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Sustainability assessment of in situ and ex situ remediation of PFAS contaminated groundwater.

15.5.2023

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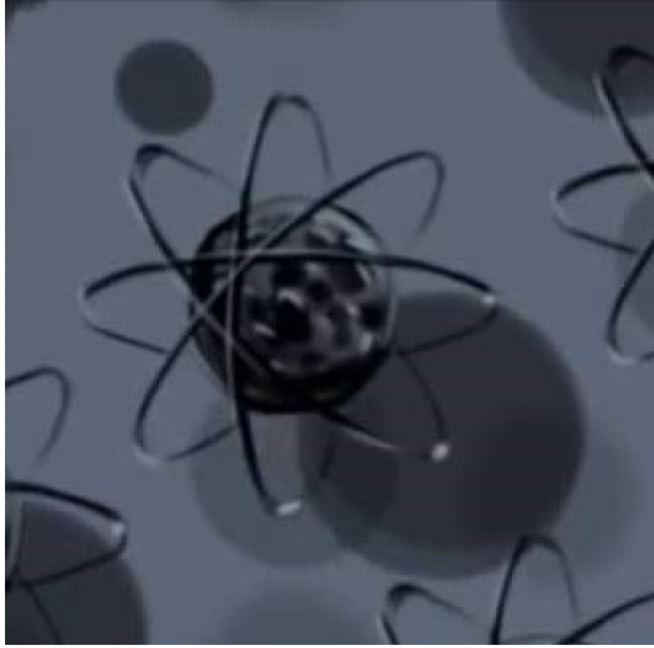
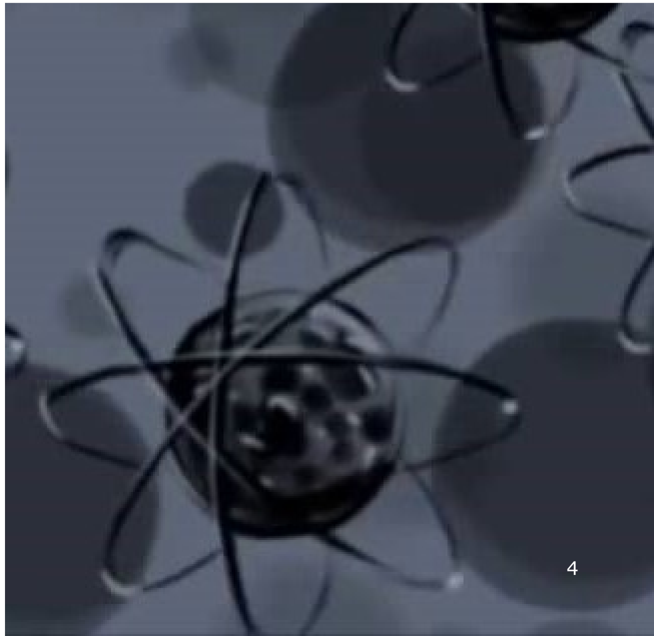
Report highlights

- This study compared the sustainability of three in situ and ex situ remediation methods for PFAS contaminated groundwater, using carbon footprint assessment, life cycle cost assessment and sustainability assessment.
- The comparison was based on an actual PFAS contaminated site, where a full-scale, in situ remediation design with PlumeStop was implemented by REGENESIS Ltd. The installation was compared against two theoretical best practice designs for Pump & Treat (P&T).
- Based on the comparison, remediation with PlumeStop had:
  - ✓ 40 - 70 times smaller carbon footprint
  - ✓ 60 to 65 % smaller life cycle cost
  - ✓ 95 % smaller raw material, energy and waste footprint
  - ✓ 100 % higher Sustainability Score
- The difference in carbon footprint, material efficiency and life cycle costs in the benefit of using PlumeStop is so large, that it precludes any significant change to the result with any adjustments to the assumptions and uncertainties.
- PlumeStop also has significant technology potential for negating climate emissions through long term carbon sequestration.

REGENESIS®



PLUME STOP™
Liquid Activated Carbon



Background and case description

Background

Aim of this study was to compare the carbon footprint of three in situ and ex situ remediation methods for PFAS contaminated groundwater.

The comparison was based on an actual remediation site, where full-scale REGENESIS Ltd. design with PlumeStop was implemented.

The actual installation was compared against theoretical best practice designs for pump & treat where the groundwater was filtered by granular activated carbon (GAC), and with an added separation stage with Foam Fractionation (FF).

The study did not focus on the remediation options appraisal or technical efficiency of the selected methods, and therefore all designs were created at a general level, to produce key information for carbon footprint. This means that ie. valves, fittings, electric cabling, etc. were excluded from designs.

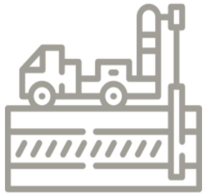
The study was commissioned by REGENESIS Ltd. and supported by REGENESIS team: Gareth Leonard, Kris Maerten, Paola Goria, Jim Forde and Kristen Thoreson

Case description

- Located in UK, an international airport
- Fire training ground area
- PFOS issue identified in 2019
- Voluntary remediation, protection of off-site SSSI ‘Site of Special Interest’
- Geology is man-made fill, alluvium and river terrace deposits onto London clay
- Groundwater level at approximately 2 m bgl.
- Groundwater contaminated from known sources
  - ✓ Total sum of 24 PFAS is 215 µg/l
  - ✓ Average DOC 15 mg/l
  - ✓ Target values for PFOA and PFOS are 0,1 µg/l
- The mean groundwater flow (Darcy flux) is 48 m/a.

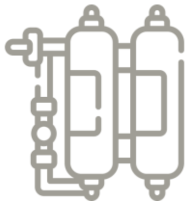
Compared remediation methods

Overview



Immobilization with CAC injection

- Remediation method based on in situ sorption and retention of contaminants.
- Immobilization is achieved by adding Colloidal Activated Carbon (CAC) to the soil/groundwater matrix, to reduce contaminant mobility.
- PlumeStop by REGENESIS Ltd. was used as the CAC remediation product.
- This approach was physically used at the site for remediation of the PFAS contamination.



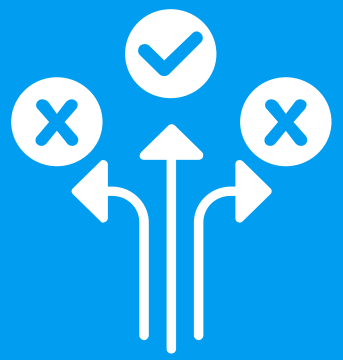
Pump & Treat with GAC filtration

- Remediation method based on extraction of contaminated water and ex situ treatment of a filter media.
- Filtration is based on adsorption to Granular Activated Carbon (GAC).
- Generig bituminous coal based GAC is used for the assessment, as majority of systems are based on it.
- Spent GAC are disposed off-site for landfilling.
- The P&T solutions are Best Available Technology (BAT) alternatives, based on theoretical design.

Pump & Treat with FF treatment

- Remediation method based on extraction of contaminated water and ex situ treatment through a series of separation and filtration.
- Separation is based on Foam Fractionation (FF).
- Filtration is based on adsorption to Granular Activated Carbon (GAC).
- Generic bituminous coal based GAC is used for the assessment.
- Separated PFAS foam and spent GAC are disposed off-site for thermal destruction or landfilling.

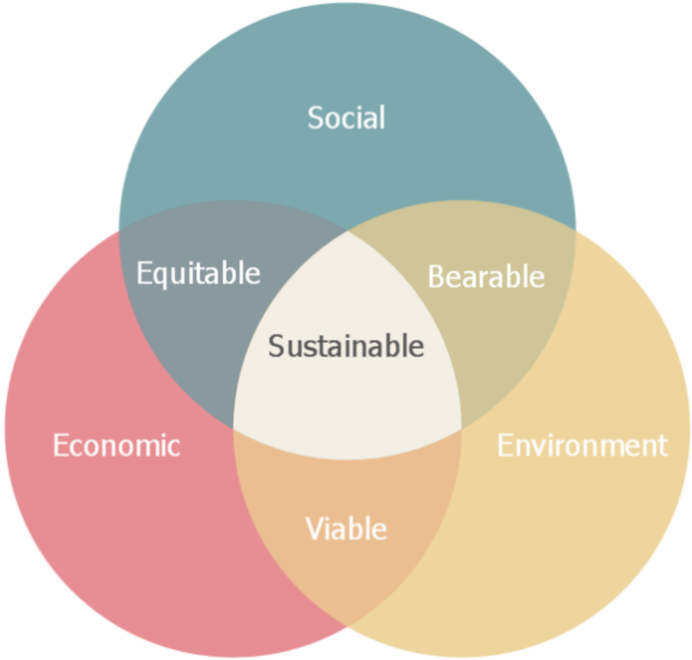
Carbon footprint assessment



Sustainable remediation

Measuring sustainability

- Sustainable remediation moves the focus from pure risk management to also optimising the environmental, social and economic value of the work.
- Minimization of negative effects is not enough; sustainable remediation must also encourage positive steps towards greater community and ecological sustainability, towards a future that is more viable, pleasant and secure.
- What constitutes as sustainable remediation, needs to be determined on a case-by-case basis.
- Determination must be systematic, process based and well documented, to provide explicit justification for any trade-offs and for burden of argument.



- Various tools can be used for determining sustainability of remediation and to present the information in a way that can assist the decision-making process.
- Most frequently used tools are:
  - ✓ Environmental Risk Analysis (ERA)
  - ✓ Life Cycle Assessment (LCA)
  - ✓ Life Cycle Costing (LCC)
  - ✓ Cost-Benefit Analysis (CBA)
  - ✓ Multi-Criteria Analysis (MCA)
  - ✓ Biodiversity matrix (BDM)
- Multiple tools can be used in connection to provide a more holistic perspective on sustainability.

References:
1. Interstate Technology & Regulatory Council (2021) Sustainable Resilient Remediation
2. ISO 18504 (2017) Sustainable remediation
3. ASTM E2893-16e1 (2013) Standard Guide for Greener Cleanups
4. Interstate Technology & Regulatory Council (2012) Green and Sustainable Remediation: A Practical Framework
5. CL:AIRE (2010) A Framework for Assessing the Sustainability of Soil and Groundwater Remediation

Assessment methodology

Carbon footprint

- The methods applied in this assessment were based on the international standards for life cycle- and carbon footprint assessment.
- The assessment was carried out in the following four stages:
  - Goal and Scope
  - Life Cycle Inventory
  - Life Cycle Impact Assessment
  - Interpretation
- The assessment also focused on other relevant sustainability factors, including general level:
  - Carbon handprint
  - Life cycle cost assessment
  - Sustainability assessment
- In addition to the carbon footprint assessment, the project included a full product level LCA on the REGENESIS Ltd. PlumeStop product. The product LCA is reported separately.

What is a carbon footprint?

Carbon footprint, also known as a greenhouse gas (GHG) emissions assessment, evaluates the total greenhouse gas (GHG) emissions caused by the ‘scope of assessment’, and is expressed as carbon dioxide equivalent (CO_2e) emissions.

Is it same as LCA?

Carbon footprint analysis is a subset of life cycle assessment (LCA). The difference between an LCA and a carbon footprint relates to the impact categories studied. Carbon footprint is focused on one environmental impact category: greenhouse gas emissions (CO_2), but an LCA can take more impact categories into account, ie. land use, water use and ocean acidification.

Goal definition

- The goal of this carbon footprint assessment was to compare the potential global warming impacts of three alternative in situ and ex situ remediation methods for PFAS contaminated groundwater on a case study basis, based on best available technologies (BAT).
- The aim of the assessment was to provide REGENESIS Ltd. and their customers with reliable and comparable information on the environmental impact of REGENESIS' products in PFAS remediation.
- The main results of the assessment are presented in this report. Results also include a (Excel) spreadsheet with detailed results of the assessment and an LCA model prepared in the (GaBi) LCA software.
- The results of the assessment are intended for external business-to-business communication and to be used internally for development purposes.

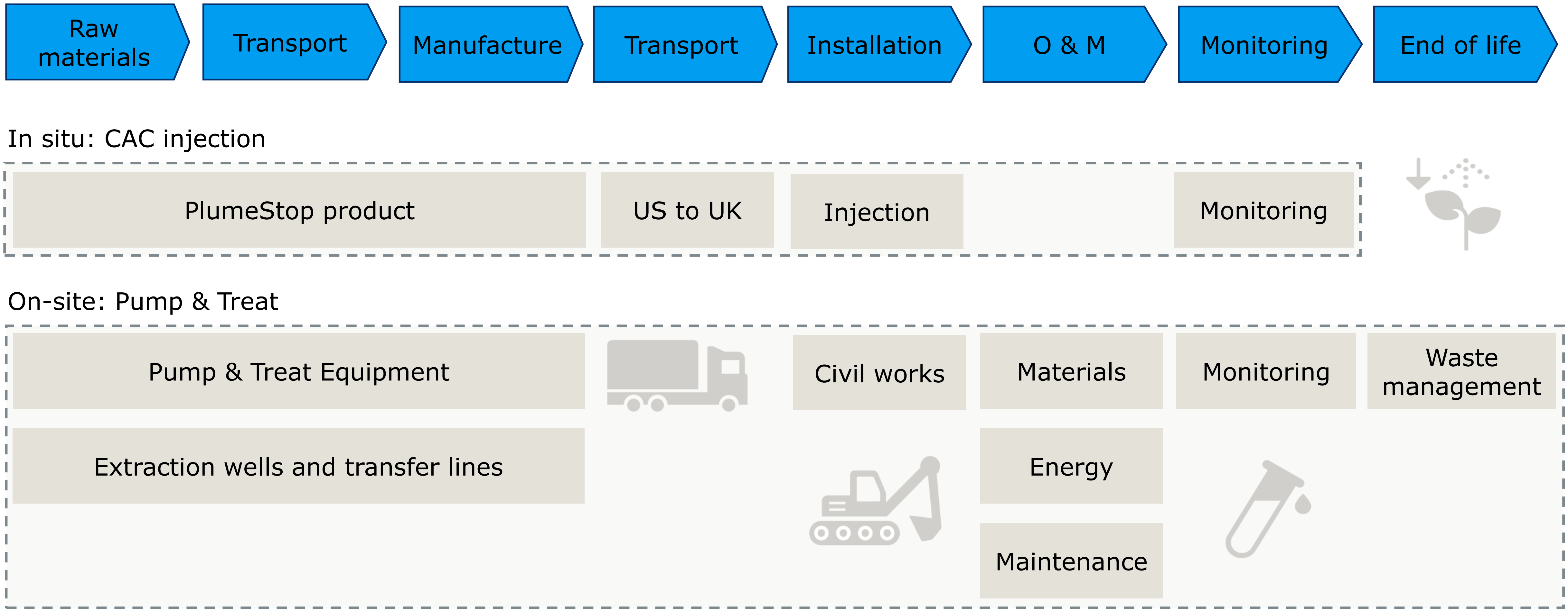
Scope of the assessment

Overview

- The assessment includes the comparison of three alternative remediation methods, namely:
  - ✓ Alt. 1: PlumeStop by REGENESIS Ltd,
  - ✓ Alt. 2: generic pump & treat system with GAC filtration, and
  - ✓ Alt. 3: generic pump & treat system with (FF) Foam Fractioning.
- The site was located in United Kingdom. Localized approach and data for production and use was applied.
- The assessment was concluded using a cradle-to-grave approach for all three alternatives.
- The reference timeframe used for the assessment was 15 year. It was assumed that most of the remedial benefits would be achieved within this timeframe.
- The assessment focused on project level carbon footprint assessment and the functional unit used was the carbon footprint (t CO2e) generated during the whole assessed project life cycle.
- The system boundaries for the assessment were set according to ISO 14040:2006: Life Cycle Assessment, ISO 14044:2006 Life cycle assessment requirements and guidelines, ISO 14067:2018 Quantifying carbon footprint, and for the PlumeStop EN 15804 Environmental product declarations and PCR for Basic Chemicals (version 1.1 dated 2022-01-14).
- The life cycle data used in this assessment was primarily based on the LCA software GaBi 10 Professional and the life cycle inventory datasets provided by Sphera and Ecoinvent 3.8. For some inputs flows not available on the databases, information on the environmental impact of raw materials was obtained from scientific literature or from an EPD.

Scope of the assessment

System boundary

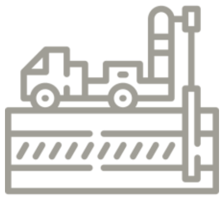


Life cycle inventory analysis

- The life cycle inventory analysis was conducted based on the set system boundary, and included the compilation and quantification of the environmental inputs and outputs involved in the temporal and spatial life cycle of the alternatives.
- The main quantified inputs and outputs for the carbon footprint were:
  - ✓ Raw materials use
  - ✓ Energy use
  - ✓ Waste production
  - ✓ Atmospheric emissions
- The data collection was done in collaboration between REGENESIS and Ramboll, and internal validation by discipline professionals was used where applicable.
- The P&T designs were done by Ramboll in discussion with REGENESIS. The in situ design was provided by REGENESIS.
- The LCIA for the immobilization alternative was based on independent LCIA and LCA conducted at product level for the REGENESIS PlumeStop product. The key variable modified was the allocation of average transport distance to actual distance.

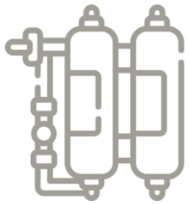
Life cycle inventory analysis

Key system variables between alternatives



Immobilization with CAC injection

- Single injection round
- Expected efficiency 15 years
- 102 injection points
- 33.600 kg CAC (PlumeStop)
- 1.600 l fuel use, injection
- 3 pcs. monitoring wells, depth 10 m.
- 2 times/a, environmental monitoring



Pump & Treat with GAC filtration

- Fixed equipment installation
- Continuous operation 15 years
- 8 pcs. extraction wells, depth 8 m.
- 3 pcs. monitoring wells, depth 10 m.
- 2.300 l fuel use for installation
- Remediation equipment (see later)
- Operational uptime 95 %
- 100 l/min groundwater pumping rate
- 24.000 kg/a GAC usage rate
- 64 000 kWh/a electricity consumption
- 4 times/a, O&M inspection from Bristol
- 2 times/a, monitoring from Runcorn

Pump & Treat with FF treatment

- Fixed equipment installation
- Continuous operation 15 years
- 8 pcs. extraction wells, depth 8 m.
- 3 pcs. monitoring wells, depth 10 m.
- 2.300 l fuel use for installation
- Remediation equipment (see later)
- Operational uptime 95 %
- 100 l/min groundwater pumping rate
- 8.500 kg/a GAC usage rate
- 128 000 kWh/a electricity consumption
- 4 times/a, O&M inspection from Bristol
- 2 times/a, monitoring from Runcorn

Life cycle inventory analysis

GAC design: Assumptions

- Granular activated carbon (GAC) is an established filtration media, proven to effectively treat aqueous phase PFAS.
- Different GAC types have varying loading capacities and breakthrough times for long- and short-chained PFAS, but both can be removed.
- Generic bituminous coal based GAC is used for the assessment, as majority of GAC filter systems globally are based on it. ITRC also refers that current data shows bituminous-based products being more effective for PFAS removal.
- In the design, the GAC media are placed in packed-bed flow-through vessels that are operated in lead-lag configuration to increase linear velocity and minimize breakthrough.
- In the use case for FF, it was assumed that GAC would be used as a polishing step and for risk management in the process.
- Spent GAC can be thermally reactivated, but it is not a common practice for PFAS and hence in this assessment it was assumed that all used GAC is of virgin nature and disposed after use off-site for landfilling.
- The mass of disposed GAC was assumed the same as of the original virgin GAC used, though it changes during operation due to wetting.

Life cycle inventory analysis

GAC use rate: Parameters and uncertainties

- Availability of long term references on PFAS filtration are limited. According to literature and existing case studies:
  - ✓ PFAS removal efficiencies of > 99% have been generally observed
  - ✓ GAC adsorption capacity for PFAS varies from 10 to 1 000 mg/kg
  - ✓ In addition to adsorption capacity, various other aspects impact GAC use rate, such as water source, PFAS speciation, TOC/DOC concentrations, co-contaminants, contact time, flow rates, GAC source, discharge targets, etc.
  - ✓ Typical filter (EBCT) contact time varies from 10 to 30 minutes
  - ✓ Breakthrough occurs typically after 100 to 20 000 Bed Volumes treated

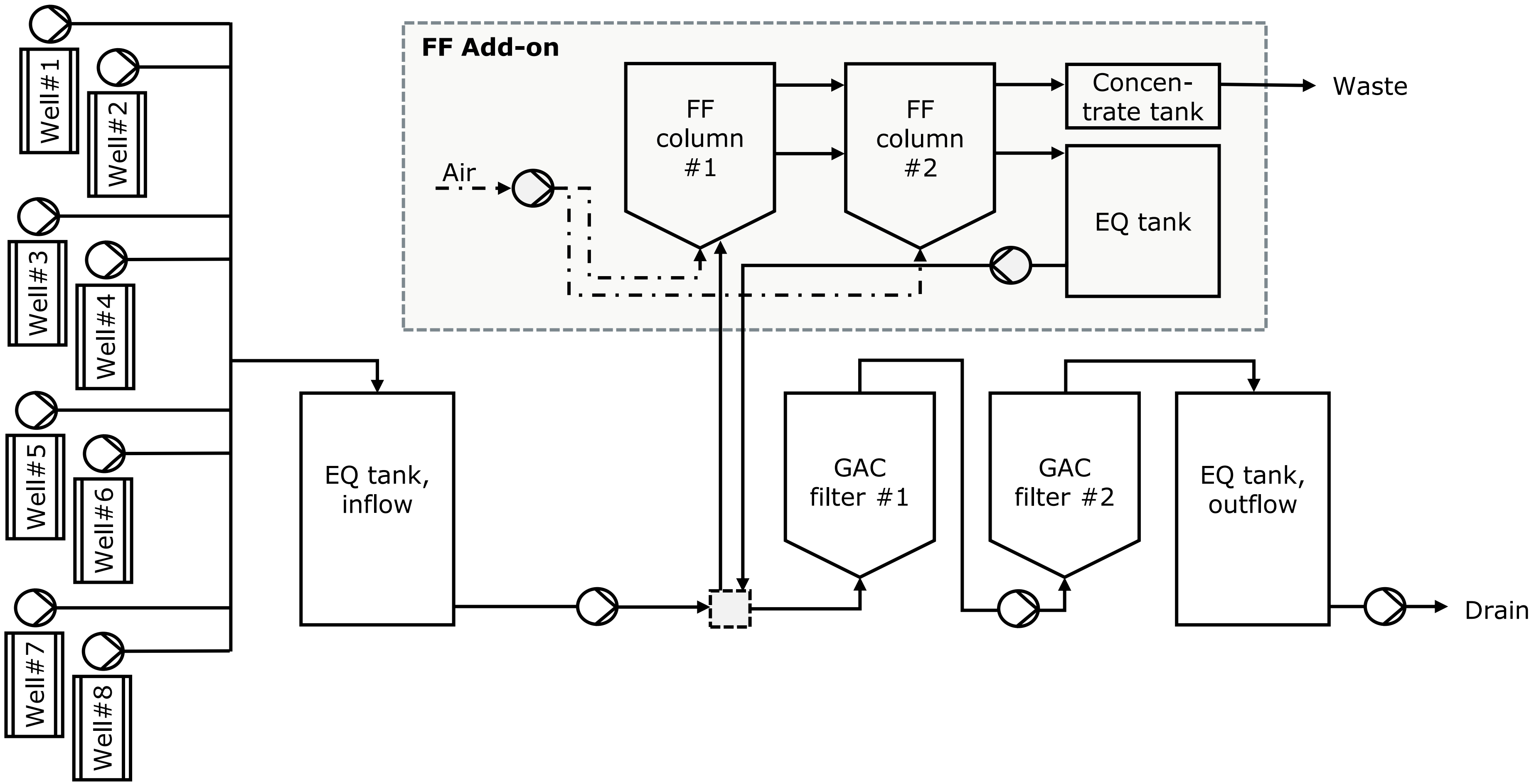
- Due to the high variation in available data, averaged and case-based assumptions were used to model the GAC use rate for the P&T remediation, as presented in table 1.

Table 1. Average values used for GAC dimensioning for P&T remediation.

Parameter	Value	Unit
Flow rate	100	l/min
Influent PFAS (sum)	50	ug/l
Influent DOC	15	mg/l
EBCT	30	min
Breakthrough	1 000	BV
Filter changeout	90	days
Adorption capacity	100	mg/kg
GAC use rate	**24 000**	**kg/a**

Life cycle inventory analysis

Pump & Treat, simple PI diagram



Life cycle inventory analysis

Equipment and fixed installations, bill of quantities

Item	pcs./m.	Kg/kWh	Specification
EXTRACTION			
In well pump	8 pcs.	16.000 kWh	Ie. Grundfos TWI4.01; Power at 1 m3/h @ 2,5 bar ~ 0,25 kW; 8 x pumps operating 8000 h/a
Extraction well	64 m	140,8 kg	PE DN110/PN8, weight 2,2 kg/m; 8 wells, avg. depth 8 m
Transfer line	320 m	25,6 kg	PE DN18/PN16, weight 0,08 kg/m; 8 lines, avg. distance 40 m/well from remediation plant
PUMP & TREAT			
Container	1 pcs	20 ft	Intermodal shipping container
In line pump	3 pcs	48.000 kWh	Ie. WILO Helix EXCEL 606-2; Power at 8 m3/h @ 5 bar ~ 2 kW; 3 x pumps operating at 8000 h/a
EQ tank	2 pcs	120 kg	HDPE container, 2 m3 size, mass 60 kg
GAC filter	2 pcs	1.500 kg	Stainless steel, 3 m3, weight 750 kg/pcs
System piping	30 m	18 kg	PVC pressure pipe, DN32/PN18, weight 0,6 kg/m; length 30 m
FF ADD-ON			
FF filter	2 pcs	750 kg	Stainless steel, 1,5 m3, weight 375 kg/pcs
EQ tank	1 pcs	60 kg	HDPE, 2 m3 size, weight 60 kg
Concentrate tank	1 pcs	30 kg	HDPE, 1 m3 size, weight 30 kg
In line pump	1 pcs	16.000 kWh	Ie. WILO Helix EXCEL 606-2; Power at 8 m3/h @ 5 bar ~ 2 kW; 1 x pumps operating at 8000 h/a
Air compressor	1 pcs	48.000 kWh	Ie. Atlas Copco, LF range; Power at 10 l/s @ 5 bar ~ 6 kW; 1 x compressor at 8000 h/a
System piping	15 m	9 kg	PVC pressure pipe, DN32/PN18, mass 0,6 kg/m; length 15 m
MONITORING WELL			
Monitoring well	30 m	14,4 kg	PE DN63/PN6, weight 0,48 kg/m; 3 wells, avg. depth 10 m

Assumptions and limitations

Limitations	Impact
Modelled P&T equipment system was limited in complexity (ie. no valves, fittings, sensors, cabling, etc. were included in PID)	Low
Generic LCIA data was used for a some P&T equipment (ie. one waterpump with available EPD was extrapolated to all pumps)	Low
Laboratory analyses were left out, due to lack of available LCA data. Total sample amount is anyhow very high (up to 1000+)	Medium
There is high variability in available GAC design parametres for PFAS, that can affect GAC usage rate estimates.	High
There is high variability in FF design factors, such as GAC need for polishing.	High
Landfilling for spent GAC was assumed, as thermal reactivation is not widely available and incineration is not required in UK.	Medium
There is no long term data for the CAC dimensioning for PFAS, which can affect product use estimates.	High
Multiple data sources were used in the modelling, such as Sphera, Ecoinvent and peer-reviewed articles	Low
Site O&M inspections and environmental monitoring were assumed as independent visits from fixed distance	Low
Average use life of P&T machinery was estimated at 10 years (in well pumps 5 years), fixed equipment 15+ years.	Low
All extracted groundwater was expected to be discharged in drain to be further managed in a municipal WWTP	High
Amount (mass) of spent GAC is assumed equal to virgin GAC, as the amount (mass) of adsorbed contaminants is low	Low

What is Global Warming Potential (GWP)?

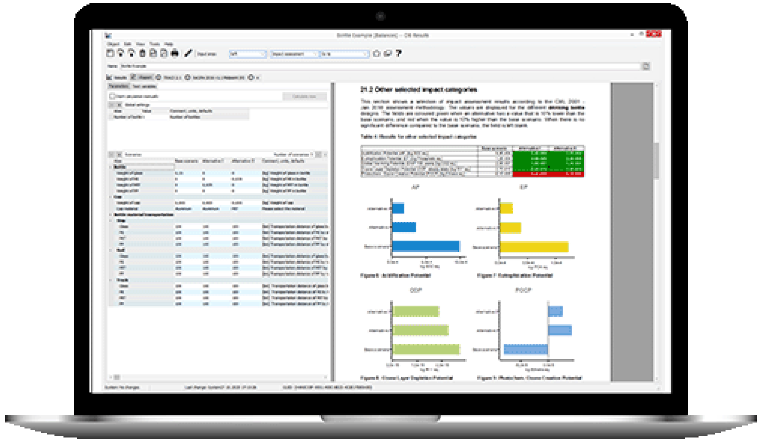
The GWP is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time (usually 100 years), relative to the emissions of 1 ton of carbon dioxide (CO_2). GWPs provide a common unit of measure, which allows to add up emissions estimates of different gases, like CO_2, CH_4, N_2O, CFC's, that have different warming potential.

Examples of GWP factors

- Carbon dioxide (CO_2) = 1
- Methane (CH_4) = 25
- Nitrous oxide (N_2O) = 298

Life Cycle Impact Assessment

- The life cycle impact assessment was conducted based on the inventory analysis, to assess the total carbon footprint (CO_2e) defined as global warming potential (GWP) for the life cycle assessment impact categorization.
- The carbon footprint assessment was conducted on the LCA software GaBi 10 Professional.
- Detailed LCA models are presented as annex.



Data sources and references

Life cycle assessment

Ecoinvent database version 3.8

GaBi Professional database version 10.0.1.92.

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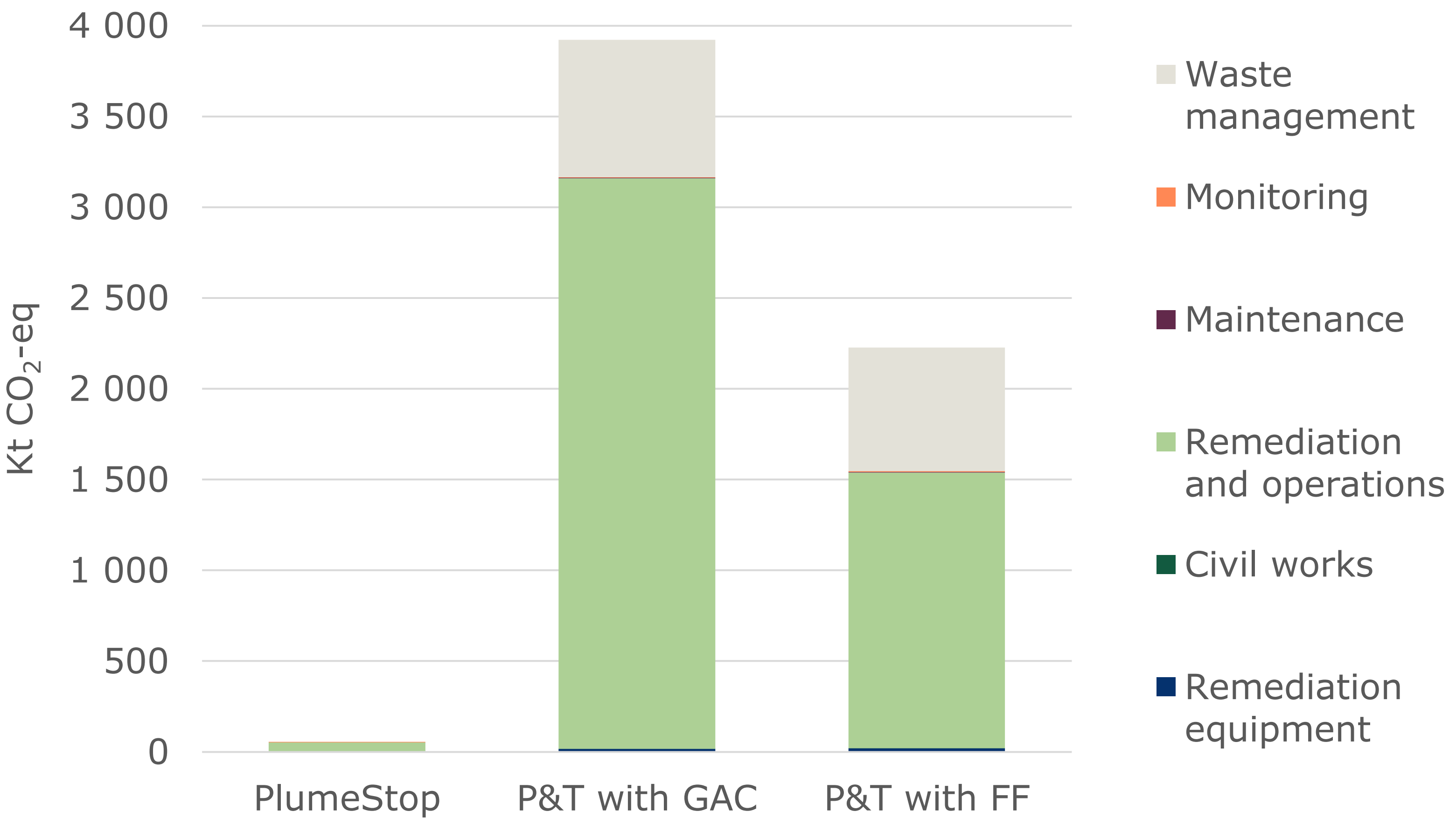
Svensk Vatten, C. Baresel, L. Karlsson, A. Malovanyy, G. Thorsén, M. G. Feldtmann, H. Holmquist, S. Dalahmeh, L. Ahrens, K.W. Pütz (2022) PFAS - hur kan svenska avloppsreningsverk möta utmaningen? Kunskapssammanställning och vägledning för VA-aktörer kring PFAS

IVL Svenska Miljöinstitutet, A. Malovanyy, F. Hedman, M. G. Feldtmann, M. Harding, J. Yang, IVL Svenska Miljöinstitutet (2021) Rening av PFAS-förorenat vatten från avfallsanläggningar

Carbon Footprint Results

Calculated project carbon footprint

Metric tonnes (kt) CO_2-eq. / 15 years operation



Footprint categories

Remediation equipment includes the P&T equipment used on site.

Civil works includes the *fixed installations* such as extraction- and monitoring wells, pump lines, utilities; and *machinery* required for drilling, injection or excavation.

Remediation and operations includes any consumables, such as the PlumeStop or GAC, and electricity.

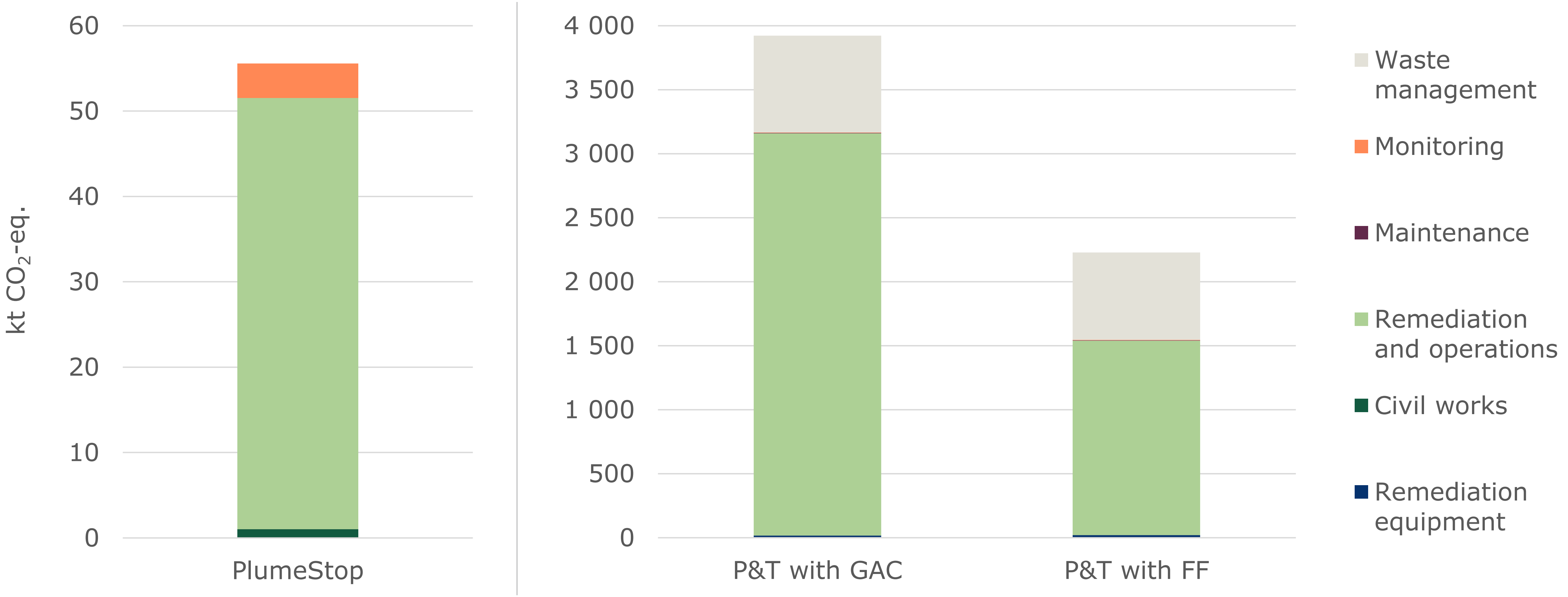
Maintenance includes travel for O&M inspections.

Monitoring includes travel for monitoring inspections.

Waste mangement includes off-site treatment of *hazardous waste*, including spent GAC, PFAS foam and *wastewater treatment* for the P&T effluent.

Calculated project carbon footprint

Metric tonnes (kt) CO_2-eq. / 15 years operation



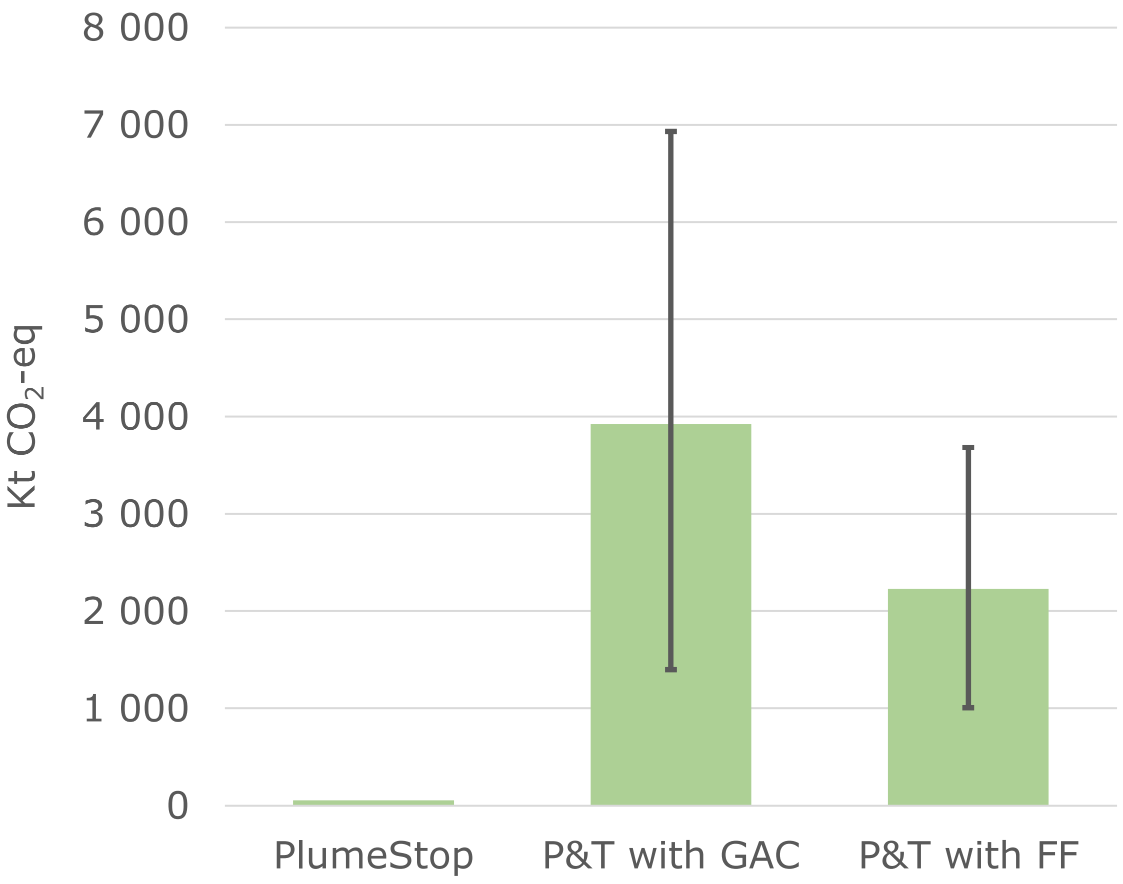
Calculated project carbon footprint

Metric tonnes (kt) CO_2-eq. / 15 years operation

	PlumeStop	P&T w/ GAC	P&T w/ FF
Remediation equipment		15,2	19,0
Civil works			
Fixed installations	0,05	0,9	0,9
Machinery	1,0	1,3	1,3
Remediation and operations			
PlumeStop / GAC	50,5	2 860	954
Electricity		281	563
Maintenance		3,6	3,6
Monitoring	4,0	4,0	4,0
Waste management			
Hazardous waste		112	37,7
Wastewater treatment		644	644
Total carbon footprint	**56**	**3 922**	**2 228**

Sensitivity analysis

Metric tonnes (kt) CO_2-eq. / 15 years operation



Key drivers for variance

Key drivers for variance in the carbon footprint assessment originate from 'Remediation and operation', and 'Waste management'. In terms of sensitivity, the accurate estimation of the GAC usage rate is the key driver for variance, whereas other category impacts are more binary by nature.

Determining the most accurate GAC usage rate without field-scale tests and only based on theoretical assumptions will always be inaccurate. The assumptions made for GAC use in this life cycle inventory analysis are as 'precise' as can be expect with the many variables impacting. Most referenced studies point to very low GAC usage rates (<10 mg/kg), though these often, but not always, correspond with also having changeout triggers for shorter chain PFAS species. The largest reported GAC usage rate found was 400 mg/kg.

To assess the impact on variance from various GAC usage rates, a sensitivity analysis with 50 and 500 mg/kg as the bookends values was conducted to illustrate its impact on the carbon footprint assessment (shown in the mix/max bars in the graph).

Carbon handprint assessment

Carbon handprint assessment

- There is no global standard on carbon handprint assessment. The applied carbon handprint assessment was based on the Carbon Handprint Guide by VTT Technical Research Centre of Finland (Pajula, T. et al. 2018).
- The aim of the carbon handprint assessment was to compare the potential CO_2 equivalent emissions savings in the assessed remediation method comparison for the PFAS groundwater remediation.
- Based on the LCA study, in situ immobilization with CAC and P&T with FF treatment were compared against baseline method P&T with GAC filtration.
- The carbon handprint for in situ immobilization with CAC was assessed as:
  - ✓ 3 867 t CO_2 eq. in comparison to pump & treat with GAC filtration
  - ✓ 2 172 t CO_2 eq. in comparison to pump & treat with FF treatment
- The carbon handprint for ex situ P&T with FF was assessed as:
  - ✓ 1 695 t CO_2 eq. in comparison to pump & treat with GAC filtration
- The handprint assessment should only be used for business-to-business communication, because a critical review of the carbon handprint assessment has not been conducted and the quantification is based on a comparative footprint assessment relative to alternative organization's solutions.

Carbon handprint

Carbon handprint is an indicator of climate change mitigation potential. It is about comparing alternative products, services or activities and their climate impact against a baseline solution (one that is used for the same purposes as the handprint solution within a specific time period and region). Carbon handprint equals the difference between the compared options in their carbon footprints, measured as CO_2 equivalent.

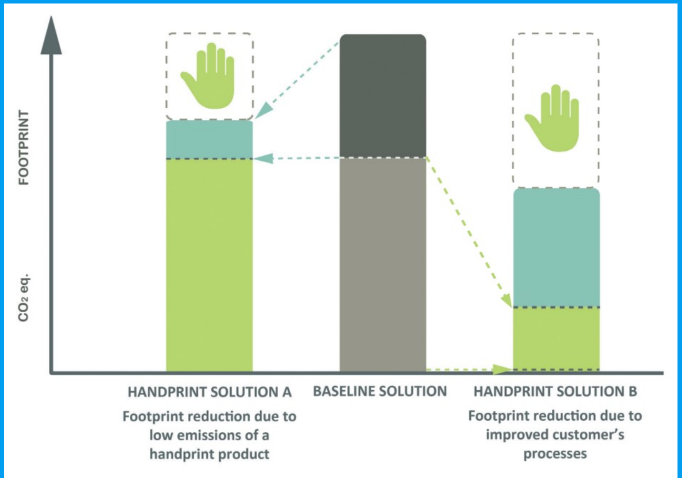


Image: Pajula, T. et. al. 2018

Biogenic carbon

Carbon can either be classified as biogenic or fossil. Biogenic carbon is the carbon that is stored in biological materials, such as plants or soil. Product manufactured from biogenic carbon can often be considered a "negative emission‟, because of the CO_2 sequestered in the material. Also, CO_2 emissions from biogenic sources are not included in GWP according to most LCA methodologies.

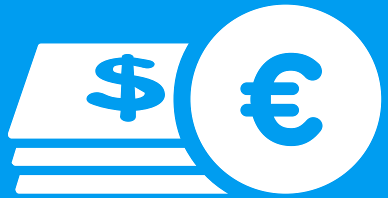
Carbon sequestration

Carbon sequestration is the process of removing CO_2 from the earth's atmosphere in a carbon pool. Carbon sequestration is a naturally occurring process, with two main types: biological and geological. It can also be achieved with technology, for example with carbon capture and storage (CCS).

Biogenic carbon and carbon sequestration

- Activated carbon can be produced not only from bituminous coal, but also from biogenic waste products such as coconut husks, wood residues, willow or peat, that are converted into charcoal before being 'activated'.
- Production of activated carbon from biogenic sources is syncronous with ‘biochar' production, that is seen as one of the prominent solutions for climate change mitigation and in prevention of soils degradation.
- Biochar produced in high pyrolysis temperatures (as activated carbon is) has a high carbon (C-wt%) content > 90 %, it decomposes very slow and remains stable in field conditions for thousands of years. This makes it a good solution for carbon sequestration.
- Depending on the end-of-life scenario, carbon sequestration in a safe long-term storage (ie. In situ or landfill) could be considered a "negative emission". If the carbon is not stored but incinerated, the GWP impact is significant.
- Assuming that the carbon used in the three compared alternatives would originate from biogenic sources and stored in a long term storage, based on pure mass balance approach, the elemental carbon within the products could be considered to sequester up to 3,7 times in CO_2-eq. emissions.
- There are a number of studies on the expected carbon sequestration from biochar, and the estimated reduction potential varies significantly between 1 - 4 t CO_2-eq. per tonne of biochar. The detail review of these studies was left out of this project.

Life Cycle Cost Assessment



Life cycle cost assessment

- Life Cycle Cost Assessment (LCCA) was used to compare the three remediation alternatives based on the Total Cost of Ownership (TCO) in Net Present Value (NPV).
- NPV is a financial metric that seeks to capture the present day value of a future stream of payments or investments, by applying a discount rate equal to the minimum acceptable rate of return.
- The aim of the LCCA assessment was to complement the LCA assessment.
- The costs of ownership included:
  - ✓ Initial CAPEX, that included the remediation & equipment, and civil works.
  - ✓ Future OPEX, that included any material inputs, O&M, monitoring and waste.
  - ✓ No Residual Value was allocated for any of the compared alternatives, though some P&T equipment might have value in secondary use.
- Study period for the assessment was similar to the GHG assessment 15 years.
- The calculation was based on Constant-Currency assumption, and a (real) Discount Rate of 3 %, reflecting only a nominal Return-On-Investment (ROI).
- The results were assessed based on analogous breakdown as in LCA, and on a more traditional CAPEX/OPEX and annual accumulation method.
- Detailed assumptions for the assessment are presented in the annexed spreadsheets.

Life Cycle Cost Assessment (LCCA)

LCCA is an economic method for assessing the total life cycle cost of ownership, taking into account all costs of acquiring, building, owning, and disposing of an object, process or project.

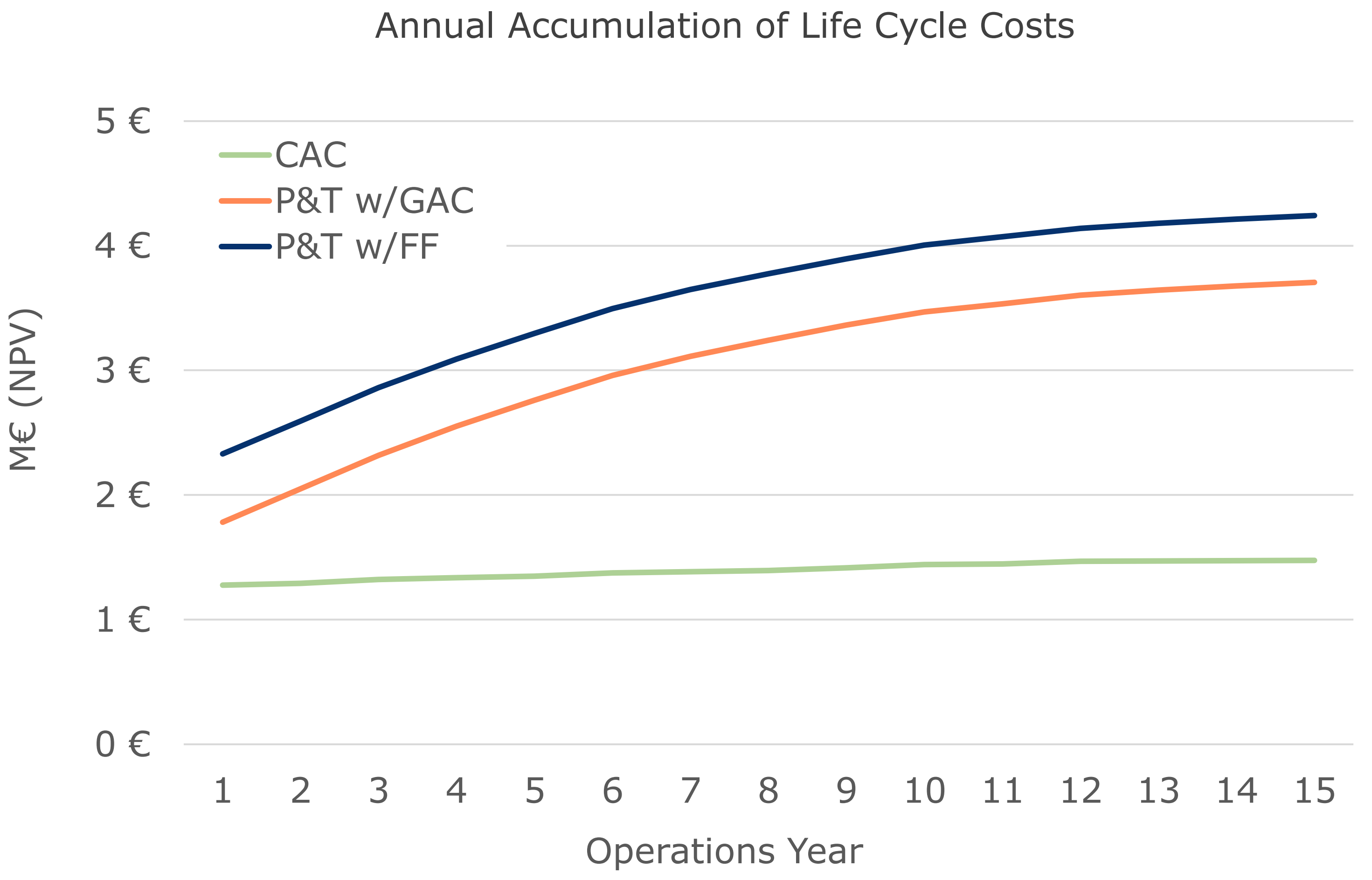
The main variables of LCCA assessment are the costs of ownership, the period of time over which costs are incurred, and the discount rate that is applied to future costs.

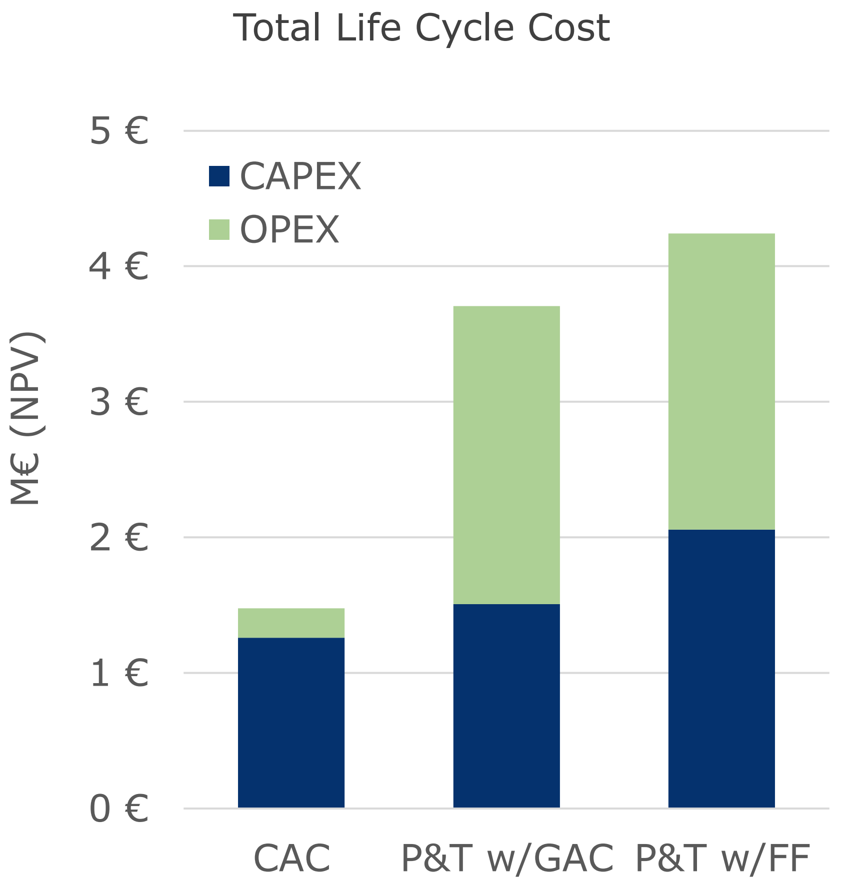
LCAA is useful in comparing alternatives that fulfil the same performance requirements, but differ with respect to initial costs and operating costs.

Fundamentally, LCAA can help to determine the most cost-effective alternative.

Total life cycle costs and accumulation

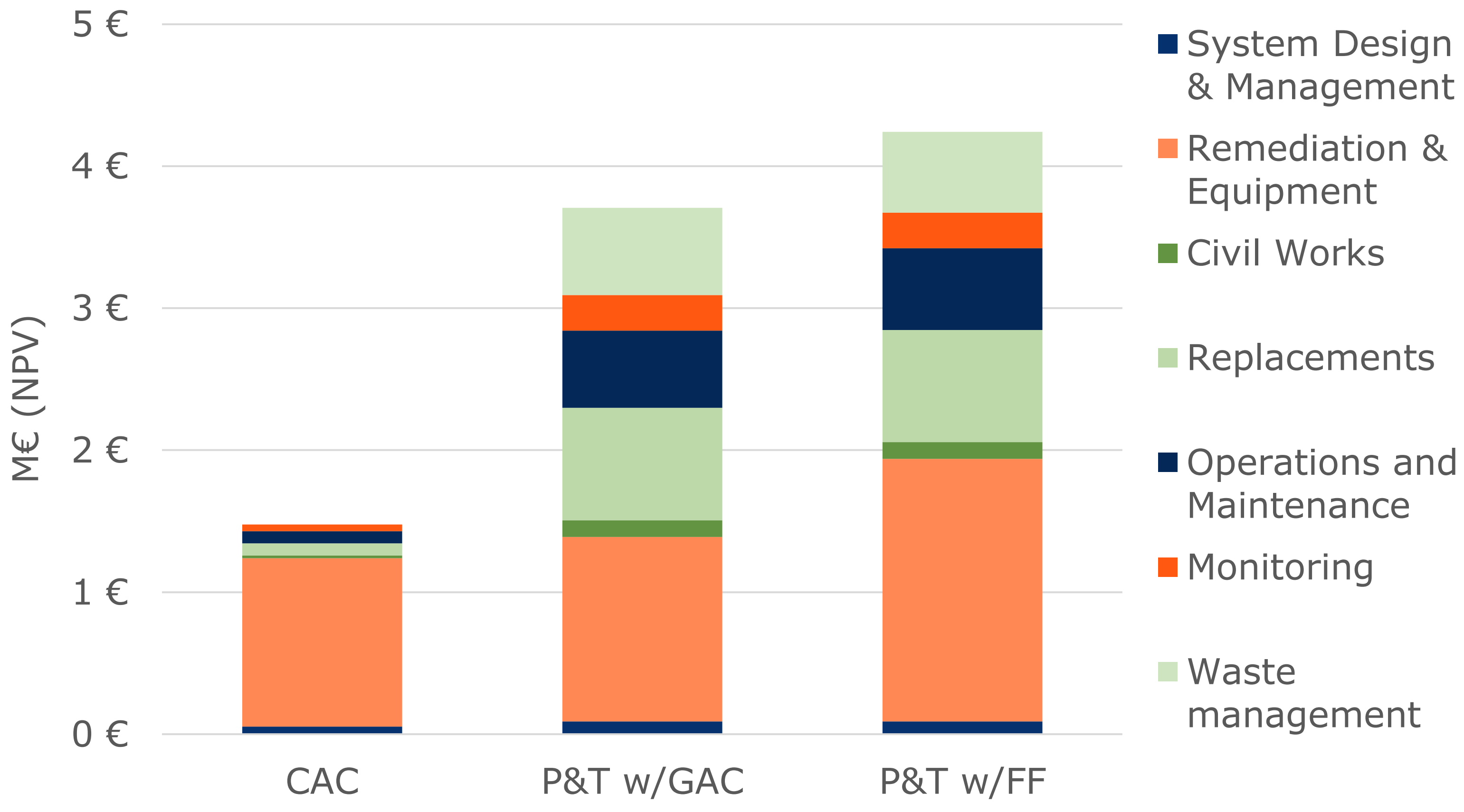
Discounted Net Present Value, EUR / 15 years operation





Project life cycle costs breakdown

Net Present Value, EUR / 15 years operation



Life Cycle Cost Categories

System Design and Management includes the design and related management during commissioning.

Remediation & Equipment includes the CAC material and application, or the P&T equipment.

Civil Works includes any site infrastructure, wells, pumping & transfer lines and installation works.

Replacements includes the any equipment renewals, GAC used and electricity.

Operation and Maintenance includes general works, O&M inspections and GAC changes

Monitoring includes sampling and analysis.

Waste Management includes all solid and wastewater treament.

Project life cycle costs breakdown

Net Present Value, EUR / 15 years operation

Category / Alternative	CAC	P&T w/GAC	P&T w/FF
System Design & Management	54 000 €	89 000 €	89 000 €
Remediation & Equipment	1 185 000 €	1 300 000 €	1 850 000 €
Civil Works	20 000 €	117 500 €	117 500 €
Replacements	84 000 €	792 266 €	790 093 €
Operations and Maintenance	86 939 €	543 371 €	575 973 €
Monitoring	45 990 €	250 740 €	250 740 €
Waste management	- €	612 922 €	568 004 €
Residual Value	- €	- €	- €
Discount Rate	3 %	3 %	3 %
Unit Cost, €/m^2 treated	2,0 €	4,9 €	5,7 €
Net Present Value	**1 475 929 €**	**3 705 799 €**	**4 241 310 €**
Undiscounted value (*	**1 584 500 €**	**5 717 150 €**	**6 231 800 €**

*) The key difference between Net Present Value (discounted value) and undiscounted value is that the discounted value is adjusted to incorporate the time value of money whereas undiscounted total value is not adjusted to incorporate the time value of money.

Sustainability Assessment

Sustainability Assessment

SURE by Ramboll

- A 'tier 2' sustainability assessment was completed by using SURE by Ramboll (SURE).
- SURE is an on-line tool for sustainable remediation assessment, communication, and reporting. It is based on standards from ISO and ASTM, and aligned with the Sustainable Remediation Forum (UK) guidance.
- SURE relies on a multi-criteria analysis (MCA) method and is designed to incorporate both qualitative and quantitative information.
- In brief, the sustainability assessment was conducted as follows:
  - ✓ The assessment was conducted by a round-table of three Ramboll remediation professionals and further commented by Regenesis.
  - ✓ The assessment focused on evaluating the three remediation alternatives against 15 selected qualitative and/or quantitative sustainability indicators.
  - ✓ Each indicator was initially assigned a weighting on a scale of 1 to 5, that reflects its relative degree of importance in the assessment (assigned weight = 3).
  - ✓ Each indicator was then numerically scored for each option on a scale of 1 to 5, with 1 reflecting the worst option and 5 the best in respect to sustainability.
  - ✓ In the assessment, quantitative information was used where available from the project brief, LCA or LCCA and values scaled accordingly on a scale of 1 to 5.
- Detailed assumptions for the sustainability assessment are presented in the annexed SURE sustainability assessment report.

Sustainability Assessment

A sustainability assessment evaluates the potential effects of remedial options in terms of the three domains of sustainability: environment, society, and economy.

In sustainability assessment, remedial options are typically compared using a set of sustainability indicators, each of which represents a sustainability effect (positive or negative).

The aim of sustainability assessment is to guide decision-making that moves towards sustainable triple-bottom line approaches, and as such transcends a purely technical/scientific evaluation.

Sustainability assessment

Selected assessment categories and indicators

Environment

- Emissions to Air (category)
  - ✓ *Greenhouse gases (indicator)*
- Groundwater and Surface Water
  - ✓ *Water movement*
- Natural resources and waste
  - ✓ *Energy and fuel use*
  - ✓ *Primary resources and waste*
  - ✓ *Water use and disposal*

Society

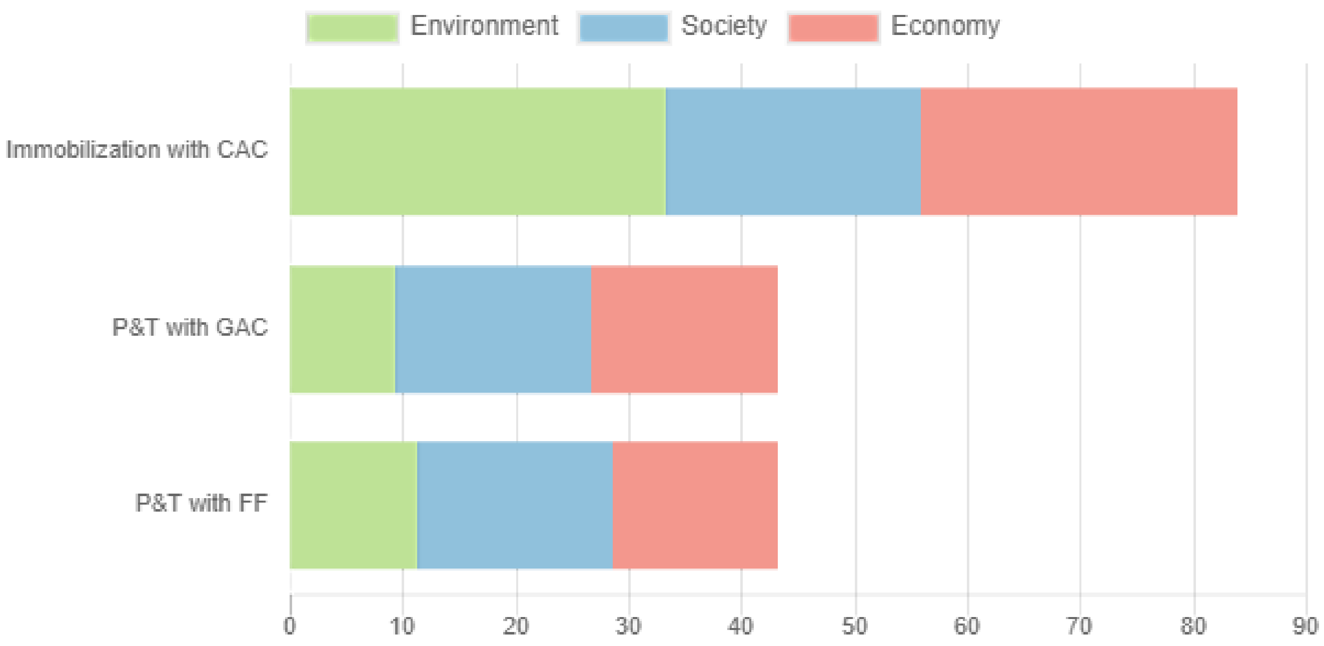
- Human health and safety
  - ✓ *Long-term risk management*
- Ethics and equality
  - ✓ *Upholding 'polluter pays' principle*
- Neighbourhood and locality
  - ✓ *Built environment*
- Communities and involvement
  - ✓ *Quality of communications*
- Uncertainty and evidence
  - ✓ *Degree of uncertainty*

Economy

- Direct economic costs and benefits
  - ✓ *Direct costs and benefits*
- Employment and employment capital
  - ✓ *Job creation*
- Induced economic costs and benefits
  - ✓ *Innovation and new skills*
- Project lifespan and flexibility
  - ✓ *Flexibility to changing circumstances*
  - ✓ *Ongoing institutional controls*

Sustainability assessment

Total Sustainability Assessment Score



Total Sustainability Assessment Score

The following slides and graphs display the Sustainability Assessment Scores for each evaluated option, divided in sustainability domains and indicator categories.

The scores are scaled from 0 to 100, where **a score of 100 reflects an ideal remediation alternative** (i.e., an alternative which has received maximum scores on all assessed indicators).

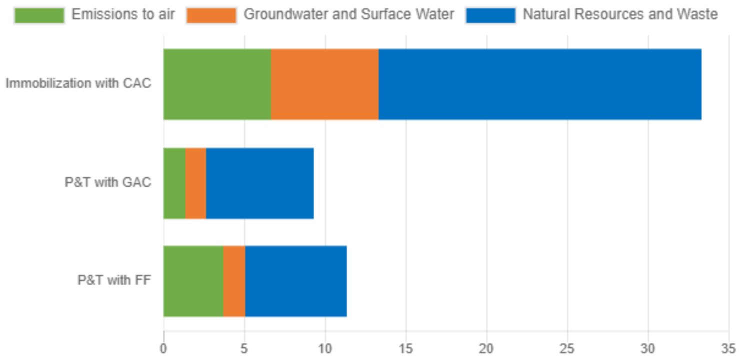
Due to the nature of sustainability assessment methodology, the scores should be considered assessment specific and thus not compared against scores received from other (similar) assessments.

A detailed description of the calculation methodology is described in the annex report.

Sustainability assessment

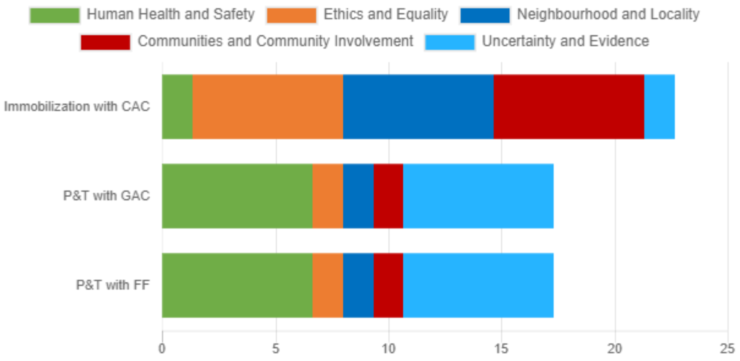
Sustainability Assessment Score, indicator categories

Environment



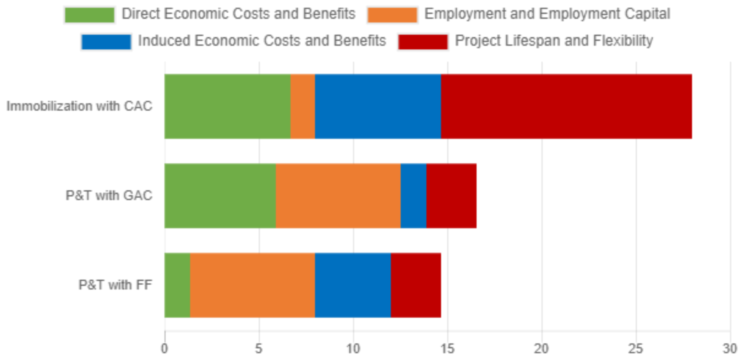
- Immobilization with CAC has clear sustainability benefits due to low greenhouse gas emissions and minimal energy / material footprint.

Society



- Immobilization with CAC has clear sustainability benefits from supporting the ’PP’ –principle, minimizing the impact on the built environment, and supporting simple communications.
- P&T benefits the site by removing some CoC offsite, reduced residual CoC in the subsoil and from low perceived technological uncertainty.

Economy



- Immobilization with CAC has clear sustainability benefits from low TCO and high financial flexibility, increased skills in new technology (sustainable remediation), and minimal supervision/ O&M after implementation.
- P&T with benefits from creating more local jobs due to extensive installation and constant O&M.

Conclusions and key findings

Conclusions

Carbon footprint

- Though the numerical results of the study are case and site specific, a generalised assessment of the potential impacts and their main sources between remedial alternatives can be clearly concluded.
- Immobilization with CAC had 40 - 70 times smaller carbon footprint for PFAS remediation (in CO_2-eq. emissions), compared to the P&T based remediation alternatives.
- Life cycle stages having the largest individual impact on the carbon footprint were
  - ✓ ’Remediation and operation’, with an impact from 70 to 80 %
  - ✓ ’Waste management’, especially wastewater, with an impact from 20 to 30 %
- Most significant life cycle inventory factor affecting the carbon footprint calculation was related to activated carbon use, in all three remediation methods.
- The carbon footprint “break-even” for immobilization with CAC remediation over the P&T based remediation alternatives occurs after 2,5 months of operation.
- The difference in carbon footprint regarding the benefit of using PlumeStop was between 1-2 Orders Of Magnitude, a difference so large that it precludes any significant change to the result with any adjustments to the assumptions and uncertainties.

Conclusions

Total cost of ownership

- The Life Cycle Costs Assessment clearly identified the most cost-effective remediation alternative in terms of Total Cost of Ownership.
- Immobilization with CAC had 60 to 65 % smaller TCO in Net Present Value (*, compared to the P&T based remediation alternatives.
- Differences in the CAPEX for the three remediation alternatives were significant, but the main difference in TCO was due to the 15 year OPEX from continuous O&M, regular replacements, and off-site waste management activities
- Largest differences on the TCO between the remediation alternatives were:
  - ✓ CAPEX, with a difference from 10 to 35 %
  - ✓ GAC replacements and electricity use, with a difference of 90 %
  - ✓ O&M and monitoring, with a difference of 80 to 85 %
  - ✓ Waste management, with a difference of 99+ %
- The financial "break-even" in terms of TCO for immobilization with CAC remediation over the P&T based remediation is immediate.
- In terms of financial flexibility, a complete re-application of CAC can be conducted every 4-5 years, still allowing for a lower TCO, respectively.

*) In terms of undiscounted value, the difference was 70 to 75 %

Conclusions

Sustainability assessment

- The semi-quantitative ‘tier 2’ sustainability assessment aligned with the findings from the LCA and LCAA.
- Immobilization with CAC had 100 % higher Sustainability Assessment Score, compared to the P&T based remediation alternatives.
- Most significant impacts on the Sustainability Asessment Score were:
  - ✓ Immobilization with CAC superseded the P&T based remediation alternatives especially in ’Environmental’ and ’Economic’ sustainability, but also in ’Social’ sustainability.
  - ✓ Immobilization with CAC had clear sustainability benefits due to low greenhouse gas emissions, minimal energy / material footprint, induced economic benefits, low TCO, and high financial flexibility.
  - ✓ P&T with GAC/FF benefits the site by removing the CoC off-site thus resulting in a reduction of residual CoC in the subsoil, and from low perceived technological uncertainty. P&T with GAC/FF also benefits local employment more, due to extensive installation and constant O&M.

Key findings

Summary

- Based on the LCA and LCAA, immobilization with CAC was more ecological and economic than P&T based alternatives, having:
  - ✓ 40 to 70 times smaller carbon footprint (in CO_2-eq. emissions)
  - ✓ 95+ % smaller raw material, energy and waste footprint (in kg, kWh)
  - ✓ 60 to 65 % smaller total life cycle costs (in Net Present Value)
- Based on the SURE by Ramboll semi-quantitative 'tier 2' sustainability assessment, immobilization with CAC had 100 % higher Sustainability Score, compared to the P&T based alternatives.
- In addition, immobilization with CAC has potential for:
  - ✓ significant carbon handprint in comparison to P&T based alternatives
  - ✓ negating climate emissions through long-term biogenic carbon sequestration in soil
- Simple examples for reducing the main negative sustainability impacts with all assessed remediation methods could be:
  - ✓ Using biogenic waste materials for activated carbon production
  - ✓ Reducing off site waste treatment and increasing circularity
  - ✓ Using electricity from renewable sources

Bright ideas. Sustainable change.

RAMBOLL