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HEATSTORE risk assessment approach for HT-ATES applied to demonstration case Middenmeer, The Netherlands

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Summary

In order to make the transition to a low-carbon energy system, sustainable energy sources are required as alternatives for fossil fuels. The heating and cooling sector is of major importance for the final energy consumption in Europe, and therefore the deployment of the thermal energy sector could be a good contribution to a sustainable energy system. In the HEATSTORE project the technical, economic, environmental, regulatory and policy aspects required to support efficient, safe and cost-effective deployment of underground thermal energy storage (UTES) technologies in Europe are being investigated. Within this report potential risks associated with high temperature aquifer thermal energy storage (HT-ATES) have been assessed. This has been done by building a Risk Inventory tool, which includes potential risks for HT-ATES systems. This tool has been built from an extensive literature study and from expert interpretations, which led to the development of a structured Risk Inventory tool. The Risk Inventory contains risks and their potential mitigation measures associated with HT-ATES. The aim of the inventory is to serve as a checklist for identifying and managing all risks that are applicable for a specific case study. The robustness and value of the Risk Inventory was tested by applying the tool to the Dutch demonstration case on HT-ATES in Middenmeer in The Netherlands, from which the added value of the tool could be validated.

Contents

1 Introduction

The decrease in production and consumption of natural gas and the increasing necessity of the transition to a low-carbon sustainable energy system in the Netherlands require sustainable alternatives to natural gas (Platform Geothermie et al., 2018). As the heating and cooling sector is responsible for half of all consumed energy in Europe the deployment of the geothermal energy sector is of prime importance for working towards a sustainable energy system. HEATSTORE is one of nine projects under the GEOTHERMICA - ERA NET Cofund with the aim to accelerate the uptake of geothermal energy. In HEATSTORE there are 23 contributing partners from 9 countries with complementary expertise and roles, composed of a mix of scientific research institutes and private companies. In the HEATSTORE project the focus is on underground thermal energy storage (UTES) as a complementary technology to increase the flexibility for managing variations in supply and demand of heat at different scales, and during different times/seasons. The main objectives of HEATSTORE are: 1) advancing and integrating different types of UTES in the energy system, 2) providing means to maximize geothermal heat production and optimize the business case of geothermal heat production doublets, and 3) addressing technical, economic, environmental, regulatory and policy aspects that are necessary to support efficient, safe and cost-effective deployment of UTES technologies in Europe (Kallesøe & Vangkilde-Pedersen, 2019; Nielsen & Vangkilde-Pederson, 2019).

The objectives of the HEATSTORE project are primarily being achieved by applied research on 6 demonstration pilots and 8 case studies of existing systems with distinct configurations of heat sources, heat storage and heat utilization. One of these UTES demonstration pilots is planned at Middenmeer in the Netherlands, which is carried out by Energie Combinatie Wieringemeer (ECW). The UTES system is a new High Temperature Aquifer Thermal Energy Storage (HT-ATES) system in the Netherlands where water will be stored at temperatures of up to 90ºC in an aquifer at a depth between 300 and 400 meters (Kallesøe & Vangkilde-Pedersen, 2019).

The development and operation of a HT-ATES site does not come without risks. The risks can be of various nature; i.e. technical, economic, environmental, commercial, organisational, political and social (TEECOPS). In this chapter the assessment of the risks of HT-ATES in general, and for the Middenmeer case specifically will be discussed. The evaluation of risks and potential mitigation measures can be of great support for reducing technical uncertainties, optimizing the business case, the social acceptance and the license to operate (including permitting) of thermal energy systems. In a first phase an extensive literature study has been done on potential risks and mitigations associated with HT-ATES. The literature study was used to develop a Risk Inventory. This Risk Inventory contains risks and mitigation measures associated with HT-ATES that are relevant for all phases and system components of an HT-ATES system, and each of these risks are assigned to their respective TEECOPS category. The aim of the inventory is to serve as a contribution and/or checklist for identifying and managing all applicable risks and to provide their associated potential mitigation measures for preventing or decreasing the consequence of the risk. This inventory will aid in identifying risks that were perhaps overlooked by project teams. In order to test the robustness and value of the Risk Inventory Tool we applied it to the ECW Middenmeer pilot study.

2 Risk Inventory

The aim of the Risk Inventory, developed in Excel, is to serve as an instrument to: 1) visualize and increase awareness of important risks, and 2) indicate the impact of mitigations relevant for communication and/or permitting. The Risk Inventory can be found in Appendix 1 – Risk Inventory (van Unen, M., et al., 2020) and can be shared on request.

The goal of the Risk Inventory was to build a structured template, which is self-explanatory, has a clear scope and boundaries, and has the possibility to filter risks on relevance. This has been achieved by categorizing each risk to its respective project phase and system component, and to classify each risk into the TEECOPS criteria.

The risks in the inventory are categorized in 5 project phases (Figure 1) and one general category for risks that apply to all (or the majority of the) phases.

- Pre-execution phase: All work done prior to the start of the execution phase, including analysis, design, permitting, forging a consortium and contracting.
- Execution phase: Phase where the facility is built or updated for energy storage.
- Operational phase: The phase where energy is actually being stored and produced.
- Decommissioning phase: Includes the moment when wells are abandoned, surface facilities are being removed and the site is being cleared for future use.
- Post-abandonment phase: The phase after decommissioning, where risks could come to light by monitoring of the abandoned site.
- All phases: Risks that apply to all (or the majority) of the above defined project phases.

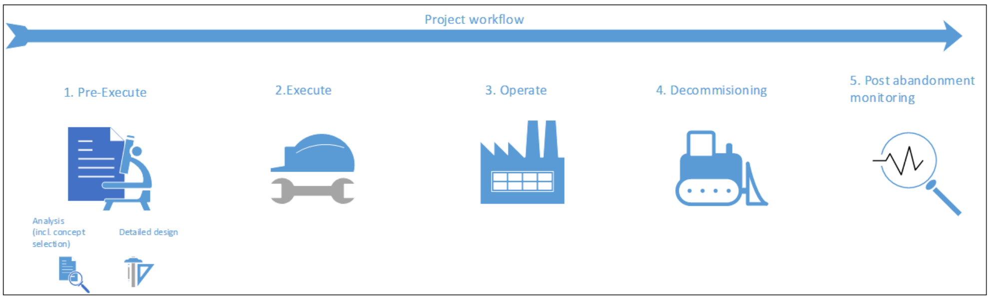

Figure 1. *The structure of the Risk Inventory in Appendix 1 is composed of 5 project phases, which are consistent with the typical project workflow.*

Each of these project phases is divided into four system components, which provide boundaries to the system:

1) General: Risks that are relevant for all (or multiple) of the system components
2) Surface Facilities: These include compressors, piping, instrumentation, process facilities
3) Well: This includes the X-mas tree, wellhead, well (completion and cemented casings), sand-face completion

4) Subsurface (reservoir): The target storage reservoir, the caprock and overburden

Also an unfilled section of a project specific system component is present in the template. In this section risks that are project specific and probably not relevant for (most) other projects can be noted.

Furthermore, each individual risk was classified into the TEECOPS criteria (based on Peterhead CCS project, 2016):

- Technical: (Sub)surface, Infrastructure, Technology, Operability, Availability, Integrity, Sustainability, Maintenance
- Economical: Life-Cycle Cost, Phasing, Valuation method, Capacity, Economic model, Regret costs
- Environmental: Surface exposure, Subsurface environment
- Commercial: Contracting & Procurement, Financing, Business controls, Legal, Terms & Conditions, Competition, Marketing, Liabilities, Collaboration Agreement
- Organisational: Structure, Resources, Procedures, Project Controls, Knowledge Management, Systems & IT, Interfaces, Partners, Governance
- Political: Government, Stakeholders, Employment, Regulation, Security, Reputation, NGOs, Export Control, Localisation
- Societal: Community, Public opinion, Social License to Operate

The Risk Inventory is compiled from risks found in literature and derived from internal TNO experts, supplemented with expertise from partners in the HEATSTORE consortium. The risks were ordered into the categories described above, incorporated in the Risk Inventory template and updated when required. This led to a total of 143 HT-ATES selected risks derived from 26 references and expert interpretations. The Risk Inventory template allows to filter for each of the project phase, system component and TEECOPS, which makes it an efficient template for the determination of specific risks within different fields of interest. Based on their consequence and probability rating the template also allows for a first estimation of the impact of the selected risk (see Appendix 2 – Consequence-probability matrix; based on DAGO, 2019).

3 Risk assessment

The Risk Inventory has not been used for advanced case studies on UTES systems yet. However, in order to test the robustness and added value of the Risk Inventory we used the template for the HT-ATES ECW pilot study in Middenmeer in The Netherlands, which is planned to be operational by the summer of 2020.

Prior to the workshop experts from IF Technology, ECW and TNO were asked to select the most important risks for each system component in the Risk Inventory applicable for the case, through a questionnaire (Mentimeter, Figure 2). TNO assessed the input and selected the following top 10 risks/risk themes:

1) Recovery (efficiency) of the system
2) Demand and price forecast (in)accuracy
3) Water treatment performance
4) Scaling (surface facilities and well)
5) Sand production/erosion
6) Gases in fluids
7) Corrosion (surface facilities and well)
8) Skin formation due to drilling fluids
9) Reservoir quality
10) Temperature effect on the reservoir

During the workshop each of the experts provided their knowledge on these selected risks by addressing the following four topics: 1) definition of the risk for the Middenmeer case study, 2) rating of the risk (addressing probability versus consequence) before mitigations, but including mitigations that are already in the design, 3) discuss potential (additional) mitigation options, and 4) rating of the risk after applying (additional) mitigation measures (by using the ranking matrices in Appendix 2 and 3). The ranking results of the selected risks prior and after mitigations have been applied are demonstrated in Figure 3.

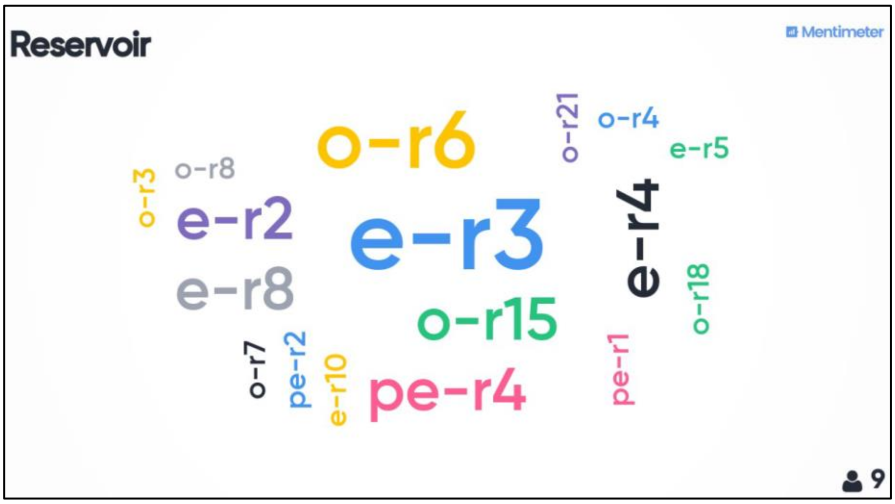

Figure 2. Mentimeter results for the system component 'Reservoir'. Nine persons identified their top 3 risks for the reservoir, resulting in 17 risks. Only few risks were considered by more than one person for this system component.

Consequences			***Probability (chance)***				
			1	***2***	***3***	***4***	***7***
			Rare	Unlikely	Credible	Likely	Very likely
Impact (effect)	***Impact label***	***Project***	Never happened in the industry	Could happen in the industry	Happened in the industry	Happens a few times per year in the industry	Happens multiple times per year in the industry
1	***A***	Very small consequences		10b		10b	
2	***B***	Small consequences	6	7, 8	6, 7, 8		
3	***C***	Some consequences	10a	1, 2, 3, 4, 5, 5, 9, 10a	9	3, 4	
4	***D***	Large consequences			1	2	
7	***E***	Very large consequences					

Figure 3. *Consequence - probability matrix demonstrating the ranking results of the 10 selected risks described above from the workshop with ECW, IF and TNO; blue numbers= pre-mitigation impact; black numbers: post-mitigation impact (the matrix is based on DAGO, 2019).*

4 Conclusions

The aim of the Risk Inventory is to provide a database of risks and associated potential mitigation measures that can be used for HT-ATES case studies. However, it must be noted that this Risk Inventory is not necessarily complete and not every risk is applicable for every case study. Therefore, we recommend to use the Risk Inventory as a template/checklist for the identification of potential risks, and to select the important risks for a specific case study with relevant experts. Additionally, for ranking the selected risks from the Risk Inventory it is recommended to rate the consequence and probability with experts in the field of interest and to use the ranking templates shown in Appendix 2 – Consequence-probability matrix. The aim of the Risk Inventory is to serve as a contribution and/or checklist for visualizing, identifying (overlooked) and managing applicable risks, and to visualize the impact of the proposed mitigations on selected risks.

The workshop on HT-ATES in Middenmeer with experts from ECW, IF and TNO was highly valuable and provided additional insight in risks and the benefit of potential mitigation measures in terms of decrease in probability and consequence of these risks. It demonstrated the use of the Risk Inventory in the structuring of expert discussions. Since the Risk Inventory contains 143 risks, a good preparation for an expert workshop is highly recommended, which can be done by pre-selecting the relevant risks for the specific site.

References

Platform Geothermie, DAGO, Warmtenetwerk & EBN, 2018. Masterplan Aardwarmte in Nederland: Een brede basis voor een duurzame warmtevoorziening.

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Peterhead CCS project, 2016. Risk management plan & risk register. Doc No: PCCS-00-PT-AA-5768-00001, Date of issue: 19/01/2016, DECC Ref No: 11.023

Kallesøe, A.J. & Vangkilde-Pedersen, T. (eds). 2019: Underground Thermal Energy Storage (UTES) – state-of-the-art, example cases and lessons learned. HEATSTORE project report, GEOTHERMICA – ERA NET Cofund Geothermal. 130 pp + appendices.

Nielsen, J.E. & Vangkilde-Pedersen, T. (eds.). 2019. Underground Thermal Energy Storage (UTES) – general specifications and design. HEATSTORE project report, GEOTHERMICA – ERA NET Cofund Geothermal. 58 pp.

van Unen, M et al., 2020: Heatstore Risk Inventory for HT-ATES, GEOTHERMICA – ERA NET Cofund Geothermal. 12 pp.

Appendix 1 – Risk Inventory

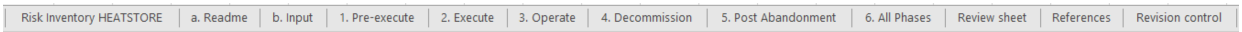
Please find below the full risk inventory.

The Excel file of the risk inventory can be shared on request by mailing to Marianne.vanunen[at]tno.nl or Kaj.vandervalk[at]tno.nl.

The following pages will show the inventory in order of the tabs that are in the excel file, these also include how the inventory is set-up and could be used.

Tabs:

Risk Inventory HEATSTORE
a. Readme
b. Input
1. Pre-Execute
2. Execute
3. Operate
4. Decommission
5. Post Abandonment
6. All Phases
Review sheet
References
Revision control



TAB: Risk Inventory HEATSTORE

Heatstore Risk Inventory for HT-ATES (High Temperature Aquifer Thermal Energy Storage) Version 1.0

General description

This risk inventory for subsurface thermal energy storage projects has been produced by TNO in the context of the Geothermica 1 project Heatstore. It details risks associated with storage of high temperature thermal energy in the subsurface.

It is compiled from risks found in literature, supplemented with expertise from partners in the HeatStore consortium. References used can be found listed in the 'References' tab, the reference is numbered to be able to trace back the risks in this sheet to the literature. It is suggested to use this as an inventory from which the most relevant risks for a particular project can be identified. This procedure has been successfully used for the Dutch Heatstore demonstration case, the method is described in Van Unen et al., 2020, HEATSTORE risk assessment approach for HT-ATES applied to demonstration case Middenmeer, The Netherlands. 15 pp. (reference 31).

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Contributors: M. Koenen[a]
Project Manager: H. Cremer[a]

DISCLAIMER: This risk inventory is based on risks and mitigations that are found in literature. Some of the risks are a combination of multiple references or interpretations of risks that are found in literature. The mitigations in this inventory are found in literature and are supplemented by the team. Please refer back to the references if anything is unclear. The inventory of risks and associated mitigations is not necessarily complete and can be used as a starting point in identifying the most relevant risks for a project. Using this risk inventory does not replace a dedicated risk assessment workshop with the required epxertise.

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Start using this Risk Register by making a separate copy of the file before adjusting it, then please go to sheet a. 'Readme' to understand how the sheet works.

Go to sheet a. Readme

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TAB: a. Readme

Readme

This Readme is prepared to make it easier to understand how this Risk Inventory is set-up. Below definitions for the structure of the risks has been defined (TEECOPS, project phases, risk ratings, system components and storage types). Tab b. 'Input' gives the option to define the project. Tabs 1. to 6. are the core of the risk register; they contain the risks and allow for ranking of the risks (both unmitigated and mitigated). The risk ranking (color code) will automatically follow from what is chosen as likelihood and as consequence rating.

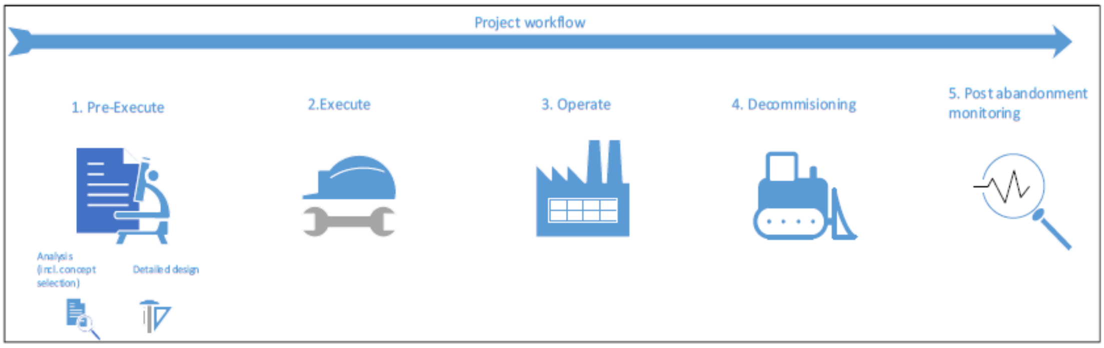
Filtering:
One could filter on the risks earmarked with relevant TEECOPS category by clocking the dropdown button in any of the blue coloured TEECOPS cells and only select the category. The categorisation is an indication and will be made more specific in a potential update version.

TEECOPS Definitions

TEECOPS Definitions[1]		
T	Technical	(Sub)surface, Infrastructure, Technology, Operability, Availability, Integrity, Sustainability, Maintenance
Ec	Economical	Life-Cycle Cost, Phasing, Valuation method, Capacity, Economic model, Regret costs
En	Environmental	Surface exposure, Subsurface environment
C	Commercial	Contracting & Procurement, Financing, Business controls, Legal, Terms & Conditions, Competition, Marketing, Liabilities, Collaboration Agreement
O	Organisational	Structure, Resources, Procedures, Project Controls, Knowledge Management, Systems & IT, Interfaces, Partners, Governance
P	Political	Government, Stakeholders, Employment, Regulation, Security, Reputation, NGOs, Export Control, Localisation
S	Societal	Community, Public opinion, Social License to Operate

[1] These definitions are based on reference 30 from the reference list; Risk management plan for the Peterhead project

Project phase definitions



Project work flow phases; Risk associated with the underground storage of thermal energy	
1. Pre-execute	All work done prior to the start of the execution phase; including analysis and design
2. Execute	The Execution phase; in this phase the facility is built (or updated) for energy storage
3. Operate	The operational phase; the actual phase where energy is stored and produced
4. Decommission	The Decommissioning phase; this includes the abandonment of wells, removal of the surface facilities and clearing the site for future use
5. Post-abandonment	The post decommisioning phase; these include risks that could come to light by monitorring of the abandoned site
6. All phases	All of the above defined project phases (to prevent having them in all phases)

Risk rating

Risk rating			
Probability / Consequence	**Low**	**Medium**	**High**
Low	L	L	M
Medium	L	M	H
High	M	H	H

System components

System component definition	
General	Risks that are relevant for all (or multiple) of the system components
Surface Facilities	These include compressors, piping, instrumentation, process facilities
Well	This includes the X-mas tree, wellhead, well (completion and cemented casings), sand-fa
Subsurface (reservoir)	The target storage reservoir, the caprock and overburden
Project specific	Any risks that are project specific and probably not relevant for (most) other projects

TAB: b. Input

Input (project definition)	
Date:	17 March 2020
Risk assessor(s):	*name of assessors or team*
Project name:	*Project name*
Project type:	*e.g. demonstrator*
Type of Energy Storage:	HT-ATES

TAB: 1. Pre-execute

	Date last modified:									Risk assessor:		Project:		Type of energy storage			Version
	18 March 2020									*name of assessors or team*		*Project name*		HT-ATES			1.0
Pre-execute (scoping, analysis, concept select, detailed design)																	
Risk ID	Risk description	Reference	Risk category							Consequence	Probability of consequence	Unmitigated Risk rating	Mitigations	Mitigated consequence	Mitigated prob. of consequence	Mitigated risk rating	Comments
			T	Ec	En	C	O	P	S								
General																	
PE-G1	Demand analysis and forecast are inaccurate	2	T	Ec		C			S				- Get a good overview on the demand and forecasts and estimate uncertainties - energy demand profile (high temporal resulution) and variations (capacity variations and total seasonal volume variations) -energy temperature profile and variations -cut off temperature -contract duration of demand (letter of intent) per demand entity				
PE-G2	Low social acceptance for heat storage stops project	2; 27		Ec		C	O	P	S				- Prepare and execute communication and participation plans - Early inclusion of stakeholders in decision making - Stakeholder analysis/mapping				
PE-G3	Unsuitable contracts (roles and responsibility not clearly defined) leading to suboptimal performance or exploding costs	2	T	Ec			O						- Select experienced and suitable management				
PE-G4	Not getting a permit for the project	4; 5; 10						P	S				- Early informing and involvement of competent authorities and stakeholders				
PE-G5	Organization is not experienced / financially robust enough for the challenge	2					O						- Contractor / investor shall hire additional proper external experts (domestic, foreign) for the project				
PE-G6	Incomplete understanding of natural systems and/or ecosystem changes	12	T	Ec	En	C		P	S				- Thorough understanding about aspects of the natural system, habitats and operate accordingly, modeling of natural processes				
PE-G7	Unclear permit requirements	4		Ec		C		P					- request clarity with competent authority on duration of permit -request clarity on monitoring and reporting requirements in relation with the permit -request clarity on the performance requirements for the project and potential go / no-go indicators stage gates				
PE-G8	Unclear subsidy requirements	4		Ec		C		P					- obtain clarity on duration of subsidy, amount and payment intervals - obtain clarity on monitoring and reporting requirements for subsidy -obtain clarity on the performance requirements for subsidy grant and payment				
Surface facilities																	
PE-S1	Inappropiate/inadequate surface technologies design (due to inexperience)	1	T										- Design with flexibility - Detailed design surface facilities after well test (also postponing start date) - component by component review and assess appropriateness for higher temperature operation				
Well																	
P-W1	Inappropiate/inadequate well design	8	T										- Design with flexibility - Detailed design wells -confirm material suitability with higher storage temperatures and cyclic temperature differences				
PE-W2	No (international) (design) standards available dedicated to geothermal or (HT)-ATES	1	T					P					- Start procedure for international standards - Determine fit for purpose design considerations				
PE-W3	Heat loss from well	1; 8		Ec	En	C		P	S				- perform 3D subsurface calculations to assess anticpated heat losses from well in overburden -assess opportunitie for insulation nad perfrom cost benefit analysis -transparency of results with competent authorities and stakeholders				
Reservoir (subsurface)																	
PE-R1	Not able to find a suitable aquifer in the area of interest	5; 27	T	Ec									- To estimate the potential of the project one must define the minimum permeability, aquifer thickness, heterogeniety depth range, impermeable layer requirements, background temperature and the injection and production temperatures of the hot and cold wells				
PE-R2	Available subsurface data of insufficient quality (e.g. permeability of reservoir, overburden and seal) resulting in uncertainty of permeability, heterogeneity and reservoir thickness	1, 7; 17; 27	T	Ec	En	C	O	P	S				- Gather new information of sufficient quality (2D or 3D seismic) - Look at offset wells (if available) - Drill additional exploration wells - Subsurface monitoring (determine thicknesses of the sedimentary intervals, permeability) - Reprocess available data to improve quality - Drill dedicated exploration well(s) - To estimate the potential of the project one must define the minimum permeability, aquifer thickness, depth range, impermeable layer requirements, background temperature and the injection and production temperatures of the hot and cold wells				
PE-R3	Insufficient information on the thermal and loading capacity of the storage site	27	T										- A detailed 3D subsurface heat and groundwater flow modelling is needed to better estimate the thermal capacity and status of loading of the system over time				

TAB: 1. Pre-execute (continued)

PE-R4	Unfavourable subsurface conditions lowering the performance of the storage site	27		Ec									- Good reservoir thickness and petrophysical properties are required. - Reservoirs need good connected porosities and high permeabilities - Reservoir should be positioned at a depth allowing for a wide pressure range for the applicable and approved minimum and maximum injection and withdrawal pressures. - Extensive reservoir characterisation and reservoir modelling needs to be performed - The heat demand and supply profiles must be determined - Make economic assumptions on heat sources, HT-ATES and competing (or reference) technologies - Economic indicators such as payback period (PP) and levelized costs of energy (LCOE) should be chosen and calculated to compare economic effectiveness of different options. - The economic potential is further narrowed down to the market potential by taking into account the impacts of policy and regulations as well as factors such as willingness to pay and local implementation. - Stakeholder acceptance and the distance to protected areas need to be taken into account. - Existing policies like renewable energy subsidies, incentives on purchasing renewable heat and regulations of energy tax should be included. - A sensitivity analysis is helpful to identify the parameters with the strongest impact on the results and the degree to which the uncertainty range in single input values can potentially change the results				
											Project specific						
P-P1																	
P-P2																	
P-P3																	

TAB: 2. Execute

Date last modified:	Risk assessor:	Project:	Risk assessor:	Version
18 March 2020	*name of assessors or team*	*Project name*	*name of assessors or team*	1.0

Execute (incl. well test and injectivity test)

Risk ID	Risk description	Reference	Risk category							Consequence	Probability of consequence	Unmitigated Risk rating	Mitigations	Mitigated consequence	Mitigated prob. of consequence	Mitigated risk rating	Comments
			T	Ec	En	C	O	P	S								
General																	
E-G1	Over-expenditure on CAPEX because of unforeseen costs or unfavourable tender	7		Ec		C	O						- Design fit for urban environment - Tender strategy fit for market supply - Detailed design narrow down the uncertainty range				
E-G2	Roles and responsibility are not clearly defined leading to suboptimal performance or exploding costs	2	T	Ec			O						- Select experienced people together with suitable management				
Surface facilities																	
E-S1	Malfunction of the control panel that is connected to the transformer facility leading to an interruption in the electricity cycle	2	T										- Additional wires for most risky connections - Additional transformers that can step in when needed				
Well																	
E-W1	Wrong choice of stimulation fluids or techniques damaging well	2	T		En								- Training and certifying of the personnel - Select experienced and suitable management - Thorough well design including stimulation load simulation				
E-W2	Wrong choice of mud density or mud losses leading to damage to well, which can lead less injection/production due to additional skin	2	T		En								- Thorough geological survey/core sample analysis - Thorough well design including stimulation load simulation - Avoid extreme overpressure drilling - Proper preperation and determination of the composition and parameters of the drilling fluid /mud program				
E-W3	Not able to lower the casing string, which can result in hole instability	2	T										- Ensure safe clearance and drift diameter of the well				
E-W4	Trajectory issues (deviation from target)	2	T		En								- Thorough drill plan/program and its execution				
E-W5	Drilling is more complicated/more expensive than anticipated	2	T	Ec													
E-W6	Technical failure during drilling	2	T	Ec									- Exploitation of the equipment according to the manual - Accurate collection and interpretation of expected geology and their features for securing information on the forecasted drilling difficulties - Doing new surface geophysical measurements for the better understanding of expected geology and their features for securing information on the forecasted drilling difficulties - Careful selection of subcontractors and careful contracting, including their insurances				
E-W7	Rig issues (standard drilling risks)	2	T	Ec													
E-W8	Issues in transporting/handling radioactive sources for logging	2	T		En								- Radioactive waste management plan - Applying radiation safety protocols				
E-W9	Well casing collapse	2	T	Ec									- Extreme caution at the instable formations - Throrough well design				
E-W10	Blow-out (risking license to operate)	2	T	Ec	En			P	S				- Thorough drill plan/program and its execution - Exploitation of kick detection equiment - Training and certifying of the personnel				
E-W11	Standard drilling risks also common to O&G operations (e.g. hitting overpressured layer, shallow gas pockets, getting stuck, losses, losing circulation)	1	T										- Drill according to newest lessons learned - Early involvement of contractors and experts - State of the art drilling program				

TAB: 2. Execute (continued)

Reservoir (subsurface)																	
E-R1	Wrong choice of stimulation fluids or techniques damaging the reservoir potentially leading to reduced injection and production rates	2	T		En								- Training and certifying of the personnel - Select experienced and suitable management - Thorough geologicals survey/core sample analysis				
E-R2	Wrong choice of mud density leading to damage to reservoir	2	T		En								- Thorough preparation of mud Program - Thorough geological survey/core sample analysis				
E-R3	Flow rate lower than expected (e.g. because of lower permeability, heterogeneity of the reservoir)	2; 7; 8	T	Ec									- Adaptation of the drillpath to reach multiple targets - Avoid excessive contamination of the well - Use of clay-mineral free drilling mud - Avoid the use of loss control material during drilling of the production section - Avoid the cementing of previous casing string in the production section - Try to drill long enough production section for securing the expected yield - Use of external casing packer between the loose formation and the productive layer - In case of porous reservoir use of underreamig and gravel pack in the production section - Design the production section of the well with 8 1/2 " diameter - Accurate collection and interpretation of productivity data of wells for securing information for the expected yields - Doing new measurements in existing wells for securing information for the expected yield - Dedicated exploration well - Update design and include more sources to increase supply - Include potential extra wells in risk margin for project				
E-R4	Pressure lower or higher than expected	2	T	Ec		C							- Adapt the power plant design under given temperature/pressure				
E-R5	Fluid chemistry / gas content / physical properties are different from expected	2	T		En								- Adapt the material selection to the chemical/physical properties of the fluid - Additional chemical sampling and hydrogeological analyses - Re-evaluate hydrogeological model				
E-R6	Target formation has no fluid, which is a major risk for the economic success of this HT-ATES site	2	T	Ec		C							- Thorough geological survey/core sample analysis - Accurate collection an interpretation of expected geology for securing information on the target reservoir - Doing new surface geophysical measurements for the better understanding of expected geology for securing information on the target reservoir				
E-R7	Geological lithology or stratigraphy is different than expected (unexpected subsurface characteristics)	2	T										- Thorough geological survey/core sample analysis - Accurate collection an interpretation of expected geology for securing information on the target reservoir - Doing new surface geophysical measurements for the better understanding of expected geology for securing information on the target reservoir				
E-R8	Re-injection of the fluid is more difficult than expected	2	T			C							- Thorough geological survey/core sample analysis - Adapt the power plant design under given temperature/pressure - Adaptation of the drillpath to reach multiple targets - In case of porous aquifers, make use of underreaming and gravel pack in the production section				
E-R9	Well misses target formation (ends up in a non-suitable layer)	2	T	Ec		C							- Thorough geological survey/core sample analysis - Accurate collection an interpretation of expected geology to provide information on the target reservoir - Doing new surface geophysical measurements for the better understanding of expected geology - Drilling further				
E-R10	Induced seismicity (e.g. during drilling or stimulation)	2	T	Ec	En			P	S				- Installation of seismic monitoring system				
Project specific																	
E-P1																	
E-P2																	

TAB: 3. Operate

	Date last modified:		Risk assessor:	Project:	Risk assessor:	Version
	18 March 2020		*name of assessors or team*	*Project name*	*name of assessors or team*	1.0

Operate

Risk ID	Risk description	Reference	Risk category							Consequence	Probability of consequence	Unmitigated Risk rating	Mitigations	Mitigated consequence	Mitigated prob. of consequence	Mitigated risk rating	Comments
			T	Ec	En	C	O	P	S								
											General						
O-G1	Public opposition against nuisances/emissions (such as noise, dust, light) from the exploitation	2		Ec		C		P	S				- Keep continuous monitoring of standards, technologies and political situation - Maximum noise levels and noise plan (day night rhythm) - Insulation - Early involvement of neighbourhood				
O-G2	Significant changes of energy costs, volume and price risks for heat supply	2		Ec		C		P	S				- Accurately predict heat demand up front - Secure heat demand up front for economical life of system - Heat delivery contracts -subsidy price contracts -price risk hedges implemented				
O-G3	Recovery efficiency of the system lower than expected because of disappointing subsurface properties (losing heat in subsurface), suboptimal operation or extreme seasonal variances. This can appear from thermal advection under high bouyancy forces induced by density contrasts)	7; 10; 27	T	Ec		C							- Boundary low temperature should be as low as possible - Monitor performance of project (mainly temperature) - Robust (operating) strategy, e.g. additional heat source at surface, heat pump, and update if required - Dedicated exploration well - Update source configuration of wells (if additional wells are planned or sidetracks are feasible) - Make sure to not neglect the charging phase with low production capacities and efficiencies (of about 1-3 years) - The use of low permeability aquifers and the use of salinity contrast for density difference compensation are proposed to improve the thermal recovery efficiency -consider application of heat pump for additional heat recovery				HT-ATES installations have relatively low recovery efficiencies during the first years of operation. After the first few cycles, the injected heat in previous years increases the aquifer ambient temperature, which results in a higher recovery efficiency
O-G4	Growth heat network lower than expected	9					C	P									
O-G5	Interruptions in signal transfers due to failures or maintenance	2	T										- In order to have a continuously active data transfer, two communication connections will be needed. One of the two connections functions as a backup, with functionality to switch over automatically if the primary connection is interrupted.				
O-G6	Changing temperatures, downstream users of groundwater and aqueous ecosystems can be negatively affected	4	T		En				S				- To assess the long-term cumulative effects of heat discharge adequately, the autonomous trends caused by changing environmental stresses to the groundwater system should also be considered.				
O-G7	Reduced efficiency of HT-ATES because of changing temperatures	4	T	Ec									- To assess the long-term cumulative effects of heat discharge adequately, the autonomous trends caused by changing environmental stresses to the groundwater system should also be considered.				

<u>TAB: 3. Operate (continued)</u>

Surface facilities																	
O-S1	Excessive scaling in the surface facilities leading to reduced or ceased production	2; 10	T			C							- Installation of inhibitor dosing station - Temperature maintenance - Regular maintenance of the equipment - Adapt the material selection to the chemical/physical properties of the fluid - New sampling and chemical analyses - Perform adequate evaluation of scaling potential - Use of inhibitors				
O-S2	Excessive corrosion in surface facilities (e.g. compressors) leading to leakage	2	T		En	C		P	S				- Installation of inhibitor dosing station - Temperature maintenance - Corrosion allowance - Adapt the material selection to the chemical/physical properties of the fluid - New sampling and chemical analyses - Perform adequate evaluation of corrosion potential - Applying corrosion resistant alloys (CRAs) - Material selection and design principles fit for expected potential corrosion mechanisms - Corrosion avoidance by the injection of dry air between steel and the casings - Strict monitoring of minimum pressures				
O-S3	Particle production leading to surface facility damage (e.g. erosion, damage to heat exchanger, leaks)	2	T		En	C		P	S				- Filtering (preferably downhole) - Reduce velocities to stay below erosional velocities				
O-S4	Technical failure/malfunction/loss of integrity of the surface equipment/ infrastructure/ technical operating system	2	T										- Preparation of backups/hot spares - Have a preventative maintenance plan - Measurement of mass flow and volume, pressure, temperature and pumping rate - Installation of the leakage detection system - Design with safety measures (e.g. emergency shutdown, PRVs)				
O-S5	Toxic emissions (Green house gas) due to gases and fluids produced in-situ	2; 4	T		En			P	S				- Installation of toxic substance(gas/fluid) detection system - Installation of CO_2 (and other gases) removal technology - Safe waste disposal plan - Strong quality assurance with associated training and certification programs are needed urgently to prevent negative environmental impacts and damage to the public perception of the technology				
O-S6	Incident with IBC filled with corrosion inhibitor on site resulting in leak outside barrier	3	T	Ec	En								- Do not handle corrosion inhibitor outside barriers				
O-S7	Losing too much heat in surface facilities	7	T	Ec		C							- Update design of surface facilities				
O-S8	Obstruction of pump turbine	2	T										- If necessary double pump turbines or extra maintenance				
O-S9	Control panel connection malfunction	2	T										- Additional wires for most risky connections				
O-S10	Trend in household effects changes (associated with a different energy demand)	2		Ec					S				- Monitor the heat supply at the households in different seasons (energy profile and trends)				
O-S11	Bad performance water treatment	3		Ec		C			S				- monitor and back-up option for water treament				
O-S12	Damage to and water problems of buildings and agriculture	14		Ec	En			P	S				- Monitor the areas (buildings, agriculture) that are making use of the heat -Monitor the adjacent and overlying areas for damage/problems				
O-S13	Subsidence due to seismicity and collapse of the subsurface structures	2	T	Ec	En								- Pressure monitoring of the subsurface				

TAB: 3. Operate (continued)

Well																	
O-W1	Excessive scaling in the well leading to ceased or lowered production	2	T			C							- Scaling inhibitor injection downhole in well - Use well materials less likely to scale - Production management to prevent entering scaling regime - Lower the temperature				
O-W2	Excessive corrosion in the well and components (Corrosion of pipelines and components (injectors, wells and their casings/cements) leading to loss of integrity (can lead to leakage into brackish/drinking water layers due to integrity loss of injection well)	2; 3; 7; 11	T	Ec	En	C		P	S				- Installation of corrosion inhibitor in producer - Temperature maintenance (if possible) - Determine corrosion allowance (Corrosion management plan) - Adapt the material selection to the chemical/physical properties of the fluid - New sampling and chemical analyses - Perform adequate evaluation of corrosion potential - Perform regular corrosion logs (e.g. callipers) - Two barrier policy for drinking water layers - Include corrosion surplus into casing design - Continuously monitor corrosion or amount of corrosion inhibitor injected for injection well (to be designed, not readily available at the moment)				
O-W3	Particle production leading to well damage (e.g. erosion of well casing and components)	2, 7	T		En	C		P	S				- Thorough well design - Filtering (preferably downhole) - Reduce velocities to stay below erosional velocities				
O-W4	Precipitation of carbonates, which can lead to clogging of the well	21	T										- Make sure storage does not take place at too high temperatures - Keep the calcite in solution by adding CO2 or HCl to the infiltrating water - Track the pH value of the groundwater				
O-W5	Lack or loss of integrity of the well/technical failure of the well equipment (can lead to cross flow into shallower formations and thermal, chemical and micro-biological effects, which can change the cement bond strength)	2; 7; 11	T		En	C		P	S				- Thorough cementing procedures - Throrough well design - Risk analysis in design phase - Monitoring of risks during operational phase - Preparation of backups/hot spares - Perform well intervention				
O-W6	Suboptimal design of well leads to reduced flow rate	2	T	Ec		C											
O-W7	change the cement bond strength	2; 7; 11	T		En	C		P	S				- Thorough cementing procedures - Throrough well design				
O-W8	Blocked or buckled (corrosion) inhibitor injection line preventing corrosion inhibitor downhole or leaking of corrosion inhibitor above designed injection depth	1, 3	T			C							- Replace corrosion inhibitor line if signs of damage are found - Corrosion inhibition plan allowing for other options (material selection) - Only inject corrosion inhibitor when injecting into well				
O-W9	ESP reliability less than expected	1, 7	T			C							- Redundancy in design - Operation & maintenance planning - Monitoring of pumps				
O-W10	Losing too much heat in the well	7	T			C							- Heat insulating well material -adjust operations (flow, temperature)				
O-W11	Cyclic (thermal) loading of the wells used for both injecting and "producing" introduces risk of fatigue loads for the steel and cement (e.g. cycles: inject - idle - produce - idle - inject)	1; 9; 11	T										- Detailed prediction of temperature profiles that could be expected - Material selection - Insulated materials to limit temperature variations - State of the art well design - Stay below a temperature variation of 80 degC				
O-W12	Possibly extreme temperature loading for "hot well"	9	T										- Design for expected temperatures - High temperature cement and steel				
O-W13	General well failure similar to O&G (installation loads, pressure loads, temperature loads, material production error)	1	T										- Well design according to state of the art - QA/QC procedures on well equipment				

TAB: 3. Operate (continued)

O-W14	Quality changes of groundwater (e.g. high concentrations of dissolved gas in groundwater), which can lead to rapid gas clogging of the well. Pertubations in the groundwater flow pattern can have a direct impact on the size and location of the capture zone of a groundwater well.	4; 13; 29	T	Ec	En	C							- Determine the concentrations of gas in the groundwater (Fe and Mn-containing). - Maintain sufficient overpressure in the well - Prevent the entrance of air (keep the circuit airtight), which will precent from the precipitation of Fe and Mn in the well. - Enforce the annulus of wells to be grouted to increase the thermal efficiency of the well and reduce the risk of cross contamination - Enhanced grout types can reduce the likelihood of debonding (debonding of conductor pipe and grout can occur because of differences in thermal expansion behavior)				
O-W15	Due to the introduction of biologically available nutrients by well drilling fluids the groundwater quality can change (drinkwater problems). ATES can alter the nature of groundwater-surface water interactions when surface waters are present in the capture zone causing enlargements/alterations of capture zone	4	T		En								- Reinforces the necessity to have protection zones around drinking water wells that prohibit the use of UTES - Transient pumping at an ATES system can act cumulatively and exacerbate the variation in capture zone location induced by the transient nature of groundwater recharge and surface water-groundwater interactions				
O-W16	Injection rate or quality of geothermic water with inhibitors might effect the well integrity/quality	3; 18	T		En		O						- Determine the amount and type of inhibitor - Determine the decay products of the inhibitor and analyze the damage they can do. - Determine the effect of the inhibitor on the environment				
O-W17	Excessive tubing vibrations which can lead to well failure	2	T		En				S				- A good design and keeping a safety margin on the speed at which water is injected/withdrawn.				
O-W18	Uncontrolled fluid release (possibly due to a failure of the subsurface safety valve), which can lead to a blow-out	1	T	Ec	En	C	O	P	S				- Make sure the safety valve is working well, e.g. preventative maintenance - Make a safety assessment in the case of a blow-out				
O-W19	Injection rate, risk of fracturing/ leakage of the inhibitor when the injection rate of the (scaling/corrosion) inhibitor is too high	3	T				O										
O-W20	Hydraulic connectivity between wells is suboptimal	2	T			C							- Thorough well testing - Thorough reservoir planning - Perform adequate interference or tracer tests to provide information for the re-evaluation of the hydrogeological model - Stimulation (thermal, chemical or hydraulic)				
O-W21	Contamination of groundwater due to any types of leakages or emissions	2	T	Ec	En	C		P	S				- Evaluate the overburden - The spill point of the targeted structure and any flow must be determined - Leakage along fractures must be excluded - Monitoring water levels and water chemistry in observation wells completed above the cap rock. - Strong quality assurance with associated training and certification programs are needed urgently to prevent negative environmental impacts and damage to the public perception of the technology				
O-W22	Incident that leads to rip off of the very robust well head with its multiple safety installations	2	T	Ec	En				S				- Carefully monitor the well head - Blow-out can be prevented by an automatically closing subsurface safety valve, installed some meters below the well head - Strong quality assurance with associated training and certification programs are needed urgently to prevent negative environmental impacts and damage to the public perception of the technology				

TAB: 3. Operate (continued)

Reservoir (subsurface)																	
O-R1	Other users of the subsurface resources cause a change in the exploitation parameters	2						P					- Integrated management of the aquifer at regional level				
O-R2	Flowrate degrades over time, temperature lower then expected	2; 18	T										- Thorough reservoir management plan (e.g. Thermal fluid re-injection) - Select suitable production rates - Perform adequate interference or tracer tests to provide information for the re-evaluation of the hydrogeological model - Stimulation (thermal, chemical, hydraulic) - Decrease of production rate (temporary) - Increase of the flow rate - Adaptation of the drillpath to reach multiple targets - Accurate collection and interpretation of temperature data measured in existing wells to provide information for temperature forecast - Doing new temperature measurements in existing wells to provide information for temperature forecast - Use of cement with increased heat insulation properties				
O-R3	Fluid density contrasts, thermal expansion/strong temperature decrease can cause convection and thermal stress, which subsequently influences the reservoir pressure. This can result in fracturing/embrittlement (can lead to leakages from the subsurface to the surface).	2; 4; 18	T	Ec									- Thorough reservoir management plan (e.g. Thermal fluid re-injection) - Select suitable production rates - Similar to "temperature lower than expected" - Spatial subsurface planning is required to minimize negative interference or, in some cases, combine individual subsurface activities to achieve greater mutual benefit. - Careful site management - Monitoring of the fluid density during transport - Determine porperties of the fluid (e.g. denisity, composition, viscosity				
O-R4	Pressure is changing during the operation in an unexpected way (due to e.g. high injection pressures, isostacy)	2	T										- Thorough reservoir management plan (e.g. Thermal fluid re-injection) - Accurate collection and interpretation of pressure data measured in existing wells to provide information about overpressure - Doing new pressure measurements in existing wells to provide information about overpressure - Include safety margins - Upfront pressure modelling				
O-R5	Chemical reactivity of the drilling fluid, which may alter the physical properties of the in-situ rock and in-situ fluids by their reaction with the drilling fluids	4; 11	T		En				S				- Thorough reservoir management plan (e.g. Thermal fluid re-injection)				
O-R6	Geochemical deterioration of the reservoir (scaling, and blocking of source by carbonate scaling. Can be due to injection of e.g. geothermic waters with inhibitors)	2; 3; 7; 18	T		En								- Production/injection management plan - Limit amount of added chemicals injected into formation - Water treatment procedure and update if required - Material selection - Dedicated exploration well - Determine the amount and type of inhibitor - Determine the decay products of the inhibitor and analyze the damage they can do. - Determine the effect of the inhibitor on the environment				
O-R7	Particle production leading to reservoir damage (e.g. reservoir collapse)	2	T		En								- Decrease production rate - Use screens in lower completion				
O-R8	Re-injection of the fluid becomes more difficult than expected	2	T										- Adequate filtering of the re-injected water - Monitoring of change of produced water's particle content - Monitoring of scaling porential of the produced fluid - Regular logging and maintenance of the reinjection well - Use of killing agent to inhibit bacteria invasion in active layers of the injection well				
O-R9	Fluid communication/mixing between different formations due to bad isolation of the well	2; 4	T		En			P	S				- Thorough cementing procedures - Use of external casing packer between aquifers				
O-R10	Induced seismicity during operation (e.g. because of temperature difference)	2	T		En			P	S				- Installation of seismic monitoring system - Avoid high re-injection presure/rate - Seismic modelling up front				
O-R11	Subsidence or uplift	2	T		En			P	S				- Avoid high re-injection presure/rate - Thorough reservoir management plan (e.g. Thermal fluid re-injection)				

TAB: 3. Operate (continued)

O-R12	Leaching from installation materials, leading to reservoir alterations or precipiations of chemical substuents (injection of corrosion inhibitor/antifreeze into reservoir during injection phase might alter the reservoir properties)	3	T		En								- Continuously monitor amount of corrosion inhibitor injected for injection well (to be designed, not readily available at the moment) - Only inject corrosion inhibitor downhole in producer				
O-R13	Changing water levels and fluxes leading to desiccation, water logging, settlements	4			En												
O-R14	Changing other well's capture zone, leading to increase in vulnerability and pollution	4			En												
O-R15	Changing groundwater temperature leading to changed temperatures and reaction kinetics (may mobilize otherwise immobile contaminants by increasing solubility and reducing sorption or may increase contaminant toxicity)	4; 27			En								- Monitoring of groundwater quality, energy efficiency, hydrothermal effects, geo-chemical effects and effects on microbiological populations in the subsurface				
O-R16	Mixing processes and chemical reactions leading to salinity, IMIPO (inorganic micro-pollutants) or OMIPO (organic micro-pollutants)	4			En												
O-R17	Unexpected hydrogeologic conditions. Reactivation of otherwise stable groundwater pollution plumes leading to IMIPO and OMIPO (see O-R16 for meaning)	2; 4			En								- Careful site management (e.g. land ownership, proximity to critical infrastructure (natural gas pipeline and transmission), and nearby exploration wells)				
O-R18	Oxidation processes leading to precipiation of chemical substances	4			En												
O-R19	Dissolution/precipitation of carbonates /silicates/other solids, creating extra pore space (increase porosity and permeability), potential collapse of the system and leakages	4; 17			En				S				- Monitoring of subsurface and subsidence - Careful site management				
O-R20	Mixing of different chemical groundwater types (e.g. through dispersion in the transition zone), mobilization of nutrients, and increased groundwater temperature may accelerate biodegradation (alter microbiological population). Bio-chemical reactions in the ground water system and interferences with groundwater production	4; 22; 29	T		En								- Isotope and mineral sampling of the groundwater - Sampling of the monitoring wells and the thermal production wells				
O-R21	Subsurface erosion of rocks/salt, increase leakage potential of (contaminating) fluids	1			En	C			S				- Careful site management - Spatial subsurface planning is required to minimize negative interference or, in some cases, combine individual subsurface activities to achieve greater mutual benefit.				
O-R22	Ground expansion often as a result of compaction due to cooling of the area (ground) around the well	21	T										- Monitor the expansion with the formula of Koppejan				
O-R23	Piezoelectricity generating an electric potential when specific stress/strain conditions are applied (cycled stress conditions especially near boreholes, may facilitate this phenomenon).	2	T										- Monitor the cycles stress conditions near the borehole				
O-R24	Leakage through the overburden (along contact surface of the sealing structure, fractures. Stored product can migrate away and become unrecoverable and a valuable commodity is lost	2		Ec	En								- Risk analysis of geological storage facilities - Determine significance of risk - Adequate cap rock characterization				
											Project specific						
O-P1																	
O-P2																	

TAB: 4. Decommission

	Date last modified:									Risk assessor:		Project:		Risk assessor:			Version
	18 March 2020									*name of assessors or team*		*Project name*		*name of assessors or team*			1.0
Decommission																	
Risk ID	Risk description	Reference	Risk category							Consequence	Probability of consequence	Unmitigated Risk rating	Mitigations	Mitigated consequence	Mitigated prob. of consequence	Mitigated risk rating	Comments
			T	Ec	En	C	O	P	S								
General																	
D-G1	Leakage of the product as a result of either deliberate or accidental release during dismantling and removal of tanks and pipework.	2; 28	T	Ec	En								- On abandonment, closure and monitoring of subsurface pressure can be done to prevent over-pressurization and possible failure of the walls or roof rock and the wellhead/valves				
D-G2	Risks associated with uncertainty regarding the state of structures, installations and equipment	26	T				O						- Gain extensive information on what activities are included and not included in the decommisioning phase				Fixed steel platforms: Most of the platforms which have been removed are relatively small structures. The variation in weight is however from around 1000 t up to more than 100.000 t. Typical manhour consumption per project is therefore probably closer to the lower value than the upper value quoted above. 500.000 manhours has been assumed as an average per jacket. - Subsea: Removal of subsea equipment is much simpler than for fixed installations. No data on this is available, but 100.000 manhours has been assumed. - Pipelines: Removal of pipelines is similar to subsea equipment although the variation in work may vary considerably.
D-G3	Postponing decommissioning because of economical attractiveness increasing difficulty of decommissioning	1	T	Ec		C	O		S				- Have clear cut-off point and decommissioning moment based on equipment properties				
D-G4	Financial risk during the decommissioning phase	2		Ec			O		S				- Include time/cost buffer in the planning				
D-G5	Contamination of groundwater due to any type of leakages or emissions	2	T	Ec	En			P	S				- Modelling of leakage and monitoring of the well				
D-G6	Occurance of off-site risks when contaminated tanks and pipework are not disposed of in an appropriate manner	5; 28	T		En								- Careful disposal of contaminated tanks and pipework - Any residual product should be removed from the tanks and pipework - Consignment to a suitable waste treatment facility - The operator needs to assess together with the competent authority if and how the surplus of heat that remains in the subsurface after closure can have a useful function - (Monitoring) wells need to be closed (filled) within one month after ending operation - The initial subsurface profile needs to be restored				

TAB: 4. Decommission (continued)

Surface facilities																	
D-S1	Surface facility material covered in radioactive (NORM/LSA) scaling	1	T		En								- Scaling inhibitor/dissolver - Monitoring of scaling during production - LSA/NORM planning				
D-S2	Interruptions in signal transfers due to failures or maintenance	2	T				O						- In order to have a continuously active data transfer, two communication connections will be needed. One of the two connections functions as a backup, with functionality to switch over automatically if the primary connection is interrupted.				
D-S3	Facilities are left in-situ, which could arise the risk that if any residual product remains in the tanks and the integrity of the equipment would no longer be maintained or monitored, risks (e.g. leakage, contamination) might appear	28	T		En								- Remove all redundant tanks and pipework - If equipment is being left in-situ they must be made safe				
Well																	
D-W1	Well material to be retrieved covered in scale with radio active contents (NORM/LSA)	1	T		En								- Scaling inhibitor/dissolver - Monitoring of scaling during production - LSA/NORM planning				
D-W2	General well decommisioning risks from O&G (stuck items, phishes in hole, unable to create barrier)	1	T	Ec									- Use lessons learned from industry - Design for decommisioning already at start - Include decommisiong in all decisions - Monitoring				
Reservoir (subsurface)																	
D-R1																	
Project specific																	
D-P1																	
D-P2																	
D-P3																	

TAB: 5. Post Abandonment

	Date last modified:									Risk assessor:		Project:		Risk assessor:			Version
	18 March 2020									*name of assessors or team*		*Project name*		*name of assessors or team*			1.0
Post abandonment																	
Risk ID	Risk description	Reference	Risk category							Consequence	Probability of consequence	Unmitigated Risk rating	Mitigations	Mitigated consequence	Mitigated prob. of consequence	Mitigated risk rating	Comments
			T	Ec	En	C	O	P	S								
											General						
PA-G1	Stress change due to e.g. seismicity	1	T		En			P	S				- Monitoring of pressure changes - Seismic monitoring				
PA-G2	Subsidence and sinkhole formation (can be associated with damage to infrastructure)	2	T	Ec	En				S				- Renewed injection of other substituents - Pressure monitoring				
PA-G3	Uncertainty on future utilisation	2		Ec									- Make a clear time schedule on the operation time of the plants				
											Surface facilities						
PA-S1																	
											Well						
PA-W1	Abandonment plug deteriorating over time	1	T		En			P	S				- Monitoring if possible				
											Reservoir (subsurface)						
PA-R1	In-situ lithostatic pressure change (caused by a change in the weight of the overburden, thermal expansion of the overburden)	1; 2	E	Ec	En				S				- Thorough post-abandonment monitoring of reservoir pressure changes and weight of the overburden				
PA-R2	Thermosyphoning and thermal stratification, which implies that the upper part of the hot water reservoir is higher than the lower part (thermal contrasts).	13	T						S				- In periods without flow unwanted thermosyphoning must be prevented, which can take place when a pipe is connected to a hot water store that is part of the pipe loop. - Insulate the upper part of the hot water store - Place the thermal bridges (e.g. pipe connections, tank securings) at the bottom of the hot water reservoir - Pipe loops that go through the reservoir can be equiped with a valve to prevent thermosyphoning				
PA-R3	Leakage of the fluid out of the storage site (due to e.g. changed permeabilities, seismicity) into surrounding porous strata via porous non-salt interbeds	2; 14	T	Ec	En								- Leakage monitoring - Monitoring of the subsurface				
PA-R4	Fast temperature drop after the abandonment of the storage site, which can alter the composition of the microbiological population	27	T		En								- Groundwater sampling				
PA-R5	Post abandonment reservoir changes because of (HT)-ATES in reservoir (temperature, chemical, micro biological)	27	T		En			P	S				- Monitoring of the subsurface - Cold injection				
											Project specific						
P-P1																	
P-P2																	
P-P3																	

TAB: 6. All Phases

Date last modified:		Risk assessor:	Project:	Risk assessor:	Version
18 March 2020		*name of assessors or team*	*Project name*	*name of assessors or team*	1.0

All phases

Risk ID	Risk description	Reference	Risk category							Consequence	Probability of consequence	Unmitigated Risk rating	Mitigations	Mitigated consequence	Mitigated prob. of consequence	Mitigated risk rating	Comments
			T	Ec	En	C	O	P	S								
General																	
AP-G1	Lack of financing for next phases	2		Ec		C							- Thorough feasibility study including risks - Thorough cost management - Thorough analysis of funding opportunities				Including bankruptcy of project developer (SPV), developping in unknown region
AP-G2	Lack or loss of clients	2				C	O						- Good bonding with the clients - Make the clients feel comfortable and keep them informed at all steps				Including wrong design of filters/sheets, well architecture, materials for casing, other equipment, etc (data aquisition, modelling, decision making, design of wells/plantsm construction)
AP-G3	Best practices not applied leading to incidents or decreased performance	2	T			C							- Detailed safety and health assessment - Assess the possible risks for each step				
AP-G4	Changes in policies, laws, taxes and regulations put development / economy in jeopardy	2		Ec		C		P					- Keep continuous monitoring of standards, technologies and political situation				Include abandonment, drilling, maintenance, etc.; the cause be a change in the economic environment such as inflation
AP-G5	Low financing for work leading to low safety standards	2	T	Ec									- Preparation of cash reserves - Harm fund				
AP-G6	Human error leading to failure (e.g. during drilling / work)	2; 19	T										- Training and certifying of the personnel - Contracting skilled workforce - Robotisation				
AP-G7	Unanticipated delays and costs (materials, services, maintenance)	5	T					P					- Include time/cost buffer in the planning				
AP-G8	Investment costs higher than expected	7		Ec									- Dedicated exploration well to learn more about the subsurface - Subsurface modelling - Offset well data				
AP-G9	Consortium organisation exiting or going bankrupt (when for example the building rate of new households to be connected to the grid stay below expectations and thus insufficient demand remained)	24		Ec			O						- Robust consortium - Consortium agreement anticipating on these risks				
AP-G10	Accidents and unplanned events	2	T	Ec	En	C	O	P	S				- Strict safety, operational, administrative measures				
Surface facilities																	
AP-S1	External natural hazard damaging surface infrastructure	2	T	Ec	En	C		P	S				- Thorough emergency planning (ERP) - Include adequate specifications for possible emergency scenarios				Magmatic area is aggravating factor
AP-S2	Antropogenic hazard damaging surface infrastructure	2	T	Ec	En	C		P	S				- Thorough emergency planning (ERP) - Include adequate specifications for possible emergency scenarios				Terrorism, trucks
G-S3	Fire in a compartment	25	T										- Obtain the spatial distribution of a temperature profile simulating the growth of fire. Such information is useful for evaluating the thermal integrity of the internal systems within the room where the fire is postulated to occur. - The techniques and computer tools used for evaluating the safety of a specific facility should be commensurate with the associated hazards and complexity of the facility, as well as with the availability of data - Computerized mathematical models can be used to quantify the consequences of the release of radioactive material as a result of decommissioning activities				

TAB: 6. All Phases (continued)

Well																	
AP-W1	External natural hazard damaging well	2	T	Ec	En	C		P	S				- Thorough emergency planning (ERP) - Include adequate specifications for possible emergency scenarios - Well design has safety measures (e.g. SSSV) if well can flow by itself				Magmatic area is aggravating factor
AP-W2	Antropogenic hazard damaging well	2	T	Ec	En	C		P	S				- Thorough emergency planning (ERP) - Include adequate specifications for possible emergency scenarios - Well design has safety measures (e.g. SSSV) if well can flow by itself				Terrorism, trucks
Reservoir (subsurface)																	
AP-R1	Induced seismicity, which can result in alteration of the storage site and consequently leakages	1	T		En			P	S				- Careful determination of the location - Subsurface modelling - Seismic monitoring				
AP-R2	Thermal stress on the reservoir	4	T		En								- Analyzing the thermal impacts of HT-ATES on the underground, the temperature effects of climate change and urbanization on the aquifer system should also be monitored/predicted for				All changes in the in-situ stress regime, which can be caused by many events/processes such as (man induced) pore pressure increase, plate tectonics, temperature (thermal stress), diapirism and glaciation
AP-R3	Degradation of the reservoir	2; 4; 7	T			C							- Proper reservoir management plan - Decrease of production rate (temporary) - Stimulation (thermal, chemical or hydraulic) - Reinterpretation of reservoir model - Drill additional reinjection well - Monitoring program - Risk management system - Spatial subsurface planning is required to minimize negative interference or, in some cases, combine individual subsurface activities to achieve greater mutual benefit.				
Project specific																	
G-P1																	
G-P2																	

TAB: Review sheet

Risk inventory review sheet

Please log below the risk review sessions that have been held and the names and expertises of the reviewing group.

Sessions	
Date	Session/topic

Name	Expertise	Company	Role
General			
Surface facilities			
Wells			
Subsurface (reservoir)			

TAB: Review sheet

Reference ID	Reference	Link
1	TNO Risk register team - internal expertise	
2	Le Guénan, T., et al., 2019, GeoRISK D2.1 Risk Register	https://www.georisk-project.eu/publications/risk-register/
3	Van de Watering, F., et al., 2019, Onderzoek (milieu)impact inhibitoren geothermie	https://www.kasalsenergiebron.nl/content/user_upload/Eindrapport_Onderzoek__milieu_impact_inhibitoren_geothermie.pdf
4	Bonte, M., et al., 2011, Underground Thermal Energy Storage: Environmental Risks and Policy Developments in the Netherlands and European Union	https://www.researchgate.net/publication/48209431_Underground_Thermal_Energy_Storage_Environmental_Risks_and_Policy_Developments_in_the_Netherlands_and_European_Union
5	Kallesøe, A.J. & Vangkilde-Pedersen, T. (eds). 2019: Underground Thermal Energy Storage (UTES) – state-of-the-art, example cases and lessons learned. HEATSTORE project report, GEOTHERMICA – ERA NET Cofund Geothermal. 130 pp + appendices.	https://www.heatstore.eu/documents/HEATSTORE_UTES%20State%20of%20the%20Art_WP1_D1.1_Final_2019.04.26.pdf
6	IFTechnology, 2011, Notitie bij project: hoge temperatuuropslag GeoMEC te Brielle, onderwerp: aanmeldingsnotitie voor de vormvrije m.e.r.-beoordelingsplicht	http://ro-onlineprod.brielle.nl/DE6C7277-9669-4956-8722-299CACDAB215/tb_NL.IMRO.0501.geomec4p-0140_6.pdf
7	Drijver, B., Struijk, M. and Koornneef, J., 2018, Hoge temperatuur opslag warmtenet Zuid-Holland	
8	Koornneef, J., et al., 2016,- Feasibility study of a High Temperature Aquifer Thermal Energy Storage at AVR Duiven	
9	ECN.TNO & IF Technology, Projectplan Hernieuwbare Energie - HTO: Hoge Temperatuur Opslag van restwarmte van AVR Duiven	
10	Struijk, M. et al., 2019, Haalbaarheidsstudie ondergrondse hoge temperatuur opslag (HTO) voor tuinbouwgebied NEXTgarden	
11	TNO & IFTechnology, 2016, Analyse effecten van Hoge Temperatuur Opslag op voorraad zoet grondwater	
12	Pluymakaekers, M., et al., 2013, HTO - Hoge temperatuur opslag in de ondiepe ondergrond	https://www.tno.nl/media/2491/tno_rapport-hoge-temperatuur-opslag-in-ondiepe-ondergrond.pdf
13	Cabeza, L.F., 2014, Advances in Thermal Energy Storage Systems	
14	Zaadnoordijk, Hornstra and Bonte, 2013, Grondwaterbescherming en hoge-temperatuur opslagsystemen	
15	Rothuizen, R. 2012, Results STER-model VO BC rev. oct GeoMEC 4P	
16	Drijver, B., Struijk, M., and Koornneef, J., 2018, Hoge temperatuur opslag warmtenet Zuid-Holland.	
17	Wassenaar, H., 2017, Projectplan Hernieuwbare Energie: HTO: Hoge Temperatuur Opslag van restwarmte van AVR Duiven	
18	Koornneef, J., et al., 2016, Feasibility study of a High Temperature Aquifer Thermal Energy Storage at AVR Duiven	
19	Ecovat presentation, 2019, Bouwend Nederland - Ecovat duurzame warmte in de wijk	
20	Bonte, M., et al., 2014, Underground Thermal Energy Storage: Environmental Risks and Policy Developments in the Netherlands and European Union. Ecology and Society, 16(1), 22	https://www.researchgate.net/publication/48209431_Underground_Thermal_Energy_Storage_Environmental_Risks_and_Policy_Developments_in_the_Netherlands_and_European_Union
21	de Jonge, H., 2017, Hoge temperatuuropslag Agriport in Middenmeer. Effectenstudie open bodemenergiesysteem	
22	Tholen, J., 2017, Potential for High Temperature-Aquifer Thermal Energy Storage(HT-ATES) in the Dutch subsurface	https://dspace.library.uu.nl/handle/1874/364066
23	Drijver, B., 2011, High temperature aquifer thermal energy storage (HT-ATES): water treatment in practice. In Nationaal Congres Bodemenergie Proceedings	https://www.researchgate.net/publication/280726862_Drijver_2011_High_temperature_aquifer_thermal_energy_storage_HT-ATES_-_water_treatment_in_practice
24	Wesselink, M.A., 2016, Prospects for HT-ATES in the Dutch energy system - Potentials, applications and business cases of High-Temperature Aquifer Thermal Energy Storage	https://dspace.library.uu.nl/handle/1874/337165
25	IAEA, 2013. Safety Assessment for Decomissioning. International Atomic Energy Agency, Safety reposrts series no. 77	https://www-pub.iaea.org/MTCD/publications/PDF/Pub1604_web.pdf
26	SAFETEC, 2005. Main report Risk Analysis of Decomissioining activities	http://www.hse.gov.uk/research/misc/safetec.pdf
27	Wesselink et al., 2018. Conceptual market potential framework of high temperature aquifer thermal energy storage - A case study in the Netherlands	https://doi.org/10.1016/j.energy.2018.01.072
28	DEFRA, 2002. Groundwater Protection Code: Petrol stations and other fuel dispensing facilities involving underground storage tanks	http://www.adlib.ac.uk/resources/000/082/529/groundwater_petrol_code.pdf
29	Hartog et al., 2013. Field assessment of the impacts of Aquifer Thermal Energy Storage (ATES) systems on chemical and microbial groundwater composition. EGC	http://www.nielshartog.nl/publications/nhartog_EGC2013.pdf
30	Peterhead CCS project - Risk management plan & risk register	https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/531405/11.023_-_Risk_Management_Plan_and_Risk_Register.pdf
31	Van Unen et al., 2020, HEATSTORE risk assessment approach for HT-ATES applied to demonstration case Middenmeer, The Netherlands. 15 pp	https://www.heatstore.eu/documents/TNO%20report%202020%20R10192_HEATSTORE_Final_2020.03.08.pdf

TAB: Revision control

Current version 1.0

Revision control			
Version	Revised by	Comments/changes	Date
0.1	Kaj van der Valk	Filled risk register from literature and personal expertise	01 May 2019
0.2	Logan Brunner	Added comments and edits	07 June 2019
0.3	Marianne van Unen	Added comments and edits	13 June 2019
0.4	Marianne van Unen	Added edits from literature and changed lay out	25 September 2019
0.5	Kaj van der Valk	Review	05 November 2019
0.6	Joris Koornneef	Review	11 November 2019
0.9	Marianne van Unen	Finalizing	15 November 2019
1.0	Kaj van der Valk	Final version before sharing	17 March 2020

Appendix 2 – Consequence-probability matrix

Consequences			Probability (chance)				
Impact (effect)	Impact label	Project	1 Rare Never happened in the industry	2 Unlikely Could happen in the industry	3 Credible Happened in the industry	4 Likely Happens a few times per year in the industry	7 Very likely Happens multiple times per year in the industry
1	A	Very small consequences	1	2	3	4	7
2	B	Small consequences	2	4	6	8	14
3	C	Some consequences	3	6	9	12	21
4	D	Large consequences	4	8	12	16	28
7	E	Very large consequences	7	14	21	28	49

Aim for continuous improvement

Not acceptable: Take mitigation measures until risk reduction

Not acceptable: Stop project!

Figure 4. *Consequence – Probability ranking matrix for identifying whether the effect of the risk is acceptable or not acceptable, and whether mitigations should be taken or the project should stop. The matrix is based on DAGO, 2019. 20190903 DAGO Risico Matrix (QHSEP).*

ERNST (effect)	Gevolgen									
	Q = Kwaliteit		**H = Gezondheid**		**S = Veiligheid**		**E = Milieu**		**P = Publieke Acceptatie**	
1	Geringe schade	Geen storing in het proces, geschatte reparatiekosten lager dan EUR 5.000.	Gering gezondheids effect/letsel	Niet schadelijk voor de individuele inzetbaarheid of voor de uitvoering van het werk.	Gering risico	Gering lichamelijke of psychische schade aan personen. Gering verlies / schade aan installatie(delen). Geringe verstoring van de productie.	Gering effect	Verwaarloosbare financiële gevolgen. Lokaal milieurisico, binnen de installatie en/of systeem.	Geringe invloed	Geringe invloed op de publieke acceptatie.
2	Kleine schade	Mogelijk korte verstoring van het proces, geschatte reparatiekosten lager dan EUR 50.000.	Klein gezondheids effect/letsel	Schadelijk voor de uitvoering van het werk, beperking van de activiteit, maximaal één week nodig voor volledig herstel. Gebruik chemische middelen die in beperkte mate op de gezondheid van invloed zijn, zoals bijvoorbeeld irriterende stoffen.	Klein risico	Gewonden hebben lichte medische zorg nodig en kunnen het werk direct hervatten. Beperkt verlies / schade aan installatie(delen). Beperkte verstoring van de productie.	Klein effect	Verontreiniging; schade zodanig dat er gevolgen zijn voor het milieu. Kleine incidentele overschrijding van wettelijke criteria. Geen permanent effect op het milieu.	Kleine invloed	Lichte lokale media en/of lokale politieke aandacht, met potentieel negatieve aspecten voor de operator.
3	Lokale schade	Langdurige verstoring van het proces, geschatte reparatiekosten lager dan EUR 500.000.	Groot gezondheids effect/letsel	Leidt tot blijvende of gedeeltelijke arbeidsongeschiktheid. Of ongeschikt voor het verrichten van werk over een langere periode, langdurige afwezigheid. Gebruik chemische middelen die onomkeerbare schade veroorzaken - zonder enrstige handicap, bijvoorbeeld lawaai, slechte arbeidsomstandigheden.	Lokaal risico	Gewonden hebben medische zorg nodig en kunnen het werk niet hervatten. Vervanging / reparatie van installatie(delen) beperkt zich tot een paar dagen stilstand. Berichtgeving door lokale media.	Lokaal effect	Beperkte lozing op de omgeving van een bekende stof met geringe toxiciteit. Herhaalde overschrijding van wettelijke criteria.	Aanzienlijke invloed	Regionale publieke bezorgdheid. Uitgebreide negatieve aandacht in de lokale media en/of politiek. Met als gevolg een mogelijk negatieve houding bij de lokale overheid en vorming van actiegroepen.
4	Grote schade	Installatie voor maximaal zes maanden buiten bedrijf en/of geschatte reparatiekosten lager dan EUR 5.000,000.	Permanent arbeidsongeschikt tot 1 dode	Permanente invaliditeit of de mogelijkheid tot één dode als gevolg van een incident, bijvoorbeeld een explosie. Gebruik chemische middelen die onomkeerbare schade veroorzaken met ernstige handicap of overlijden, bijvoorbeeld corrosieve stoffen of bekende carcinogene stoffen.	Groot risico	Een ernstig gewonde of zelfs een enkel sterfgeval. Herstel van installatie(delen) leidt tot een verstoring van de productie van meer dan een maand. Berichtgeving door nationale media.	Groot effect	Ernstige milieuschade; het bedrijf moet uitgebreide maatregelen treffen om de vervuilde omgeving weer in de oorspronkelijke staat te herstellen. Uitgebreide overschrijding van wettelijke criteria.	Nationale invloed	Nationale publieke bezorgdheid. Uitgebreide negatieve aandacht in de nationale media en/of politiek. Met als gevolg een mogelijk negatieve houding bij de nationale overheid en vorming van landelijke actiegroepen.
7	Uitgebreide schade	Uitvallen van delen van de installatie, geschatte reparatiekosten meer dan EUR 10.000.000	Meer dan 1 dode	Mogelijk meerdere doden als gevolg van een incident, bijvoorbeeld een explosie. Gebruik van chemicaliën met acute toxiteitseffecten (waterstofsulfide, koolmonoxide) of bekende carcinogene stoffen.	Enorm risico	Meerdere ernstig gewonden of doden. Significant verlies / schade van installatie(delen), met enkele maanden stilstand tot gevolg. Berichtgeving door internationale media.	Enorm effect	Aanhoudende ernstige milieuschade of overlast die zich uitstrekt over een groot gebied. Een groot verlies van natuurwaarde. Constante hoge overschrijding van wettelijke criteria.	Internationale invloed	Internationale publieke bezorgdheid. Uitgebreide negatieve aandacht in de internationale media en/of politiek, met potentieel ernstige gevolgen voor toegang tot nieuwe wingebieden. Vorming van internationale actiegroepen.

Figure 5. *Matrix for interpreting the consequence – probability relationship of a risk (*Figure 4*). The matrix is based on DAGO, 2019. 20190903 DAGO Risico Matrix (QHSEP).*