use	Pump rate: 6 m^3/h (52.560 m^3/y) Pumping (33 MWh/year)	Reinjection of electron donor and bacterial culture
Waste production at site	Activated carbon waste Soil waste from drilling of boreholes	Soil waste from drilling of boreholes Empty containers PS, HRC, BDI
Time use at site		
Operation time	30 years of continious pumping and activated carbon treatment Activated carbon changed every 12 months	Anticipated number of injection rounds: 3 (2-3 weeks work at site/injection round) Passive in between injections
Monitoring	Continued monitoring	Continued monitoring
Cost of remediation incl. operation and monitoring	15.800.000 DKK	6.500.000 DKK
Remediation efficiency	Expected to capture entire plume from day 1	Expected to sorb 1-3 months after injection, and to degrade within the same timeframe, therefore 1-3 months before it becomes fully effective

5.1.3 Disturbances experienced by property owner and area users during remediation

Installation of a **Pump-and-treat** facility will entail establishment of a pumping well, treatment facility and piping to transport the pumped and treated groundwater. The pumping well can be placed in an area on-site that at present does not inconvenience the property owner and site users. Pumping well and monitoring wells will take approx. 6-10 days to establish. The treatment facility will be of a size that corresponds to a container (approx. 15-30 m^2) and be placed at the south eastern part of the property. Underground piping will be fitted to pump, treatment facility and the re-infiltration system. The treatment facility will be fitted with an automatic operating system and will be visited during maintenance and any alarm from the operating system. Maintenance will include change of activated carbon in filters every 12 months and sampling of pumped and treated water frequently during the first 3 months and then less frequently. A re-infiltration well will be installed upgradient from the treatment zone and will be connected to the treatment facility.

Installation of the **PlumeStop** barrier will require establishment of approximately 18 injection points at the edge of the property, probably closing one half of the road and the pavement along the work area during the establishment period. Trees in the work area will have to be cut down and injection points will have to be prepared (top 2 m) so that cables running in and along the work area will not be harmed. The work will last approximately 15-25 days including establishment of monitoring wells. Monitoring wells will be sampled frequently during the first 3 months and then less frequently. Electron donor and perhaps bacterial culture will have to be reinjected every 10 years entailing the establishment of injection points (up to 18 per injection round) and the nuisances mentioned above.

In both cases the following will in the above-mentioned periods be bothered by the work during and for the later injections also after establishment of the remedial method:

- Pedestrians use the pavement (dog walking etc.) and must either use another road or pass along by using the road itself
- Traffic in one road lane will be slow (the other lane will be closed), which will influence traffic to a small degree as the area is not heavily trafficked, but surrounding enterprises are frequently visited by lorries carrying supplies and products to and from the enterprises. However, there is also an alternative road that may be used to enter the area. Therefore, this issue is assessed to be less important.

Tier 1 assessment

A Tier 1 assessment of the case study comparing groundwater remediation by pump-and-treat (P&T) and PlumeStop was carried out based on the application of the indicators in the simple list. The indicator scores are seen in TABLE 10. TABLE 11 include short motivations for the scores. The scoring is based on input from the project workshop, where the participants were divided in two groups, who each carried out a Tier 1 assessment for this case study site. Some changes were made to the assumptions since this workshop, mainly that the abstracted water in the P&T option is assumed to be re-infiltrated to groundwater after treatment instead of being discharged to the sewer system.

The PlumeStop method obtained better scores than the P&T in many of the environmental indicators, since it has a lower impact in greenhouse gas emission, waste production and resource use. Furthermore, the nuisance experienced by the PlumeStop method is assessed to be smaller than that of P&T, since the PlumeStop method is mainly passive and only requires reinjection every 10 years. P&T, on the other hand, requires the permanent installation of a treatment facility on the site and annual site visits to change the activated carbon. Finally, the estimated total cost of PlumeStop is also lower than the cost of P&T.

On the negative side, the uncertainty related to the technological performance is higher for PlumeStop, since this is a rather novel method which has been applied much less frequently than P&T. Furthermore, the establishment of an effective PlumeStop barrier requires a good distribution of PlumeStop, electron donor and microorganisms in the subsurface. Therefore, this method is more dependent on site-specific conditions such as aquifer inhomogeneities that can affect the spreading of the injected materials. In addition, this option also requires more site-specific knowledge. Furthermore, there may be a risk that if the barrier is not constructed properly, there may be spreading of degradation products from the reductive dechlorination of TCE to the groundwater.

TABLE 10. Tier 1 sustainability assessment for the case study site.

		Indicator weight	Pump-and-treat Score 1-5	PlumeStop Score 1-5
ENVIRONMENTAL INDICATORS		**33%**		
Indicator heading	**Indicator**			
Air	Greenhouse gas emissions	1,5	4	2
Soil and ground conditions	Residual soil contamination	0		
	Topsoil degradation and use of topsoil	0		
	Changes in geotechnical properties	0		
Groundwater and surface water	Groundwater contamination after remediation	1,5	1	1
	Ground- and surface water quality	1,5	1	2
Nature	Effects on biota and ecosystems	1,5	1	2
Raw materials	Virgin raw material use	1,5	4	2
Waste	Hazardous waste	1,5	3	1
SOCIAL INDICATORS		33%		
Indicator heading	**Indicator**			
Health and safety	Reduction in health risks	0		
	Local health impacts	1,8	1	1
	Working environment risks	1,8	2	2
Ethics and equality	Distribution of impacts	1,8	1	1
	Ethical concerns	1,8	1	2
Neighbourhood	Nuisance due to remediation	1,8	4	2
ECONOMIC INDICATORS		33%		
Indicator heading	**Indicator**			
Direct economic costs	Total cost of remediation	1,5	4	2
Lifespan and flexibility	Lifespan of remediation technology	1,5	4	4
	Need for institutional controls	1,5	1	1
	Flexibility of remediation alternative	1,5	3	2
Uncertainty and evidence	Uncertainty of technology performance	1,5	1	4
	Quality of available information	1,5	1	3

TABLE 11. Motivations for indicator scores for the Tier 1 sustainability assessment for the case study site.

		Comment to score
ENVIRONMENTAL INDICATORS		
Indicator heading	**Indicator**	
Air	Greenhouse gas emissions	Highest GHG emission related to P&T due to continuous energy use for pumping, and due to production of large amounts of activated carbon. Low GHG emission related to PlumeStop since the system is mostly passive and require relatively small amounts of chemicals
Soil and ground conditions	Residual soil contamination	Not relevant
	Topsoil degradation and use of topsoil	Not relevant
	Changes in geotechnical properties	Not relevant
Groundwater and surface water	Residual groundwater contamination	The methods are assumed to provide the same reduction in groundwater concentrations
	Ground- and surface water quality	If the PlumeStop barrier is not properly constructed, there may be a risk of leaching of degradation products. Furthermore, the injection of PlumeStop products causes subsurface changes in redox conditions etc.
Nature	Effects on biota and ecosystems	PlumeStop require that the trees are cut down in the injection area
Raw materials	Virgin raw material use	Highest consumption by P&T due to large coal use for activated carbon. Steel use for injection wells in PlumeStop
Waste	Hazardous waste	P&T produces large amounts of activated carbon waste. No significant waste with PlumeStop option
SOCIAL INDICATORS		
Indicator heading	**Indicator**	**Comment to score**
Health and safety	Reduction in health risk	Not relevant
	Local health impacts	Assessed to be similar in magnitude
	Working environment risks	Assessed to be similar in magnitude
Ethics and equality	Ethical concerns	The PlumeStop product contains proprietary additives (polymers) that are unknown Only one provider of the PlumeStop method, which creates unequal competition
	Distribution of impacts	In both cases, the main negative impacts are directed at the site owner, however they are assessed to be relatively minor. If installations were placed on a public area instead of the private area, the impact to the site owner would be less.
Neighbourhood	Nuisance due to remediation	The highest nuisance is related to P&T due to permanent installation of container with treatment system at site and annual visits for changing the activated carbon filters. PlumeStop is mainly passive, but reinjection will require work at the site every 10 years

ECONOMIC INDICATORS		
Indicator heading	**Indicator**	**Comment to score**
Direct economic costs	Cost of remediation incl. operation and monitoring	P&T is significantly more expensive than the PlumeStop method
Lifespan and flexibility	Lifespan of remediation technology	Both methods work by treating the groundwater plume and need continuous maintenance. The contaminant source is not removed
	Need for institutional controls	No need in any of the options
	Flexibility of remediation alternative	The P&T option is slightly more flexible, since it is easier to increase the pumping volume than to increase the injected amounts in PlumeStop
Uncertainty and evidence	Uncertainty of technology performance	P&T is a well-known technology, whereas PlumeStop represents a more innovative technology. There need to be contact between injected PlumeStop, contaminants, electron donor and microbes for successful application.
	Quality of available information	The PlumeStop method require more knowledge about e.g. aquifer heterogeneities and water chemistry affecting the efficiency of the method.

5.1.4 Total sustainability score

FIGURE 5 shows the combined result of the sustainability assessment. The total sustainability score is calculated as weighted sum of scores according to Equation 1, by using the weights and scores in TABLE 10. An equal weight (33%) was assigned each of the three sustainability dimensions. Furthermore, as shown in TABLE 10, the indicators under each dimension were equally weighted.

PlumeStop is the option that has the best overall sustainability score. As seen in FIGURE 5, this is mainly due to the lower environmental impacts related to this option compared to Pump-and-Treat. The societal impacts of the two options are relatively equal. The PlumeStop option performs slightly worse in the economic dimension, even though the remediation cost is estimated to be lower than that of P&T. This is due to the larger uncertainty in the technological performance related to this option, which impacts the economy score.

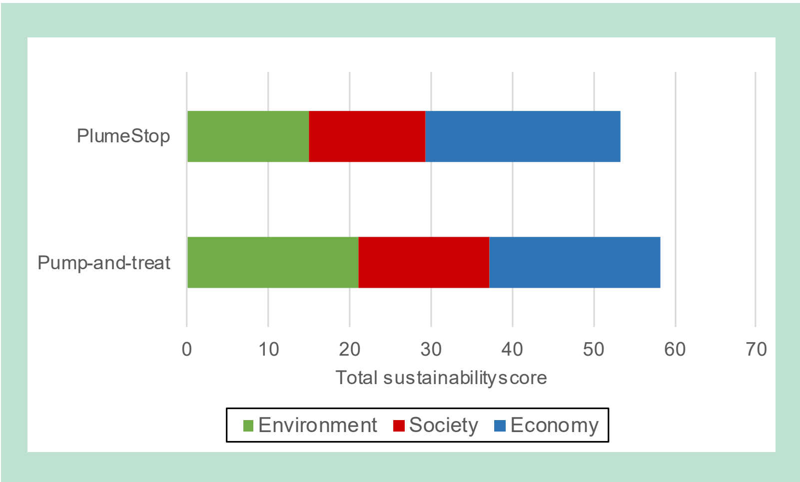

FIGURE 5. The total sustainability score (Tier 1) for each of the remediation options divided into scores for each of the three dimensions of sustainability. The score is calculated by giving an equal weight to each of the three dimensions.

5.1.5 Impact to the UN SDGs

The impact to the UN sustainable development goals (SDGs) is calculated using the coupling of indicators and SDGs presented in TABLE 6. Low scores indicate low impact, high scores indicate high impact. The negative impacts to the SDGs are generally a bit higher for pump-and-treat than for the PlumeStop option, except for SDGs 6, 14 and 15 where both options have a low impact.

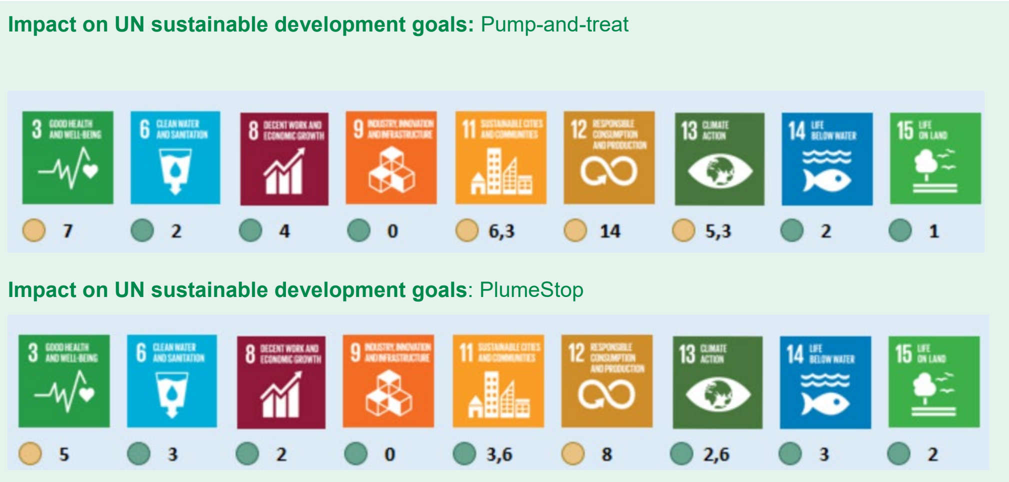

FIGURE 6. Effect on UN sustainable development goals for each of the remediation options. Low impact (< 5) indicated by a green dot, medium impact (5-15) indicated by yellow dot . High impact (> 15) indicated by red dot.

5.2 Tier 2 assessment

5.2.1 Life cycle assessment

A life cycle assessment has been carried out to compare selected environmental impacts related to the two remediation alternatives. The LCA is carried out using the RemS tool (see further description of this tool in Section 4.2.3.1) combined with the OpenLCA tool (see description of tool in Section 4.2.2).

The compared functional unit in the LCA is the containment of the contaminated groundwater plume for a period of 30 years ensuring that the groundwater concentrations downgradient of the site will not exceed the groundwater quality criteria for chlorinated ethenes.

The LCA is carried out as a streamlined LCA with focus only on the most important processes contributing to environmental impacts. The assessment covers the consumptions of energy and materials as specified in TABLE 9.

The RemS tool is applied by entering site-specific consumption data for each technology. The pre-entered data regarding technology design in RemS is overwritten by the site-specific data estimated for this case study.

The input data used in RemS are shown in Appendix 3. The consumption data for the pump-and-treat option was entered under the chosen technologies “pumping” and “treatment”. Consumables for the PlumeStop option was entered under the technology “Stimulated reductive dechlorination", since this technology includes many of the same types of consumables as PlumeStop, i.e. electron donor and microbial culture. All non-relevant consumption data were set to zero. Regarding the use of electron donor, it was represented by 50% lactate, representing a faster degradable donor and 50% emulsified soy bean oil (60% soy bean oil) representing a slowly degrading electron donor, which are the two electron donor types available in RemS.

Other consumables related to the PlumeStop method were entered under the technology choice "specific consumption". Here the activated carbon use, the injection by geoprobe and injection well materials (steel) was entered.

The specific products used for the PlumeStop option are PlumeStop (the liquified activated carbon), the electron donor (HRC) and the bacterial culture (BDI). These products are all produced in the US. PlumeStop and HRC are transported to Ireland by sea freight and further on to Denmark by sea freight, whereas BDI is transported to Denmark by air freight. In addition, the PlumeStop product is transported approximately 80 miles (130 km) by truck within the US (Forde, 2020).

Energy use for producing the milled activated carbon from a powdered activated carbon is in the order of 0,053 kWh per drum of PlumeStop containing 200 kg of final PlumeStop product with a content of around 4 % activated carbon. This gives an energy use of 3,4 kWh for the 13 tonnes of PlumeStop used at the site. This was added under "specific consumption", however this electricity use is very small and will not impact the life cycle assessment result much. The milled activated carbon is diluted and mixed with polymers to create the final PlumeStop product. The energy use for this final production step was assessed to be negligible by Regenesis (Forde, 2020).

Additional road transport of 13 tons PlumeStop by truck was added under "specific consumption" in RemS by assuming that two 3,5-7,5 t trucks each travel 130 km. Additional transport by sea freight is not available in RemS. Therefore, additional transport of PlumeStop and lactate (in total 13 tonnes of PlumeStop and 3.3 tonnes of electron donor, transported 15.458 km by sea freight) was added by calculating the impact in OpenLCA using the ELCD database, see result in Appendix 4. Emulsified soy bean oil is already assumed to be transported by sea freight from the US in RemS, and bioculture is already assumed to be transport by air from the US.

As mentioned in Section 4.2.3.1, the background data in RemS have not been updated since it was first issued in 2009. This adds some uncertainty to the LCA results. Furthermore, more novel technologies are not represented in this tool. However the use of "specific consumption" allows the user to enter specific use of energy, materials, transport etc. and may be used to model other technologies. In this case, however, additional processes were modelled using the OpenLCA tool.

5.2.2 LCA results

The LCA results in the impact categories greenhouse gas emission, acidification, photochemical ozone formation, hazardous waste, slags/ashes are shown in FIGURE 7 together with the total energy use of each remediation options. It is evident that the Pump-and-treat method generates much higher potential impacts in each of these categories than PlumeStop.

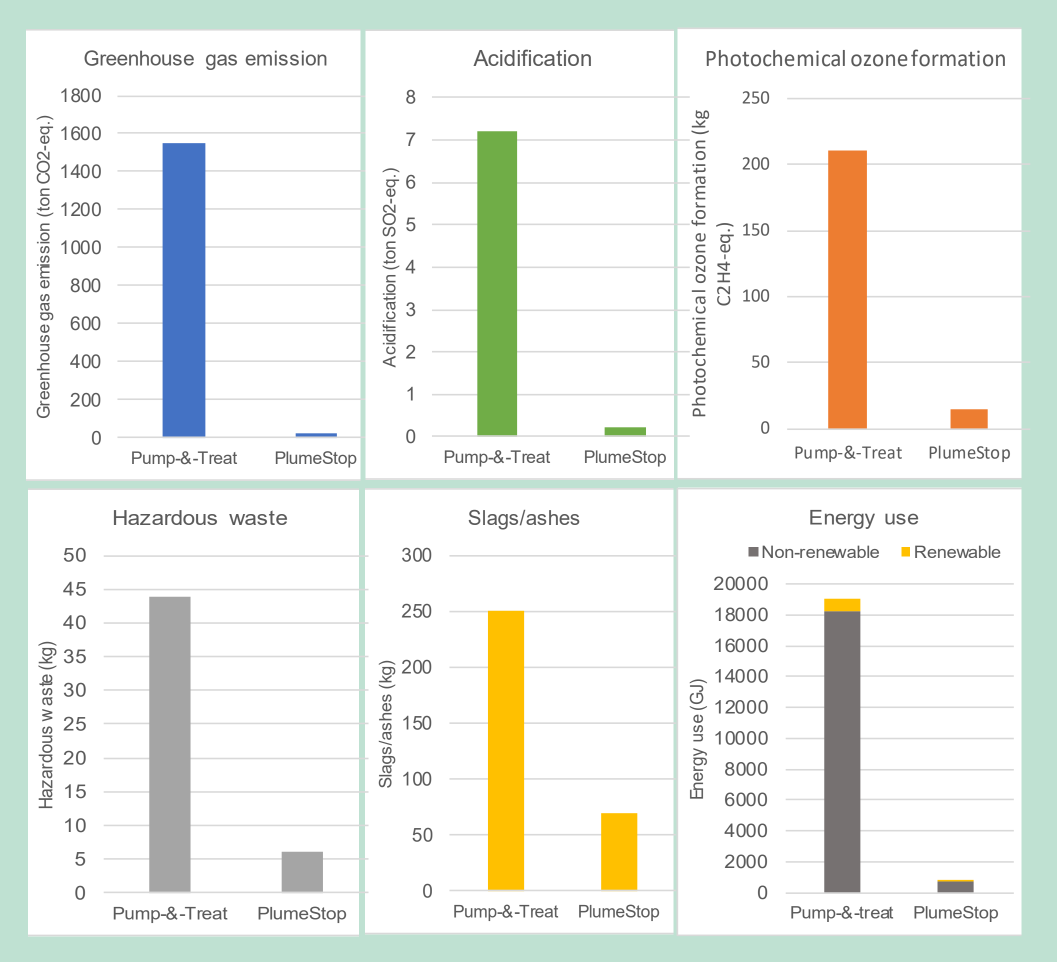

FIGURE 7. Selected results from the life cycle assessment.

5.2.3 Additional indicators assessed in the Tier 2 assessment

Based on the full list, a number of additional indicators were assessed in the Tier 2 assessment (see TABLE 12).

The LCA results were used to reassess the environmental indicators “Greenhouse gas emission” and “Hazardous waste” already assessed in the Tier 1 assessment. They also provided the background for assessing the additional environmental indicators “Local air pollution” and “Acidifying emissions”.

In the economic domain, the indicators “Change in property value”, “impact on neighbourhood reputation” and Effect in competency levels” were added to the assessment. Based on the study by Norrman et al. (2020) referenced in Section 4.2.5.1, however, the change in property value was assessed to be very low (a score of 5 for both options), since no source removal takes place in this case. The impact on the reputation of the neighbourhood due to remediation was also assessed to be similar for the two options and given a score of 4 also representing a minor impact. This is due to the fact that the site is within an industrial and commercial area that may have several contaminated sites. The impact of treating one of these sites is therefore minor.

The effect on the competency level before and after remediation is assessed to be significantly higher for PlumeStop, which is a relatively new remediation technology. The application of the technology will therefore lead to increased competency levels both for consultants and regulators involved in the project.

TABLE 12. Tier 2 sustainability assessment for the case study site.

		Indicator weight	Pump-and-treat	PlumeStop
ENVIRONMENTAL INDICATORS		**33%**	**Score 1-5**	**Score 1-5**
Indicator heading	**Indicator**			
Air	Greenhouse gas emissions	1	5	1
	Local air pollution	1	5	2
	Acidifying emissions	1	5	1
Soil and ground conditions	Residual soil contamination	0		
	Topsoil degradation and use of topsoil	0		
	Changes in geotechnical properties	0		
Groundwater and surface water	Residual groundwater contamination	1	1	1
	Contaminant mobilization and movement	0		
	Ground- and surface water quality	1	1	2
	Water abstraction and recreational use	0		
Nature	Effects on biota	1	1	2
	Changes in ecology and ecosystems	0		
	Landscape effects	0		
Raw materials	Virgin raw material use	1	4	2
	Fossil energy resources	1	5	1
	Re-used and -cycled material	0		
Waste	Hazardous waste	1	4	1
	Non-hazardous waste	0		
		Indicator weight	**Pump-and-treat**	**PlumeStop**
SOCIAL INDICATORS		33%	Score 1-5	Score 1-5
Indicator heading	**Indicator**			
Health and safety	Reduction in health risk	0		
	Local health impacts	1,8	1	1
	Working environment risks	1,8	2	2
	Risks to public	0		
Ethics and equality	Distribution of responsibilities	0		
	Distribution of impacts	1,8	1	1

	Ethical concerns	1,8	1	2
Neighbourhood	Changes in site use	0		
	Changes in the built environment	0		
	Nuisance due to remediation	1,8	4	2
Community	Involvement and transparency of decision making	0		
	Local spatial planning objectives	0		
		Indicator weight	**Pump-and-treat**	**PlumeStop**
ECONOMIC INDICATORS		33%	Score 1-5	Score 1-5
Indicator heading	**Indicator**			
Direct economic costs and benefits	Total cost of remediation	1	4	2
	Other associated (third party costs)	0		
	Changes in property values	1	5	5
Indirect economic costs and benefits	Risk of damages	0		
	Impact on neighborhood reputation	1	4	4
	Uplift to local business	0		
Employment and employment capital	Job creation	0		
	Effect on competency levels	1	5	2
	Innovation potential	0		
Lifespan and flexibility	Lifespan of remediation technology	1	4	4
	Need for institutional controls	1	1	1
	Flexibility of remediation alternative	1	3	2
Uncertainty and evidence	Uncertainty of technology performance	1	1	4
	Quality of available information	1	1	3
	Quality of sustainability assessment	0		

5.2.4 Total sustainability score in Tier 2

FIGURE 8 presents the total sustainability score result of the Tier 2 assessment. The result is calculated by assigning an equal weight to each of the three dimensions. Furthermore, the indicators in each dimension are given equal weights as presented in TABLE 12. Based on the more detailed assessment of environmental impacts in the LCA, it is evident that the PlumeStop option performs even better than the P&T option in the economical domain than it did in the Tier 1 assessment. The two options obtain very similar sustainability scores both in the social and the economic domain. As a result PlumeStop is the option with the lowest total score, thereby representing the most sustainable option.

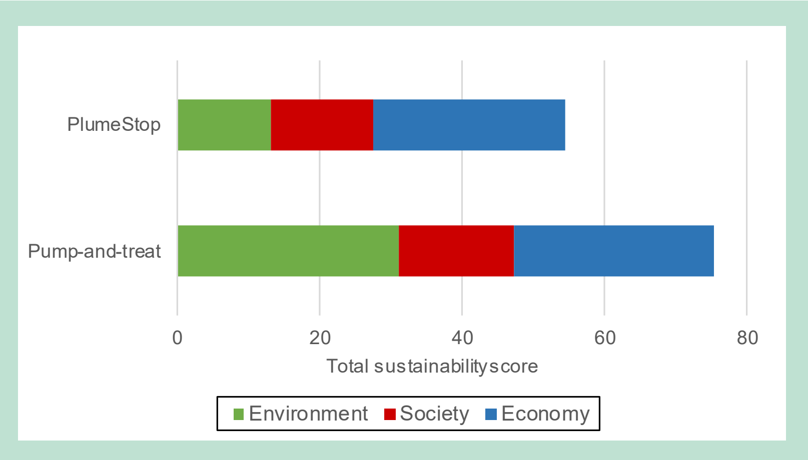

FIGURE 8. The total sustainability score (Tier 2) for each of the remediation options divided into scores for each of the three dimensions of sustainability. The score is calculated by giving an equal weight to each of the three dimensions.

The impact to the UN sustainable development goals (SDGs) is calculated using the coupling of indicators and SDGs presented in TABLE 6. The highest impacts to the SDGs are generally calculated for the pump-and-treat option as seen in FIGURE 9.

FIGURE 9. Effect on UN sustainable development goals for each of the remediation options. Low impact (< 5) indicated by a green dot, medium impact (5-15) indicated by yellow dot . High impact (> 15) indicated by red dot.

6. Discussion and recommendations

6.1 Recommended workflow for sustainability assessment on Tier 1 (initial sustainability assessment)

An initial sustainability assessment is relevant for all sites for which a remedial action is to take place. The assessment on Tier 1 is recommended to be carried out following the workflow/checklist described below:

1. The remediation objectives for the contaminated site have been defined
2. Two or more alternatives for site remediation or risk reduction have been selected. These alternatives can comply with the defined remediation objectives
3. Relevant stakeholders that can directly or indirectly affect or be affected by the project are identified.
4. An assessment of sustainability indicators is carried out preferably in a group. For smaller projects, it may not be relevant to involve stakeholders at this stage. The assessment can start out from either
    - the simple indicator list, or
    - the full indicator list

    In either case, non-relevant indicators are deselected by giving them a weighting of zero.
5. Indicators are scored on a 1-5 scale, where 1 is given to the best option and 5 is given to the worst option. Note that it is not neccesary to use the entire scale from 1 to 5 if the remediation options are relatively similar. Appendix 2 outlines relevant considerations for scoring of each indicator on the simple list. The motivation for the scores is noted during the assessment.
6. Indicators are each given a weight from 1-5, or zero if the indicator is not relevant in the specific case. It is recommended that each overall sustainability dimension (environment, society and economy) is weighted equally. This can be done by assigning the same total number of weights to indicators below each dimension either by
    - giving the same weight to each indicator in the dimension. Decimal numbers are allowed. The sum of weights is equal within all 3 dimensions; or
    - giving individual weights to each indicator in the dimension. The sum of weights is equal within all 3 dimensions
7. A total sustainability score is calculated as the weighted sum of scores according to Equation 1.

6.2 Recommended workflow for sustainability assessment on Tier 2 (detailed sustainability assessment)

The workflow follows that of Tier 1, with the following modifications:

- A wider stakeholder group is included in the sustainability assessment process. This is especially important for sites with a large and/or more complex community and societal interest. The stakeholder group may give important insight into the acceptability of the remediation alternatives (step **2**).
- In step **4** it is recommended to start from the full list of indicators and agree on relevant indicators in the stakeholder group. Furthermore, the stakeholder group is included in the assessment of the indicator scores, especially the social indicators.

- In step **5**, it is recommended to do more quantitative assessments of indicators by carrying out a life cycle assessment, and by valuation methods as applied in cost-benefit-analyses.
- In step **6**, the stakeholder group should seek to reach consensus about the weighting of individual sustainability indicators if an equal weighting of the three sustainability dimensions is not applied. The weighting may also be a political decision by the authority that is financially responsible for the remediation. In any case, it is always recommended to show the result with equal weighting together with the result with an unequal weighting of the three sustainability dimensions.

6.3 Final discussions and recommendations

Although the methodology makes it possible to calculate an overall sustainability score and compare the remediation options based on this score, the most important feature of the tool is that is provides a framework for the assessment group to go through a structured discussion about sustainability, not only focusing on the environmental aspects, but also the social and economic aspects.

The advantages of using such a methodology is that it aids to qualify the discussion about sustainability. Therefore, the discussion in itself is just as important as the final result of the assessment. In line with this, it should also be emphasized that the methodology is to be used for decision-support, it will not decide what decision to be taken in each case, but provide support for decision-makers.

The outcome can be very dependent on the applied weighting factors. Therefore, as mentioned above, it is recommended always to specify and explain the weighting applied to the three overall sustainability dimensions. The result with an equal weighting should be shown for reference.

The methodology for sustainability assessment is relevant for most remediation cases, except for very small projects. The Tier 1 assessment is a quick assessment and is recommended for all projects. However for smaller projects, the assessment may be carried out by a single assessor and not in a group. For larger sites, and megasites especially, a Tier 2 assessment including a wide stakeholder group is recommended as a supplement to the tier 1 assessment.

7. References

Bardos, RP, Thomas, HF , Smith, JWN , Harries, ND , Evans, F, Boyle, R, Howard, T , Lewis, R , Thomas, AO, Haslam, A (2018). The Development and Use of Sustainability Criteria in SuRF-UK's Sustainable Remediation Framework. Sustainability 10, 1781

Bardos, RP, Bone, DB, Boyle, R, Evans, F, Harries, ND, Howard, T, Smith, JWN (2016). The rationale for simple approaches for sustainability assessment and management in contaminated land practice. Science of the Total Environment 563-364 (2016) 755-768.

Bayer, P, Finkel, M (2006). Life cycle assessment of active and passive groundwater remediation technologies. Journal of Contaminant Hydrolog 83, (3) 171-199.

Cadotte, M, Deschenes, L, Samson, R (2007). Selection of a remediation scenario for a diesel-contaminated site using LCA. The International Journal of Life Cycle Assessment 12 (4), 239-251.

Ding, D, Song, X, Wei, C, LaChance, J (2019). A review on the sustainability of thermal treatment for contaminated soils. Environmental Pollution 253 (2019) 449-463.

English, M.R, Gibson, A.K, Feldman, D.L, Tonn, B.E (1993). Stakeholder involvement open processes for reaching decisions about the future use of contaminated sites (University of Tennessee Press).

Forde J. (2020). Personal communication via email with Jim Forde from Regenesis

Freeman RE (1984) Strategic management: a stakeholder approach. Pitman Publishing, Boston

Haninger, K, Ma, L, Timmins, C (2017). The value of brownfield remediation. Journal of the Association of Environmental and Resource Economists. 4, 197–241.

Harclerode, M, Ridsdale, DR, Darmendrail, D, Bardos, P, Alexandrescu, Nathanail, P, Pizzol, L, Rizzo, E (2015). Remediation Winter 2015, 11-42.

Huynh, E, Arana, JE, Prior, J (2018). Evaluating residents' preferences for remediation technologies: A choice experiment approach. Science of the Total Environment 621 (2018), 1012-1022.

ISO (2017): Soil quality - Sustainable remediation, ISO 18504:2017

Lemming (2010). Environmental assessment of contaminated site remediation in a life cycle perspective. PhD Thesis. DTU Environment. September 2010.

Lemming G, Chambon J, Binning PJ, Bulle C, Margni M, Bjerg PL (2010). Environmental impacts of remediation of a trichloroethene-contaminated site: life cycle assessment of remediation alternatives. Environmental Science & Technology 44, 9163–9169.

Lemming G, Chambon JC, Binning PJ, Bjerg PL (2012) Is there an environmental benefit from remediation of a contaminated site? Combined assessments of the risk reduction and life cycle impact of remediation. Journal of Environmental Management 112, 392–403.

Liao, X, Wu, Z, Li, Y, Cao, H, Su, C (2019). Effects of various chemical oxidation reagents on soil indigenous microbial diversity in remediation of soil contaminated by PAHs. Chemosphere 226 (2019) 483-491.

NAVFAC (2018). SiteWise™ Version 3.2, User Guide. SP-NAVFAC EXWC-EV-1802. October 2018.

NICOLE (2010) Road map for sustainable remediation. Network for industrially contaminated land in Europe. Issued September 2010.

Norrman, J, Söderqvist, T, Volchko, Y, Back, PE, Bohgard, D, Ringshagen, E, Svensson, H, Englöv, P, Rosen, L (2020) Enriching social and economic aspects in sustainability assessment of remediation strategies – Methods and implementation. Science of the Total Environment 707 (2020).

Polli, F, Zingaretti, D, Crognale, S, Pesciaroli, L, D'Annibale, A, Petruccioli, Baciocchi, R (2018). Chemosphere 191 (2018) 580-588.

Prior, J, Rai, T (2017). Engaging with residents' perceived risks and benefits about technologies as a way of resolving remediation dilemmas. Science of the Total Environment 601-602 (2017) 1649-1669.

Rosén L, Back PE, Söderqvist T, Norrman J, Brinkhoff P, Norberg T, Volchko Y, Norin M, Bergknut M, Döberl G (2015) SCORE: a novel multi-criteria decision analysis approach to assessing the sustainability of contaminated land remediation. Sci Total Environ 511:621–638.

Søndergaard, G, Binning, PJ, Bondgaard, M, Bjerg, PL (2018). Multi-criteria assessment tool for sustainability appraisal of remediation alternatives for contaminated sites. Journal of Soils and Sediments 18, 1334-3348.

Surf-UK (2011). A framework for assessing the sustainability of soil and groundwater remediation, Annex 1. The SuRF UK Indicator set for sustainable remediation assessment. CL:AIRE, London, UK. November 2011.

UN (1987). Our common future. World Commission on Environment and Development. General Assembly Resolution 42/187, 11 December 1987.

USEPA (2012). Methodology for Understanding and Reducing a project's Environmental Footprint. U.S. Environmental Protection Agency. EPA 542-R-23-002. February 2012.

Villa RD, Trovó, AG., Pupo Nogueira, RF (2008). Environmental implications of soil remediation using the Fenton Process. Chemosphere 71 (2008), 43-50.

Weber, K, Wodschow, N, Lemming G (2010). Remediation Strategy for Soil and Groundwater Pollution – RemS. Region Hovedstaden, Videnscenter for jordforurening og Miljøstyrelsen.

Wenzel, H.; Hauschild M.; Alting L. (1997). Environmental assessment of products - 1: Methodology, tools, and case studies in product development. Chapman & Hall, United Kingdom, 1997, Kluwer Academic Publishers, Hingham, MA. USA.

Appendix 1. Sustainability indicator lists

Appendix 1.1 Indicator descriptions, full list, English and Danish versions

TABLE 13. Sustainability indicators, Environment (full list).

ENVIRONMENTAL INDICATORS		
	Indicator name	**Short description**
Air		
ENV.1.1	Greenhouse gas emissions	Greenhouse gas (GHG) emissions include air emissions such as CO_2, CH_4, N_2O and fluorinated gases. These are gases that trap heat in the atmosphere and cause global warming. The global warming impact can be estimated as the emission in terms of kg of CO_2-equivalents.
ENV 1.2	Local air pollution	Emissions that constitute a local air pollution problem that may impact human health and the environment, e.g. NOx, VOC, CO which can cause formation of photochemical ozone which is toxic gas that can cause respiratory problems, and emissions of particulate matter (PM).
ENV 1.3	Acidifying emissions	Acidifying emissions cover SOx, NOx, HCl, HNO_3, H_2SO_4, etc. Acidification can lead to reduced inefficient forest growth, loss of aquatic life. Increased acidification may also lead to increased mobilisation of heavy metals and aluminium.
Soil and ground conditions		
ENV.2.1	Residual soil contamination	Residual soil contamination is the contamination which remains after steps have been taken to reduce the associated risks. If soil remediation is the primary aim of the project, protection over and above the required cleanup can therefore be assessed here.
ENV 2.2	Topsoil degradation and consumption	Topsoil constitutes the 0-30 cm upper, outermost layer of soil. It has the highest concentration of organic matter and microorganisms and is where most of the Earth's biological soil activity occurs.
ENV 2.3	Effects on ecosystem services	Soils ecosystem services (ES) are affected by soil type, density, organic carbon, nutrients, ion capacity and conductivity. They provision and regulate ES critical for carbon sequestration, climate regulations, nutrient cycling, water purification and genetic resources amongst others.
ENV 2.4	Changes in geotechnical properties	Changes in geotechnical properties describe the effects of the remedial actions to the physico-chemical properties of natural soils, that impact directly the mechanics of soil and construction engineering.
Groundwater and surface water		
ENV 3.1	Residual groundwater contamination	If groundwater protection is the primary aim of the project, protection over and above the required clean-up can be assessed here.
ENV 3.2	Contaminant mobilization and movement	Contaminant mobilization and movement can be affected by the remedial actions, contaminant properties such as solubility and Koc/Kow, and the environment, i.e. distance to groundwater, (non-)saturated soil type, rainfall, groundwater flow and others.

ENV 3.3	Ground- and surface water quality	Ground- and surface water quality can be affected by remediation. Typical indications are changes in hydrogeology (flow direction, velocity) and chemical factors such as pH, redox, electric conductivity, oxygen, dissolved metals or nutrients.
ENV 3.4	Water abstraction and recreational use	Water abstraction and recreational use of water can be affected by changes in water quality and contaminant levels exceeding risk thresholds.
Nature		
ENV 4.1	Effects on biota	Biota constitutes all plants and animals. They can be affected by for instance dust, noise, light or vibration, that are caused during demolition or remediation works.
ENV 4.2	Changes in ecology and ecosystems	Ecological and ecosystem effects describe changes in habitats, populations or food webs. They are indicated by changes for instance on biodiversity, ecosystem types, transport pathways and traditional environments.
ENV 4.3	Landscape effects	Landscapes are visible constituents of ecology and culture. They are affected by changes in the environment, in both space and time, indicated by e.g. aesthetics, topography, urban structure and surface coverings.
Raw materials		
ENV 5.1	Virgin raw material use	Virgin raw materials, i.e. humus, sand, gravel, rock, metals or water, that are commonly consumed as part of the remediation process or backfill and landscaping.
ENV 5.2	Energy resources	Use of fossil energy resources such as oil, coal and gas.
ENV 5.3	Re-used and -cycled materials	Re-used and re-cycled material, for instance re-cycled soil, crushed concrete or ballast. These materials can reduce the use of virgin raw materials significantly.
Waste		
ENV 6.1	Non-hazardous waste	Non-hazardous waste for instance excavated soil including small amounts of construction waste, that is transported and re-used off site or other types of non-hazardous waste
ENV 6.2	Hazardous waste	Hazardous waste, for instance excavated contaminated soil, that is treated on site or transported and treated off site or other types of hazardous waste.

TABLE 14. Sustainability indicators, Society (full list).

SOCIAL INDICATORS	Indicator name	Short description
Health and safety		
SOC.1.1	Reduction in health risks	If health protection (indoor air risk and contact risk) is the primary aim of the project, protection above the required clean-up level can be assessed here.
SOC.1.2	Local heatlh impacts	Health impacts to local inhabitants can be caused by e.g. exhaust from increased transportation and heavy machinery and dust due to remediation activities.
SOC.1.3	Working environment risks	Are there acute or chronic risks from the remediation activities to remedial workers at the site or due to off-site handling?
SOC.1.4	Risks to public	Are there acute or chronic risks on-site or off-site from the remediation activities to local inhabitants or public, for instance due to traffic, chemical storage, soil depletion/compaction?
Ethics and equality		
SOC.2.1	Distribution of responsibilities	Is the 'polluter pays' principle enacted in a just way?
SOC.2.2	Distribution of impacts	Are impacts and benefits of remediation distributed in a just way between (affected) stakeholders? Are some groups very negatively affected? Are there issues related to the long-term area use or intergenerational equity (is the problem transferred to future generations)?
SOC.2.3	Ethical concerns	Are there potential ethical considerations concerning the remedial solution (e.g. scope and residual risks) or service providers (e.g. skills and quality or subcontracting).
Neighbourhood		
SOC.3.1	Changes in site usage	How does the remediation change the neighbourhood's social and physical environment e.g. derelict land safety, urban recreational spaces, new services/business?
SOC.3.2	Changes in the built environment	Does the remediation effect the built environment and does the design works include urban conservation considerations?
SOC.3.3	Nuisance due to remediation	Nuisance related to remediation includes light, noise, odour, vibrations, increased traffic, visual pollution (i.e. aesthetic impacts). Disturbance may also be due to duration of the remediation and restrictions regarding the use and access to the site.
Community		
SOC.4.1	Involvement and transparency of decision making	Does the remediation strategy enable the realization of local stakeholder views? Are the decision criteria for risk management and remediation communicated clearly and transparently?
SOC.4.2	Local spatial planning objectives	Is the remediation in agreement with local spatial planning objectives, plans or strategies?

TABLE 15. Sustainability indicators, Economy (full list).

ECONOMIC INDICATORS	Indicator name	Short description
Direct economic costs and benefits		
ECON.1.1	Cost of remediation	Direct costs of remediation are estimated for the active remediation stage. These costs include for instance possible additional investigations, project management, installation, machinery, chemicals, energy and waste disposal.
ECON.1.2	Cost of operation and monitoring	Operation and maintenance costs are estimated throughout the project whole lifecycle. These costs include for instance operation and maintenance, consumables, spares, energy, monitoring and reporting.
ECON.1.3	Oher associated (third party) costs	Third party costs include for instance permit costs, fines, interests and litigation.
ECON.1.4	Changes in property values	Potential economic effect in property values of the remediation site and ease of divestment (sale) of property.
Indirect economic costs and benefits		
ECON.2.1	Risk of damages	Economic impacts of potential residual liabilities.
ECON.2.2	Impact on neighbourhood reputation	Possible effects on the reputation of the neighbourhood due to remediation.
ECON.2.3	Uplift to local business	How does the remediation affect the economic stability and profitability of surrounding local businesses?
Induced economic costs and benefits		
ECON.3.1	Use of funding schemes	Are there opportunities to leverage outside financing for the remediation for instance the public-private partnership (the PPP - model).
ECON.3.2	Effect on other projects/investments	Does the remediation strategy provide opportunities to leverage additional local development projects or investments to for instance blue-green infrastructure, community or recreation?
Employment and employment capital		
ECON.4.1	Job creation	Does the remediation project lead to creation of new jobs?
ECON.4.2	Effect on competency levels	Does the remediation project lead to increased skill levels for the people involved in the work?
ECON.4.3	Innovation potential	Does the remediation boost innovation and business potential? For instance. by implementation of new and innovative remediation techniques?
Lifespan and flexibility		
ECON.5.1	Lifespan of remediation technology	Lifespan of the remediation technology describes how long is the risk management is likely to be effective. Containment solution are typically time limited, whereas solutions that remove contaminations are permanent.
ECON.5.2	Need for institutional controls	Institutional controls are necessary if residual risks in relation to future land use remain after the remediation.
ECON.5.3	Flexibility of remediation alternative	Flexibility of remediation describes the resilience of the remediation strategy, and how it is affected by e.g. changes in contamination, soil lithology, climate changes, or project timeline and budget.
Uncertainty and evidence		
ECON.6.1	Uncertainty of technology performance	Uncertainty of technology performance describes how certain is it that the remediation strategy will be able to comply with the predefined success criteria.
ECON.6.2	Quality of available information	Quality of available information and investigations indicate whether the assessments and plans been made with sufficient

		rigor to answer the operational needs of the remediation method/strategy.
ECON 6.3	Quality of sustainability assessment	Are the data and information used for the sustainability assessment sufficient?

TABLE 16. Sustainability indicators, Environment (full list). *Danish version.*

MILJØMÆSSIGE INDIKATORER	**Indikatornavn**	**Kort beskrivelse**
Luft		
ENV.1.1	Drivhusgasudledning	Drivhusgasemissioner (GHG) inkluderer luftemissioner som CO_2, CH_4, N_2O og fluorerede gasser. Dette er gasser, der tilbageholder jordens varmestråling og forårsager global opvarmning. Den globale opvarmningseffekt kan estimeres baseret på emissionen i kg CO_2-ækvivalenter.
ENV 1.2	Lokal luftforurening	Emissioner, der udgør et lokalt luftforureningsproblem, der kan påvirke menneskers sundhed og miljøet, f.eks. NOx, VOC, CO, som kan forårsage dannelse af fotokemisk ozon, en giftig gas, der kan forårsage luftvejsproblemer, samt emissioner af partikler (PM) der ligeledes kan forårsage luftvejsproblemer.
ENV 1.3	Forsurende emissioner	Forsurende emissioner dækker SOx, NOx, HCl, HNO_3, H_2SO_4 osv. Forsuring kan føre til reduceret og ineffektiv skovvækst, tab af vandlevende organismer. Øget forsuring kan også føre til øget mobilisering af tungmetaller og aluminium.
Jord og terræn		
ENV.2.1	Restforurening, jord	Restforureningen i jord er den forurening, der er tilbage efter der er gennemført oprensning eller andre tiltag for at reducere risici forbundet med jordforureningen. Hvis afværge af jordforurening er det primære mål med projektet, kan oprensning udover de fastsatte oprensningskriterier dermed vurderes her.
ENV 2.2	Forringelse og brug af topjord	Topjorden udgør det 0-30 cm øverste jordlag. Det har den højeste koncentration af organisk stof og mikroorganismer, og er det område, hvor størstedelen af jordens biologiske jordaktivitet forekommer.
ENV 2.3	Effekter på økosystemtjenester	Jordens økosystemtjenester påvirkes af jordtype, densitet, organisk kulstof, næringsstoffer, ionkapacitet og ledningsevne. De leverer og regulerer økosystemtjenester, der er kritiske for blandt andet kulstofbinding, klimareguleringer, recirkulering af næringsstoffer, vandrensning og genetiske ressourcer.
ENV 2.4	Påvirkninger af geotekniske egenskaber	Ændringer i geotekniske egenskaber beskriver afværgemetodernes effekter på de fysisk-kemiske egenskaber af jorden, som påvirker jordens evne til at bære konstruktioner .
Grundvand og overfladevand		
ENV 3.1	Oprensningsgrad, grundvand	Hvis grundvandsbeskyttelse er det primære mål med afværgeprojektet, kan oprensning over det fastsatte minimumskriterie vurderes her.
ENV 3.2	Mobilisering og transport af forurening	Mobilisering og transport af forurening kan påvirkes af afværgetiltag, idet egenskaber som f.eks. opløselighed eller sorptionsevne kan påvirkes. Derudover kan afstanden til grundvandsspejlet, infiltration, grundvandsflow mv. påvirkes og have indflydelse på spredning af forureningen.

ENV 3.3	Kvalitet af grundvand og overfladevand	Kvaliteten af grund- og overfladevand kan påvirkes af afværge. Typiske indikationer er ændringer i hydrogeologi (strømningsretning, hastighed) og kemiske faktorer såsom pH, redoxforhold, elektrisk ledningsevne, ilt, opløste metaller eller næringsstoffer.
ENV 3.4	Vandindvinding og rekreativ brug af vand	Vandindvinding og rekreativ brug af vand kan påvirkes af ændringer i vandkvalitet og forureningsniveauer, der overskrider kvalitetskriterierne.
Natur		
ENV 4.1	Påvirkninger af biota (dyr og planter)	Biota omfatter alle planter og dyr. De kan påvirkes af for eksempel støv, støj, lys eller vibrationer, der er forårsaget af nedrivning eller afværgeteknikker.
ENV 4.2	Påvirkning af økologi og økosystemer	Påvirkninger af økologi og økosystemer beskriver ændringer i levesteder, populationer eller fødekæder. De er indikeret af ændringer på f.eks. biodiversitet, økosystemtyper, transportveje og traditionelle miljøer.
ENV 4.3	Landskabspåvirkninger	Landskaber kan påvirkes af ændringer i miljøet, både i rum og tid. Dette kan f.eks være ændringer, der påvirker æstetik, topografi, bystruktur og overfladebelægninger.
Råmaterialer		
ENV 5.1	Jomfruelige råstoffer	Jomfruelige råmaterialer, for eksempel sand, grus, humus, sten, metaller eller vand, der ofte forbruges som en del af afværgeprojektet eller til genfyldning og landskabsarkitektur.
ENV 5.2	Energiressourcer (fossile)	Brug af fossile energiressourcer såsom olie, kul og gas.
ENV 5.3	Genbrugte og genanvendte materialer	Genbrugte og genanvendte materialer, dvs. genanvendt jord, knust beton eller ballast. Disse materialer kan reducere brugen af jomfruelige råvarer væsentligt.
Affald		
ENV 6.1	Ikke-farligt affald	Ikke-farligt affald, for eksempel afgravet jord inklusive små mængder byggeaffald, der transporteres og genbruges off-site eller andre typer ikke-farligt affald.
ENV 6.2	Farligt affald	Farligt affald, for eksempel bortgravet forurenet jord, der behandles på stedet eller transporteres og behandles andetsteds, eller andre typer farligt affald.

TABLE 17. Sustainability indicators, Society (full list). *Danish version.*

SOCIALE INDIKATORER		
	Indikatornavn	**Kort beskrivelse**
Sundhed og sikkerhed		
SOC.1.1	Reduktion i sundhedsrisici	Hvis beskyttelse af menneskers sundhed (indendørs luftrisiko og kontaktrisiko med forurenet jord) er afværgeprojektets primære mål, kan beskyttelse over det krævede oprensningsniveau vurderes her.
SOC.1.2	Lokale sundhedseffekter	Sundhedsmæssige påvirkninger for lokale beboere kan være forårsaget af f.eks. udstødning fra øget transport og tunge maskiner og støv på følge af afværgeaktiviteter.
SOC.1.3	Arbejdsmiljørisici	Er der akutte eller kroniske risici fra afværgeaktiviteterne der påvirker arbejdsmiljøet på lokaliteten eller andetsteds, hvis der f.eks. sker behandling af afgravet jord?
SOC.1.4	Risici for offentligheden	Fører afværgeaktiviteterne til akutte eller kroniske risici for offentligheden f.eks. på grund af trafik, kemikalieopbevaring og bortgravning/komprimering af jord.
Etik og lighed		
SOC.2.1	Fordeling af ansvar	Er princippet om, at forureneren betaler, anvendt på en retfærdig måde?
SOC.2.2	Fordeling af påvirkninger	Er fordele og ulemper ved afværge fordelt på en retfærdig måde mellem (berørte) interessenter? Er nogle grupper meget negativt påvirket? Er der ulige forhold relateret til den langsigtede brug af området, eller intragenerationelle uligheder (overføres problemet til fremtidige generationer)?
SOC.2.3	Etiske problemstillinger	Er der potentielle etiske probemstillinger vedrørende afværgeløsningerne (f.eks. vedr. formål og resterende risici) eller de firmaer, der udfører arbejdet (f.eks. I forhold til kvalifikationer og kvalitet eller underentrepenører).
Lokalområde		
SOC.3.1	Påvirkninger i brugen af lokaliteten	Hvordan påvirker afværgen det sociale og fysiske miljø i nabolaget, f.eks. ved at fjerne eksponeringsrisiko, skabe nye rekreative områder, nye muligheder for lokalt forretningsliv.
SOC.3.2	Ændringer i bygningsmasse	Påvirker afværgeprojektet eksisterende bygninger, og tages der i design af afværgeprojektet hensyn til at bevare eksisterende bygninger?
SOC.3.3	Gener i forbindelse med afværge	Gener relateret til afværgeprojekter kan f.eks. inkludere lys, støj, lugt, vibrationer, øget trafik og visuel forurening (dvs. æstetiske påvirkninger). Derudover kan afværgen fører til gener som følge af restriktioner med hensyn til brug og adgang til lokaliteten.
Lokalsamfund		
SOC.4.1	Involvering og gennemsigtighed af beslutningstagen	Giver afværgeprojektet mulighed for at realisere lokale synspunkter fra interessenter? Kommunikeres beslutningskriterierne for oprensning og afværge på en klar og gennemsiglig måde?
SOC.4.2	Lokalplanens målsætninger	Er afværgeprojektet i overensstemmelse med lokalplanens målsætninger eller strategier?

TABLE 18. Sustainability indicators, Economy (full list). *Danish version.*

ØKONOMISKE INDIKATORER		
	Indikatornavn	**Kort beskrivelse**
Direkte omkostninger og fordele		
ECON.1.1	Afværgeomkostninger	Direkte omkostninger til afværge estimeres for den aktive afværgefase. Disse omkostninger inkluderer for eksempel eventuelle yderligere undersøgelser, projektstyring, installationer, udstyr, kemikalier, energiforbrug og bortskaffelse af affald.
ECON.1.2	Omkostninger til drift og monitering	Drifts- og vedligeholdelsesomkostninger estimeres for hele projektets livscyklus. Disse omkostninger inkluderer for eksempel drift og vedligeholdelse, forbrugsstoffer, reservedele, energiforbrug, monitering og afrapportering.
ECON.1.3	Øvrige udgifter (til 3. part)	Tredjepartsomkostninger inkluderer for eksempel tilladelsesomkostninger, bøder, renter og sagsanlæg.
ECON.1.4	Ændringer i ejendomsværdi	Potentiel økonomisk påvirkning af den oprensende grunds ejendomsværdi, samt muligheden for salg af ejendommen.
Indirekte omkostninger og fordele		
ECON.2.1	Risiko for erstatningsansvar	Økonomiske påvirkninger relatereret til eventuelt tilbageværende erstatningsansvar.
ECON.2.2	Påvirkning af områdets omdømme	Påvirkninger af nabolagets omdømme som følge af afværge.
ECON.2.3	Påvirkning af lokalt forretningsmiljø	Hvordan påvirker afværgen de omkringliggende lokale virksomheders økonomiske stabilitet og rentabilitet?
Afledte omkostninger og fordele		
ECON.3.1	Brug af finansierings-ordninger	Er der muligheder for at udnytte andre typer finansiering til afværgeprojektet f.eks. Offentlige-Private partnerskaber?
ECON.3.2	Effekt på øvrige projekter/investeringer	Giver afværgestrategien mulighed for at påvirke andre lokale udviklingsprojekter eller investeringer til f.eks. blå/grøn infrastruktur, rekreative områder og lign.?
Beskæftigelse og beskæftigelseskapital		
ECON.4.1	Øget beskæftigelse	Fører afværgeprojektet til skabelse af nye job?
ECON.4.2	Kompetenceniveau før og efter projekt	Fører afværgeprojektet til øget videns- og kompetenceniveau for de mennesker, der er involveret i arbejdet?
ECON.4.3	Innovationspotentiale	Øger afværgeprojektet innovation og forretningspotentiale? For eksempel ved implementering af nye og innovative afværgeteknikker?
Levetid og fleksibilitet		
ECON.5.1	Levetid af afværgeteknologi	Afværgeteknologiens levetid beskriver, hvor længe den er effektiv overfor forureningen. Afskærings- og indeslutningsløsninger er typisk tidsbegrænsede, hvorimod løsninger, der fjerner forureningen, er permanente.
ECON.5.2	Nødvendighed af administrative restriktioner	Administrative restriktioner er nødvendige, hvis restforurening efter afværge kan udgøre en risiko for fremtidig arealanvendelse, for grundvand eller overfladevand.
ECON.5.3	Fleksibilitet af afværgeløsning	Fleksibilitet af afværgeløsningen beskriver i hvor høj grad løsningen påvirkes af ændringer i f.eks. forureningsomfang, jordtyper, klima, projektets tidsplan og budget.
Usikkerhed og evidens		
ECON.6.1	Usikkerhed på afværgeløsningens præstation	Usikkerhed på teknologiens præstationsevne beskriver, hvor sikkert det er, at afværgestrategien vil være i stand til at overholde de fastsatte succeskriterier.

ECON.6.2	Kvalitet af tilgængelig information	Er der tilstrækkelig viden og data til at designe og udføre den enkelte afværgestrategi. eller er der behov for flere undersøgelser?
ECON 6.3	Kvalitet af bæredygtighedsvurdering	Er de data og oplysninger, der bruges til bæredygtighedsvurderingen, tilstrækkelige?

Appendix 1.2 Indicator descriptions, simple list, English and Danish versions

TABLE 19. Sustainability indicators, Environment (simple list).

MILJØMÆSSIGE INDIKATORER		
	Indikatornavn	**Kort beskrivelse**
Luft		
ENV.1.1	Greenhouse gas emissions	Greenhouse gas (GHG) emissions include air emissions such as CO_2, CH_4, N_2O and fluorinated gases. These are gases that trap heat in the atmosphere and cause global warming. The global warming impact can be estimated as the emission in terms of kg of CO_2-equivalents.
Soil and ground conditions		
ENV.2.1	Residual soil contamination	Residual soil contamination is the contamination which remains after steps have been taken to reduce the associated risks. If remediation is the primary aim of the project, protection over and above the required cleanup can also be assessed here.
ENV 2.2	Topsoil degradation and consumption	Topsoil constitutes the 0-30 cm upper, outermost layer of soil. It has the highest concentration of organic matter and microorganisms and is where most of the Earth's biological soil activity occurs.
ENV 2.4	Changes in geotechnical properties	Changes in geotechnical properties describe the effects of the remedial actions to the physico-chemical properties of natural soils, that impact directly the mechanics of soil and construction engineering.
Groundwater and surface water		
ENV 3.1	Residual groundwater contamination	If groundwater protection is the primary aim of the project, protection over and above the required clean-up can be assessed here.
ENV 3.S	Ground- and surface water quality	Typical indications in water quality effects are changes in hydrogeology (flow direction, velocity) and chemical factors such as pH, redox, electric conductivity, oxygen, dissolved metals or nutrients. The remediation might also lead to mobilization of contaminants.
Nature		
ENV 4.S	Effects on biota and ecosystems	Biota includes all plants and animals, and ecosystems constitute their populations and habitats. Biota can be directly impacted by for instance dust, noise or light, whereas ecosystem effects are indicated by changes on e.g. biodiversity, habitat types and transport pathways.
Raw materials		
ENV 5.1	Virgin raw material use	Virgin raw materials, i.e. humus, sand, gravel, rock, metals or water, that are commonly consumed as part of the remediation process or backfill and landscaping.
Waste		
ENV 6.2	Hazardous waste	Hazardous waste, for instance excavated contaminated soil, that is treated on site or transported and treated off site or other types of hazardous waste.

TABLE 20. Sustainability indicators, Society (simple list).

SOCIAL INDICATORS	Indicator name	Short description
Health and safety		
SOC.1.1	Reduction in health risks	If health protection (indoor air risk and contact risk) is the primary aim of the project, protection above the required clean-up level can be assessed here.
SOC.1.2	Local health impacts	Health impacts to local inhabitants can be caused by e.g. exhaust from increased transportation and heavy machinery and dust due to remediation activities.
SOC.1.3	Working environment risks	Are there acute or chronic risks from the remediation activities to remedial workers at the site or due to off-site handling?
Ethics and equality		
SOC.2.2	Distribution of impacts	Are impacts and benefits of remediation distributed in a just way between (affected) stakeholders? Are some groups very negatively affected? Are there issues related to the long-term area use or intergenerational equity (is the problem transferred to future generations)?
SOC.2.3	Ethical concerns	Are there potential ethical considerations concerning the remedial solution (i.e. scope and residual risks) or service providers (i.e. skills and quality or subcontracting).
Neighbourhood		
SOC.3.3	Nuisance due to remediation	Nuisance related to remediation includes light, noise, odour, vibrations, increased traffic, visual pollution (i.e. aesthetic impacts). Disturbance may also be due to duration of the remediation and restrictions regarding the use and access to the site.

TABLE 21. Sustainability indicators, Economy (simple list).

ECONOMIC INDICATORS		
	Indicator name	**Short description**
Direct economic costs and benefits		
ECON.1.S	Total cost of remediation	The costs of remediation that covers both the initial capital costs and the operation and monitoring costs throughout the project life-cycle.
Lifespan and flexibility		
ECON.5.1	Lifespan of remediation technology	Lifespan of the remediation technology describes how long the risk management is likely to be effective. Containment solution are typically time limited, whereas solutions that remove contaminations are permanent.
ECON.5.2	Need for institutional controls	Institutional controls are necessary if residual risks in relation to future land use remain after the remediation.
ECON.5.3	Flexibility of remediation alternative	Flexibility of remediation describes the resilience of the remediation strategy, and how it is affected by e.g. changes in contamination, soil lithology, climate changes, or project timeline and budget.
Uncertainty and evidence		
ECON.6.1	Uncertainty of technology performance	Uncertainty of technology performance describes how certain is it that the remediation strategy will be able to comply with the predefined success criteria.
ECON.6.2	Quality of available information	Quality of available information and investigations indicate whether the assessments and plans been made with sufficient rigor to answer the operational needs of the remediation method/strategy.

TABLE 22. Sustainability indicators, Environment (simple list). *Danish version.*

MILJØMÆSSIGE INDIKATORER		
	Indikatornavn	**Kort beskrivelse**
Luft		
ENV.1.1	Drivhusgasudledning	Drivhusgasemissioner (GHG) inkluderer luftemissioner som CO_2, CH_4, N_2O og fluorerede gasser. Dette er gasser, der tilbageholder jordens varmestråling og forårsager global opvarmning. Den globale opvarmningseffekt kan estimeres baseret på emissionen i kg CO_2-ækvivalenter.
Jord og terræn		
ENV.2.1	Restforurening, jord	Restforureningen i jord er den forurening, der er tilbage efter der er gennemført oprensning eller andre tiltag for at reducere risici forbundet med jordforureningen. Hvis afværge af jordforurening er det primære mål med projektet, kan oprensning udover de fastsatte oprensningskriterier dermed vurderes her.
ENV 2.2	Forringelse og brug af topjord	Topjorden udgør det 0-30 cm øverste jordlag. Det har den højeste koncentration af organisk stof og mikroorganismer, og er det område, hvor størstedelen af jordens biologiske jordaktivitet forekommer.
ENV 2.4	Påvirkninger af geotekniske egenskaber	Ændringer i geotekniske egenskaber beskriver afværgemetodernes effekter på de fysisk-kemiske egenskaber af jorden, som påvirker jordens evne til at bære konstruktioner.
Grundvand og overfladevand		

ENV 3.1	Oprensningsgrad, grundvand	Hvis grundvandsbeskyttelse er det primære mål med afværge-projektet, kan oprensning over det fastsatte minimumskriterie vurderes her.
ENV 3.S	Kvalitet af grundvand og overfladevand	Typiske indikationer på vandkvalitetseffekter er ændringer i hydrogeologi (strømningsretning, hastighed) og kemiske faktorer såsom pH, redoxforhold, elektrisk ledningsevne, ilt, opløste metaller eller næringsstoffer. Afværgen kan også føre til mobilisering af forurening.
Natur		
ENV 4.S	Påvirkninger af biota og økosystemer	Biota inkluderer alle planter og dyr, og økosystemer udgør deres populationer og levesteder. Biota kan påvirkes direkte af for eksempel støv, støj eller lys, mens økosystemeffekter er indikeret ved ændringer på f.eks. biologisk mangfoldighed, naturtyper og transportveje.
Råmaterialer		
ENV 5.1	Jomfruelige råmaterialer	Jomfruelige råmaterialer, for eksempel sand, grus, humus, sten, metaller eller vand, der ofte forbruges som en del af afværge-projektet eller til genfyldning og landskabsarkitektur.
Affald		
ENV 6.2	Farligt affald	Farligt affald, for eksempel bortgravet forurenet jord, der behandles på stedet eller transporteres og behandles andetsteds, eller andre typer farligt affald.

TABLE 23. Sustainability indicators, Society (simple list). *Danish version.*

SOCIALE INDIKATORER	Indikatornavn	Kort beskrivelse
Sundhed og sikkerhed		
SOC.1.1	Reduktion i sundhedsrisici	Hvis beskyttelse af menneskers sundhed (indendørs luftrisiko og kontaktrisiko med forurenet jord) er afværgeprojektets primære mål, kan beskyttelse over det krævede oprensningsniveau vurderes her.
SOC.1.2	Lokale sundhedseffekter	Sundhedsmæssige påvirkninger for lokale beboere kan være forårsaget af f.eks. udstødning fra øget transport og tunge maskiner og støv som følge af afværgeaktiviteter.
SOC.1.3	Arbejdsmiljørisici	Er der akutte eller kroniske risici fra afværgeaktiviteterne, der påvirker arbejdsmiljøet på lokaliteten eller andetsteds, hvis der f.eks. sker behandling af afgravet jord?
Etik og lighed		
SOC.2.2	Fordeling af påvirkninger	Er fordele og ulemper ved afværge fordelt på en retfærdig måde mellem (berørte) interessenter? Er nogle grupper meget negativt påvirket? Er der ulige forhold relateret til den langsigtede brug området, eller intragenerationelle uligheder (overføres problemet til fremtidige generationer)?
SOC.2.3	Etiske problemstillinger	Er der potentielle etiske probemstillinger vedrørende afværgeløsningerne (f.eks. vedr. formål og resterende risici) eller de firmaer, der udfører arbejdet (f.eks. I forhold til kvalifikationer og kvalitet eller underentrepenører).
Lokalområde		
SOC.3.3	Gener i forbindelse med afværge	Gener relateret til afværgeprojekter kan f.eks. inkludere lys, støj, lugt, vibrationer, øget trafik og visuel forurening (dvs. æstetiske påvirkninger). Derudover kan afværgen fører til gener som følge af restriktioner med hensyn til brug og adgang til lokaliteten.

TABLE 24. Sustainability indicators, Economy (simple list). *Danish version.*

ØKONOMISKE INDIKATORER		
	Indikatornavn	**Kort beskrivelse**
Direkte omkostninger og fordele		
ECON.1.S	Totale afværgeomkostninger	De samlede udgifter til afværge, der dækker både kapitalomkostninger og drifts- og moniteringssomkostninger gennem projektets livscyklus.
Levetid og fleksibilitet		
ECON.5.1	Levetid af afværgeteknologi	Afværgeteknologiens levetid beskriver, hvor længe den er effektiv overfor forureningen. Afskærings- og indeslutningsløsninger er typisk tidsbegrænsede, hvorimod løsninger, der fjerner forureningen, er permanente.
ECON.5.2	Nødvendighed af administrative restriktioner	Administrative restriktioner er nødvendige, hvis restforurening efter afværge kan udgøre en risiko for fremtidig arealanvendelse, for grundvand eller overfladevand.
ECON.5.3	Fleksibilitet af afværgeløsning	Fleksibilitet af afværgeløsningen beskriver i hvor høj grad løsningen påvirkes af ændringer i f.eks. forureningsomfang, jordtyper, klima, projektets tidsplan og budget.
Usikkerhed og evidens		
ECON.6.1	Usikkerhed på afværgeløsningens præstation	Usikkerhed på teknologiens præstationsevne beskriver, hvor sikkert det er, at afværgestrategien vil være i stand til at overholde de fastsatte succeskriterier.
ECON.6.2	Kvalitet af tilgængelig information	Er der tilstrækkelig viden og data til at designe og udføre den enkelte afværgestrategi. eller er der behov for flere undersøgelser?

Appendix 2. Criteria for assessing indicators

Appendix 2.1 Criteria for assessing each indicator on the simple list

TABLE 25. Criteria for assessing environmental indicators.

ENVIRONMENTAL INDICATORS		
	Indicator name	**Assessment criteria and evidence**
Air		
ENV.1.1	Greenhouse gas emissions	Assessment of tier 1 greenhouse gas (GHG) emissions should include in minimum a qualitative estimation of the emissions from direct site remediation activities, including: • excavation and transportation of soil and backfill, and • on-site energy use, e.g. for pumps, blowers, heaters and coolers. • large amounts of consumables (for instance activated carbon, chemicals, concrete etc.) will also impact the GHG emission in the production phase. A more thorough tier 2 assessment should also include a quantitative full life-cycle assessment of the global warming potential including all main processes of the remediation system including upstream production processes and downstream end-of-life processes.
Soil and ground conditions		
ENV.2.1	Residual soil contamination	Risk management and remediation strategies vary in their effect towards residual soil contamination, in e.g.: • Stabilization and encapsulation leave majority of the contaminants in soil, • Barriers prevent the risk pathways, but rarely manage the source of contamination, and • Some remediation methods can exceed the set required minimum cleanup levels. Assessment should include in minimum a qualitative estimation of the impacts of remediation to the absolute quantities of residual soil contamination. Further assessments should include also quantitative estimations of the calculated risk reductions in connection to the residual contamination levels. In the assessment of this criteria, lower absolute residual contamination levels should always be considered better.
ENV 2.2	Topsoil degradation and consumption	Topsoil degradation and consumption can be impacted during remediation by e.g. • excavating and removing the topsoil • covering the topsoil with an impermeable layer • compaction or increased erosion due to earthworks Assessment should include in minimum a qualitative estimation of the amount of excavated and removed topsoil, based on the selected remediation strategy. For further assessments, the estimation could be based on quantified calculation based on detailed remedial plans. Topsoil can also potentially be affected positively, e.g. when using phytoremediation techniques or rehabilitating brownfield areas with green areas.
ENV 2.4	Changes in geotechnical properties	Geotechnical impacts from remediation to site use or future construction can be caused by e.g.: • excavating and replacing naturally consolidated soils,

		• lowering surrounding groundwater levels, or • introducing remediation chemicals or heat to the sub-surface In situ thermal remediation will typically impact the soil geotechnical properties positively by increasing the stability, bearing capacity and compressive strength (Ding et al. 2019). For tier 1 assessment the most important soil properties are the bearing capacity of the soil, thickness of the soft soil and the soil slope. Other more detailed information can include soil specific gravity, density, particle size, compaction, consolidation, permeability and shear strength. The information used for estimating these impacts can include measurements of present geotechnical properties, estimations of constructability and designs for future construction and subgrade foundations. Geotechnical changes should be assessed in terms of construction engineering and can therefore be considered positive or negative.
Groundwater and surface water		
ENV 3.1	Residual groundwater contamination	Remediation actions directed towards contaminated groundwater may provide different clean-up levels even though they all comply with the defined minimum remedial target. The assessment of this indicator will require an assessment of the clean-up efficiency provided by each of the remediation options. If an option will provide a larger cleanup efficiency that the minimum required clean-up level, then this option should obtain a better score than options that provide the required cleanup level.
ENV 3.S	Ground- and surface water quality	The water quality of groundwater and/or surface water may be impacted by: • hydrogeology impacts covering changes in flow direction and flow velocity • chemical impacts covering changes in pH, redox conditions, oxygen content, dissolved metals or nutrients. The assessment of this indicator should also consider • will the remediation lead to mobilization of contaminants due to changes in solubility or sorption conditions? • will the distance to the groundwater table be impacted and e.g. increase/decrease the leaching of contaminants to the groundwater? • will the remediation lead to production of side products/degradation products and will these be mobile?
Nature		
ENV 4.S	Effects on biota and ecosystems	Biota and ecosystems can be impacted during remediation by e.g. • removal of nesting places and transport pathways, by removing trees and derelict buildings • decreasing biodiversity by replacing natural plants and vegetation with inorganic coverage • noise from earthworks Assessment should include in minimum estimation of the direct changes to the existing site biota through remediation works. Further assessments could include site surveys on existing biota, habitats and ecological connections to the surrounding area.
Raw materials		
ENV 5.1	Virgin raw material use	Assessment of tier 1 virgin raw material use should include an assessment of the amounts of consumed virgin materials including • virgin materials used on site during remediation. This could include virgin mineral resources for backfill after excavation, metal installations, water abstraction or use of tap water • virgin materials used on site for landscaping after remediation • virgin materials used upstream for production of consumables e.g. activated carbon or concrete
Waste		
ENV 6.2	Hazardous waste	Assessment of tier 1 waste production should include an assessment on amounts of hazardous waste produced as a consequence of the remediation including

		• hazardous waste produced on site, this could be e.g. contaminated soil for disposal, waste chemicals, hazardous waste water and activated carbon waste • hazardous waste produced off site, this could e.g. in relation to off-site treatment of soil, residues from waste treatment etc.

TABLE 26. Criteria for assessing social indicators.

SOCIAL INDICATORS		
	Indicator name	**Assessment criteria and evidence**
Health and safety		
SOC.1.1	Reduction in health risks	Remediation actions towards indoor air risks and/or contact risks may provide a better risk reduction than the specified risk reduction target. The assessment of this indicator will require an assessment of the risk reduction level provided by each remediation option considered. If an option will provide a better risk reduction than the minimum target, then this option should obtain a better indicator score than options that "only" provide the required risk reduction.
SOC.1.2	Local health impacts	The health impacts to local inhabitants should as minimum include an assessment of • The level of exhaust emissions due to increased traffic and heavy machinery experienced by local inhabitants • The level of dust caused by soil excavation or other soil works
SOC.1.3	Working environment risks	On-site risks to site workers may be due to: • exposure due to handling of hazardous materials, such as contaminated soils or chemicals • risk of accidents on site due to e.g. use of heavy machinery Off-site risks to remediation workers can be related to e.g.: • fugitive emissions and contact during handling of excavated contaminated soil • risks of road accidents, or accidents related to the use of heavy machinery
Ethics and equality		
SOC.2.2	Distribution of impacts	The distribution of positive and negative impacts between stakeholders may be unfair if e.g. • Specific groups are affected very negatively by the remediation and will not be benefitted by it • The site/area improvement leads to exclusion of lower income groups due to higher property costs after remediation • There are intragenerational equity issues. Will the contamination problem be passed on to future generations?
SOC.2.3	Ethical concerns	The assessment of ethical concerns related to the remediation options should cover • Are there any issues of ethical concern, e.g. use of genetically modified organisms, injection of amendments to the subsurface with unknown additives? • Are there any ethical concerns related to the contractors, subcontractors or in the production phase of consumables used for the remediation project?
Neighbourhood		
SOC.3.3	Nuisance due to remediation	Assessment should include as minimum an estimation of the level of nuisance experienced by residents and neighbours due to e.g. • operating hours at the site (per day and days in total) • noise, vibrations, light, odour • aesthetic/visual pollution due to installations at site • restrictions for site use during remediation • increased traffic to/from site

TABLE 27. Criteria for assessing economic indicators.

ECONOMIC INDICATORS	Indicator name	Short description
Direct economic costs and benefits		
ECON.1.S	Total cost of remediation	Assessment should include in minimum an estimation of the total investment cost for the remediation, the cost for operation, including consumables e.g. electricity, activated carbon or chemicals, and the cost of monitoring. The costs should be estimated for the whole project lifecycle. For preliminary assessment the estimation can be made qualitatively and for further assessments the estimation should be based on discounted calculations.
Lifespan and flexibility		
ECON.5.1	Lifespan of remediation technology	Lifespan of remediation technology is directly linked to the selected remediation strategy. In the assessment, remediation methods that do not focus on contaminant mass removal i.e. containment and barriers should be considered having a short lifespan, whereas methods that target mass removal have a longer lifespan. Remediation methods that target contaminant mass removal, are moreeffective in the long lifespan.
ECON.5.2	Need for institutional controls	Institutional controls are assessed by comparing estimated risk reduction from remediation with acceptable risk levels for future land use. Institutional controls might become necessary if for instance: • residual contamination remains at a depth that might pose risk if the soils are excavated in the future • contamination is located in groundwater and might cross property borders or threaten groundwater extraction. Assessment should be based on actual estimated residual contamination and existing legislation. Further assessment could use modelling to delineate the reduction.
ECON.5.3	Flexibility of remediation alternative	Assessment should as minimum include an estimation of the possible variance in the project timeline and budget. Further sensitivity analysis could be made for effects due to changes in the technical design, or due to contamination levels, soil lithology or climate impacts. Assessed information can use simple min-max analysis, sensitivity analysis or in more complex cases, e.g. by monte-carlo simulations.
Uncertainty and evidence		
ECON.6.1	Uncertainty of technology performance	Assessment should consider the uncertainty of the remediation strategy to achieve the predefined remediation criteria in terms of time, unit costs and reduction in risk levels. The assessment can be based on benchmarking similar projects and technology applications. Generally, well known methods such as excavation score better in terms of uncertainty, whereas in situ and innovative technologies tend to score worse.
ECON.6.2	Quality of available information	Quality of available information and need for additional investigations is strongly dependent on the assessed option. Different options require varying information for design, e.g.: • excavation require sufficient data on soil geotechnical properties • biological in situ remediation requires data on the site biocapacity in relation to the contaminant of concern • Pump and treat requires specific data on groundwater hydraulics and mass transport Assessment should be based in minimum on a qualitative assessment of whether the necessary pre-requisite information is sufficient, and whether there are additional needs for validation of the remediation strategy with further investigations or experiments? Further consideration could be supported by data gap analysis and modelling to identify and quantify the correlation between measurements.

Appendix 3. Input data for RemS

Appendix 3.1 Input data for pump-and-treat

Strategy A	1 Pumping - P	Standard	Auto adjusted	User adjusted	Nominal value
Preconditions					
Source area + plume area in secondary aq	m2	10000		0	
Deapth to bottom of plume in secondary ac	m	10		0	
Plume area in primary aquifer	m2	10000		0	
Deapth to bottom of plume in primary aquife	m	20		21	21
Investigations					
Driving. Supervision	km	200		0	
Driving. Drilling rig, trucks ect.	km	200		0	
Boreholes, secondary aquifer, 6" filter ø63r	stk	12		0	
Boreholes, primary aquifer, 8" filter ø 110mm	stk	6		6	6
Establishment and operation					
Driving. Supervision, establishment	km	1000		0	
Driving. Drilling rig, trucks ect.	km	200		0	
Driving. Contractor, establishment	km	2000		0	
Driving. Supervision, operation	km/year	500		0	
Driving. Contractor, operation	km/year	1000		0	
Time of operation	year		20	30	30
Pumping system: Secondary=0, Primary=1		1			1
Pumping system - secondary aquifer					
Pumping wells, 10" filter ø125 mm	stk				
Total pumping yield	m3/h				
Outlet pipe, ø75mm PVC	m				
Power consumption for pumps	kWh/ye				
Total power consumption during operation	kWh				
Pumping system - primary aquifer					
Pumping wells, 12" filter ø160 mm	stk	1			1
Total pumping yield	m3/h	10		6	6
Outlet pipe, ø110mm PVC	m	200			200
Consumption of elektricity for pumps	kWh/ye		19940	20000	20000
Total power consumption during operation	kWh		600000		600000
Treatment should be added if used					

				Standard	Auto adjusted	User adjusted	Nominal value
Strategy A		2 Treatment - T					
Preconditions							
Establishment			-------	---------	------------		---------
Driving. Supervision, establishment			km	2000		0	
Driving. Contractor, establishment			km	4000		0	
Driving. Truck, establishment			km	1000		0	
Operation			-------	---------	------------		---------
Driving. Supervision			km/yea	1000		0	
Driving. Contractor			km/yea	1000		0	
Time of operation	all facilities		years	5		30	30
Oil separator		(Yes=1, No=0):	-------			0	
Olieseparator and grit trap (Plast-PE) < 20 r			stk				
Olieseparator and grit trap (Concrete) < 20			stk				
Water treatment		(Yes=1, No=0):	-------	1			1
Capacity			m3/h	10		6	6
Consumption of elektricity excl. air stripper			kWh/ye		13000	13000	13000
Activated carbon - GAC (on water) - consu			kg/year	100	60	4200	4200
In building=1; I container=2				2		0	
Airtreatment - Water		(Ja=1, Nej=0):	-------				
Capacity (air stripping - INKA system)			m3/h				
Consumption of elektricity - air stripping			kWh/ye				
Activated carbon - GAC (on air) - consump			kg/year				
Air treatment - SVE		(Yes=1, No=0):	-------				
Capacity (airflow)			m3/h				
Consumption of elektricity - air treatment or			kWh/ye				
Activated carbon - GAC (on air) - consump			kg/year				
Air treatment - PSVE		(Yes=1, No=0):	-------				
Airflow (average)			m3/h				
Concentration level			µg/l				
Activated carbon - GAC (on air) - consump			kg/year				

Appendix 3.2 Input data for PlumeStop

		Standard	Auto adjusted	User adjusted	Nominal value
Strategy B	1 Stim. Reduc. Dechlor. - SRD				
Preconditions					
Remediation area	m2	500		0	
Thickness of remediation interval	m	2			2
Deapth to bottom of plume in sec. aquifer	m	10		0	
Deapth to bottom of plume in primary aquife	m	20		21	21
Investigations and tests	---------	---------	---------		---------
Driving. Supervision	km	1000		0	
Driving. Drilling rig, trucks ect.	km	400		0	
Boreholes, secondary aquifer, 6" filter ø63r	stk	8		0	
Boreholes, primary aquifer, 8" filter ø 110mm	stk	2		7	7
Establishment	---------	---------	---------		---------
Driving. Supervision, establishment	km	2000		0	
Driving. Contractor, establishment	km	2000		0	
Driving. Drilling rig, trucks ect.	km	400		0	
Number of injections (total if several times)	injectio	50		0	
Injection time (Total if several times)	weeks	2		0	
Substrate: EOS (60% soyabean emulsion)	l	20000		3300	3300
Substrate: Sodium formate ("lactate)	kg			3300	3300
Biomass, KB1 (bakterial culture)	l	2000	660	108	108
Pumping and re-circulation	---------	---------	---------		---------
Pumping wells´ ø63 mm	stk	5		0	
Pumping wells´ ø110 mm	stk			0	
Total yield - water	m3/h	1		0	
Consumption of elektricity for pumping re-c	kWh/we			0	
Control (operation phase)	---------	---------	---------		---------
Driving. Supervision, control analysis	km	400		0	
Driving. Drilling rig, trucks ect.	km	400		0	
Boreholes, 6" no filter	stk	8		0	
Treatment should be added if used		---------	---------		---------
EOS; 60% solution with soya been oil					
KB1; Calculation includes transport only					

Strategy B		2 Specific consumption		Standard	Auto adjusted	User adjusted	Nominal value
Preconditions							
Electricity							
Electricity (specify type/origin on tab 5)			MWh			0,0034	0
Transport							
Car (diesel)			km				
Van < 3.5 t gross weight			km				
Lorry 3.5-7.5t gross weight			km			260	260
Lorry > 32 ton gross weight			km				
Aircraft, passenger			pers. km				
Entrepreneurial works							
Entrepreneurial machines			l diesel			720	720
Plastic							
PVC, extruded (e.g. pipes)			kg				
PVC, injection moulding			kg				
PE, extruded (e.g pipes)			kg				
PE, injection moulding			kg				
Metals							
Steel, low alloyed			kg			2500	2500
Chromium steel			kg				
Activated carbon							
GAC, origin EU			kg			520	520
Concrete, asphalt							
Concrete	2.40 t/m3		m3				
Asphalt	2.25 t/m3		m3				
Bentonite							
Bentonite, local (50 km)			kg				
Bentonite, regional (600 km). "Mikolit"			kg				
Sand and gravel							
Sand and gravel, excl. transport, 1.9 t/m3			m3				
External soil treatment, excl. transport							
Biological treatment (" 1ppm leight fuel)			m3				

Input to OpenLCA

Applied ELCD process:

- Container ship ocean, technology mix, 27.500 dwt pay load capacity
- 13 tonnes PlumeStop, 3.3 tonnes electron donor. In total 16.3 tonnes transported a distance of 15.458 km by sea freight

Appendix 4. LCA results

Appendix 4.1 Results from RemS and OpenLCA

TABLE 28. LCA results from RemS and OpenLCA

Life cycle impact	Unit	Pump-and-treat (RemS result)	PlumeStop (RemS result)	PlumeStop (seafreight, OpenLCA result*)	PlumeStop, total impact
Global warming (GWP)	kg CO2-eq	1551257	25138	3872	29010
Acidification	kg SO2-eq	7186	130,2	91,1	221
Photochemical smog	kg C2H4-eq	211	15,1	119,3	134
Eutrophication	kg NO3-eq	4181	390,5		390
Ecotoxicity	m3	24168463	1504685		1504685
Human toxicity	m3	2,35E+11	6,18E+09		6,18E+09
Bulk waste	kg	47952,84	8757,394		8757
Hazardous waste	kg	43,94745	6,231989		6,23
Radioactive waste	kg	27,83427	0,616833		0,62
Slags/ashes	kg	250,1382	70,23018		70,23

* Note that not all the same life cycle impacts were calculated in OpenLCA, since the available impact assessment methods in OpenLCA does not include the EDIP97 method, which is used in RemS.

Sustainable Remediation

This report presents a methodology for assessment of the relative sustainability of different remediation options for a contaminated site.

The methodology follows the principles in the ISO standard for sustainable remediation where sustainable remediation is defined as "remediation that eliminates and/or controls unacceptable risks in a safe and timely manner whilst optimizing the environmental, social and economic value of the work". Thus, the assessment of sustainable remediation covers the assessment of environmental as well as social and economic sustainability indicators.

It is recommended that the sustainability assessment follows a tiered approach. The Tier 1 assessment is an initial early stage assessment. This assessment can be carried out using limited resources and time and is applicable for all sizes of remediation projects.

The Tier 2 assessment represents a more detailed assessment, which is mainly relevant for larger and/or complex contaminated sites. Here the scoring of sustainability indicators is backed up by the use of quantitative assessments, such as life cycle assessment and cost-benefit analysis.

Both assessments results in the calculation of an overall sustainability score calculated as the weighted sum of the individual scores. This score is used to assess the relative sustainability between the compared remediation options. Additionally, the assessment leads to scoring of the effect on the UN sustainable development goals (SDGs) based on a coupling between indicator scores and the relevant SDGs.

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