Groundwater
Monitoring&Remediation

Optimizing the Environmental Performance of In Situ Thermal Remediation Technologies Using Life Cycle Assessment

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Abstract

In situ thermal remediation technologies provide efficient and reliable cleanup of contaminated soil and groundwater, but at a high cost of environmental impacts and resource depletion due to the large amounts of energy and materials consumed. This study provides a detailed investigation of four in situ thermal remediation technologies (steam enhanced extraction, thermal conduction heating, electrical resistance heating, and radio frequency heating) in order to (1) compare the life-cycle environmental impacts and resource consumption associated with each thermal technology, and (2) identify options to reduce these adverse effects. The study identifies a number of options for environmental optimization of in situ thermal remediation. In general, environmental optimization can be achieved by increasing the percentage of heating supplied in off peak electricity demand periods as this reduces the pressure on coal-based electricity and thereby reduces the environmental impacts due to electricity production by up to 10%. Furthermore, reducing the amount of concrete in the vapor cap by using a concrete sandwich construction can potentially reduce the environmental impacts due to the vapor cap by up to 75%. Moreover, a number of technology-specific improvements were identified, for instance by the substitution of stainless steel types in wells, heaters, and liners used in thermal conduction heating, thus reducing the nickel consumption by 45%. The combined effect of introducing all the suggested improvements is a 10 to 21% decrease in environmental impacts and an 8 to 20% decrease in resource depletion depending on the thermal remediation technology considered. The energy consumption was found to be the main contributor to most types of environmental impacts; this will, however, depend on the electricity production mix in the studied region. The combined improvement potential is therefore to a large extent controlled by the reduction/improvement of energy consumption.

Introduction

In situ thermal remediation technologies enhance the volatility of subsurface contaminants by increasing the temperature in the subsurface, which thereby lead to an increased recovery of the contaminants. In situ thermal remediation technologies are attractive methods since they offer a high certainty of achieving the remedial target within a relatively short time period compared to other in situ remediation methods (Heron et al. 2005). Moreover, some of the thermal remediation technologies are particularly suited to treat low-permeability contaminant source zones, for example, clay tills, where biological and chemical in situ technologies are limited by the diffusion-controlled processes (Chambon et al. 2010; Hadley and Newell 2012). The fast and efficient cleanup offered by thermal remediation technologies is, however, attained at the cost of an extensive consumption of energy and materials at the site resulting in environmental impacts comparable to those of contaminant source excavation and off-site treatment (Lemming et al. 2010a, 2010b).

Life cycle assessment (LCA) is an established and systematic methodology for assessing the environmental impacts associated with the entire life-cycle (from "cradle-to-grave") of a certain product or service which can also be applied to remediation technologies (Lemming et al. 2010c). The LCA translates the environmental exchanges during the life-cycle of the remediation project (use of finite resources, emissions to air, soil, and water) to a number of environmental impacts including global warming, ozone formation, acidification, eutrophication, respiratory impacts, human- and ecotoxicity and resource depletion. The wide range of impacts included in the assessment give a more complete and holistic assessment than methods focusing only on single indicators such as "carbon footprint" (Laurent et al. 2012). LCA of remediation technologies has been applied in a number of studies in order to compare different remedial options for a contaminated site, for example, pump-and-treat versus a reactive barrier (Higgins and Olson 2009; Bayer and Finkel 2006), comparison of bioremediation, in situ thermal desorption and off-site treatment (Lemming et al. 2010b), and comparison of in situ, on-site and off-site bioremediation (Sanscartier et al. 2010). In addition to comparing different technological approaches

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for remediation of a contaminated site, LCA can be applied to optimize a single technology. Mak and Lo (2011) made a detailed study of the environmental design for permeable reactive barriers and Lemming et al. (2012) compared the use of oxidants for in situ chemical oxidation. The application of LCA for environmental optimization of design and implementation of remediation technologies is, however, still limited, but will be explored further in this paper with a focus on in situ thermal remediation technologies.

In this study, we investigate the environmental impacts of the four in situ thermal remediation methods most often applied at field scale (Kingston et al. 2010). These are: (1) Steam Enhanced Extraction (SEE) (Davis 1998) which heats the subsurface by the injection of steam, (2) In Situ Thermal Desorption (ISTD) (LaChance et al. 2006; Heron et al. 2009) which applies thermal conduction heating to the subsurface through the use of heater elements, (3) Electro-Thermal Dynamic Stripping Process (ET-DSP™) (McGee 2003) which is included as a representative for Electrical Resistance Heating (ERH) methods, and (4) Radio Frequency Heating (RFH) (Price et al. 1999) that heats the soil by applying energy with radio frequency. A soil vapor extraction system is included in all technologies to extract the contaminated vapors, which are subsequently treated above ground. For SEE and ET-DSP™ this is combined with a groundwater extraction system.

The goal of this study is (1) to conduct a state-of-the-art LCA of the four in situ thermal remediation technologies to compare the environmental impacts and the environmental impact drivers for each technology; and (2) to identify options and recommendations for reducing the environmental impacts of each technology by substitution of materials and change in heating strategies based on LCA evaluations. The LCA study is carried out for both a smaller and a larger contaminated site based on two Danish sites where thermal remediation has been applied. The findings of the study will be discussed in terms of their site-specificity and applicability to larger contaminated sites.

Materials and Methods

Site Descriptions

The data collection for the LCA was conducted for two contaminated sites—a smaller (180 m^2) and a larger site (1300 m^2) representing two typical Danish sites where remediation using ISTD has been conducted. Thus the material and energy consumption data for the ISTD method in this paper are based on actual project data while results for RFH, SEE and ET-DSP™ are estimated. RFH has so far only been applied at a pilot scale test (25 m^2) in Denmark and the data collection for this technology was therefore only carried out for the actual site as well as a 180 m^2 site. Table 1 gives an overview of the three test sites used in this study. Note that the treated soil volume at the large site is almost 10 times larger than at the small site.

In Situ Thermal Remediation Technologies

The four thermal technologies are based on the same overall principle in which the soil is heated to around 100 °C to enhance the volatilization of the chlorinated solvents. In this study, the solvent vapors are assumed to be continuously extracted from the subsurface under vacuum and treated above ground in an activated carbon air filtration unit and, as a proportion of the extracted vapors also condense, the condensed aqueous phase is treated in a separate activated carbon water filtration unit. A vapor cap of 40 cm foam concrete is installed above the heated zone in order to prevent intrusion of rain, create a vapor-tight seal to the surface and to reduce heat loss to the atmosphere. All technologies require the installation of a number of wells to generate soil heating as well as extraction wells. The construction of the heating wells and the distance required between the wells to maintain the heating profile (and thereby the total number of wells needed for the treatment area) differs for the four thermal methods (see Table 2). While SEE requires the injection of steam, ISTD uses specialized heaters placed in the heater wells, ET-DSP™ places steel electrodes in the wells and RFH uses specialized antennas, which also may function as extraction wells. In Table 2, the four technologies are compared in terms of site geology, energy source, heater well materials and distances as applied in this study. Above grade equipment is also listed. Note that for SEE a high-permeability geology at the contaminant source zone is assumed, whereas the other technologies are applied to a low-permeability contaminant source zone. The setup of each technology is presented in Figure 1. Furthermore it should be noted that because ISTD well distances are based on early applications on ISTD in Denmark (conducted in 2009), they tend to be more conservative than those estimated for the remaining technologies.

Table 1

Overview of Test Sites Used as a Basis for Data Collection

Site	Pilot Scale Site	Small Site	Large Site
Treatment zone area (m^2)	25	180	1300
Treatment depth (meter below ground surface)	4 to 8 m bgs.	0 to 7 m bgs.	0 to 9 m bgs.
Treatment zone volume (m^3)	100	1175	11,500
Mass of contaminant	75 kg of PCE	400 kg of PCE	2,400 kg of PCE
Remediation methods assessed for site	RFH	SEE, ISTD, ET-DSP™, RFH	SEE, ISTD, ET-DSP™

Life Cycle Assessment Approach and Data Collection

As a basis for the LCA, a systematic data collection phase has been carried out in order to establish a baseline dataset for each remediation technology in terms of energy and material consumption, as well as the use of equipment during construction and transportation activities. The assessment covers all aspects of the remediation projects, for example, the well field materials and the establishment

Table 2

Comparison of Key Assumptions for SEE, ISTD, ET-DSP™, and RFH in This Study

	SEE	ISTD	ET-DSP™	RFH
Geology of contaminant source zone	High-permeability source zone	Low-permeability source zone	Low-permeability source zone	Low-permeability source zone
Energy source	Natural gas (treatment system runs on electricity from the grid)	Electricity from grid	Electricity from grid	Electricity from grid
Heater/injection well construction materials[1]	Riser pipe: Steel Injection screen: Stainless steel Annular space: Sand, high temperature grout	Heater can: Steel Liner and heater rod: Stainless steel Heater cold pin: Nickel	Electrodes: Steel, copper, nylon Annular space: Sand, bentonite, high temperature grout	RFH antennas: Stainless steel, fiberglass Annular space: Sand, bentonite
Average heater well distance[2]				
Pilot scale	—	—	—	2.5 m
Small site	5.0 m	2.9 m	5.5 m	3.0 m
Large site	7.0 m	4.2 m	6.1 m	—
Above grade equipment used[3]	Vapor cap Activated carbon treatment system Steam generator Water softener system	Vapor cap Activated carbon treatment system Power distribution system	Vapor cap Activated carbon treatment system Power distribution system Water circulation units	Vapor cap[4] Activated carbon treatment system Power generator Matchboxes (RF adjustment box), copper shields and leads

[1] A complete overview of materials used for the well field including extraction wells, temperature and pressure monitors is found in Table S3 (supporting information).

[2] Distance between injection wells (SEE), heater wells (ISTD), electrode wells (ET-DSP™) and antenna wells (RFH).

[3] A complete overview of materials used above grade is found in Table S4 (supporting information).

[4] A vapor cap was not included at the pilot scale site which provided input for the RFH study and was therefore disregarded. It was included in the assessment for the small site.

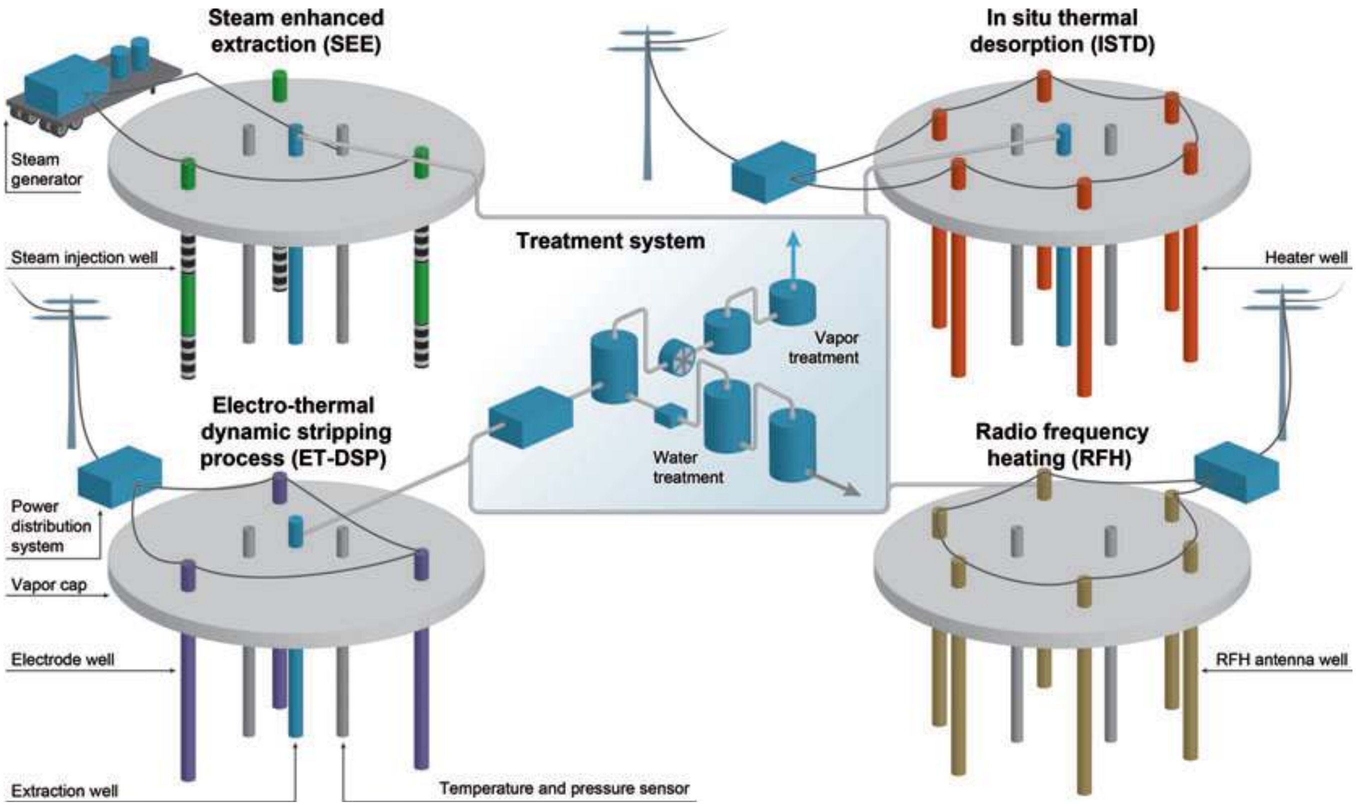


Figure 1. Conceptual sketch of SEE, ISTD, ET-DSP™, and RFH.

of the well field, the capping materials, the air and water treatment systems, the electricity consumption and the transportation of materials and personnel.

The applied life cycle impact assessment methods are the EDIP 2003 method (Environmental Design of Industrial Products, Hauschild and Potting 2005) for non-toxic impacts (global warming, acidification, eutrophication, and ozone formation) and the USEtox™ method (UNEP-SETAC toxicity model, Rosenbaum et al. 2008) for toxic impacts (human toxicity cancer, human toxicity noncancer and ecotoxicity). All life cycle impact results are normalized to the impacts of an average person. Thus they are converted to so-called person equivalents (PE) by division with the impact from an average European or world citizen in 2004 for regional and global impacts respectively. The applied normalization references are based on 2004 data (Laurent et al. 2011a, 2011b) and can be seen in Table S1 (see supporting information). Resource depletion results are reported as person reserves (PR). A person reserve represents the person equivalents which are weighted with the reciprocal of the supply horizon of each resource, so that a resource with a short supply horizon is weighted higher than a resource with a long supply horizon. The applied weighting factors for resource depletion are based on 2004 data (LCA Center 2005) and can be seen in Table S2.

Input to the life cycle assessment is divided into the following five categories, described in Table 3: On-site energy consumption, above grade materials, well field materials, machines, and transportation. In Tables S3 to S8a detailed overview of all inventory data can be found.

The Ecoinvent database (Hischier et al. 2010) is the main source of life cycle inventory data for production of consumables such as steel, stainless steel, concrete, plastics, and for transportation processes, electricity production, etc. This is combined with additional inventory data collected from the literature, for example, regarding the production of activated carbon. Note that the assessment is made for the application of in situ thermal remediation under Danish conditions, that is, electricity mix and transportation distances are determined based on average Danish conditions. Tables S9 and S10 list the applied LCA processes and modifications made.

Estimation of Energy Use and Operation Time

Since both the small and the large site scenarios are defined based on full scale ISTD remediation conducted at two Danish sites, the materials and energy usage for the two ISTD scenarios are based on the actual consumption.

The material and energy consumption for the remaining ET-DSP™, SEE, and RFH scenarios are based on simplified mass and energy balance principles relevant for thermal operation. Calculations were conducted to evaluate the effects of groundwater flux, thermal method power input, energy extraction rates, and heating strategy and included the following input parameters:

- Area and volume of the treated areas.
- Estimation of heat losses based on the shape and size of the treated areas.
- Geological site parameters such as soil type, porosity, soil and water heat capacity, etc.
- Hydrogeological site parameters such as initial soil saturation, location of water table, hydraulic conductivities, gradients, etc.
- Well counts based on actual conceptual well layouts for the different scenarios.
- Energy balance calculations, including total site heat capacities, site energy input and estimated energy extraction as steam and hot water.

The groundwater flow into the treatment areas for each scenario were estimated based on actual measurements performed at the test sites used in this study. For the ET-DSP™ and SEE methods, where water is actively injected during operation, this additional injected water was included in the total water and energy balance. Water extraction rates and the corresponding energy removal were then calculated based on the net water influx and by estimating an average temperature of the extracted water. Steam removal rates

Table 3

Description of Content of the Overall Input Categories Used for Presenting the LCA Results in Figures 2 and 3

Category	Content
On-site energy	Includes energy for heating of the subsurface, extraction of vapor and water, and treatment of vapor and water
Materials (above grade)[1]	Includes materials from above grade installations, for example, the vapor cap concrete, the vapor and water treatment systems, office containers, and specific equipment for each technology. A full description is available in supporting information (Table S3)
Materials (well field)[1]	Includes materials used for the well field, for example, materials for annular space, wells, extraction wells, temperature/pressure gauges, electricity cables, and heaters/electrodes/antennas if applied. A full description is available in supporting information (Table S3)
Machines	Includes the fuel use and emissions related to construction equipment such as drill rigs, bob-cats, and wheel loaders
Transportation	Includes the local transportation of personnel and equipment to and from the site (90 km return trip) and long distance transport for specialized equipment, namely ISTD heaters (shipped from the United States), power distribution systems, water circulation units and electrodes for ET-DSP™ (shipped from Canada) and power distribution system and matchboxes for RFH (from Germany). In addition, air travel of Canadian ET-DSP™ experts to Denmark is included in the transportation category for this technology due to the lack of local experienced personnel.

[1] For equipment with a longer service life than this remediation project, only a fraction of the material use is ascribed to this project. Reuse rates are found in supporting information (Tables S3 and S4).

were estimated as a percentage of the energy input and were derived based on actual field data from already completed ISTD, SEE, and ET-DSP™ projects.

The mass and energy balance calculations serve as the background for the estimation of:

- Duration of construction, operating and demobilization phases;
- Size of treatment systems, power delivery systems and other field equipment;
- Operational time for supporting equipment such as drill rigs, excavators, fork lifts, etc. during each phase of the project;
- Transportation required during each phase of the project.

Based on these calculations, the total consumption of materials and energy has been estimated and serves as the basis for the LCA calculations.

Results and Discussion

Comparison of Life Cycle Impacts of In Situ Remediation Technologies

The life cycle assessment results for all four in situ thermal remediation technologies are shown in Figures 2 (environmental impacts) and 3 (resource depletion). Note that all results are presented per unit volume (1 m^3) of soil remediated in order to compare results for each site. Environmental impacts are given in mPE (10^{-3} person equivalents) per m^3 of soil remediated and resource depletion is given in mPR (10^{-3} person reserves). For all technologies, on-site energy consumption for soil heating and above grade treatment system is the main cause of the non-toxic environmental impacts followed by impacts due to the above grade materials. The energy consumption for heating of the subsurface is responsible for most of the impacts in the subcategory on-site energy consumption (73 to 95%), the rest of the impacts are due to the electricity consumption for the on-site treatment system.

The relatively high contribution to environmental impacts from the above grade materials is primarily ascribed to the vapor cap concrete and the activated carbon (see detailed result for the subcategory above grade materials in Figure 4). Well field materials followed by above grade materials are the main causes of impacts to human toxicity and ecotoxicity. This is due to the consumption of steel and stainless steel for the well fields and the above grade installations, and is caused by toxic emissions during steel production. The environmental impacts related to the use of heavy machines are relatively low at the large site, but more important at the small site. This is due to the closer network of heater wells at small sites requiring more drilling work. Transportation impacts due to transport of equipment and personnel to and from the sites (90 km return trip) are negligible compared to the other impacts except for ET-DSP™ where equipment and experts are assumed to be transported from Canada, and for the RFH pilot scale site due to the lower amount of energy and materials consumed here.

Depletion of energy resources (coal, brown coal, natural gas, oil, and uranium) is as expected mainly due to the on-site energy consumption, but a significant part of the oil depletion is also ascribed to the fuel consumption by heavy machinery and a minor part to transportation. In addition to energy resources, a significant depletion of nickel and chromium is found for all technologies due to their use as alloying materials in stainless steel, which is used in large amounts in the well field and above grade materials. As the only technology, ET-DSP™ also uses significant amounts of tin due to the bronze contained in the water circulation units.

The treated soil volume at the large site is almost 10 times larger than at the small site. The environmental impacts and resource consumption are, however, only about five times larger. Thus, the results indicate that in situ thermal remediation becomes more environmentally efficient for larger sites. This is not only especially because of a relatively larger heat loss for the small site compared to the large site, but also because of a relatively greater quantity of installations as wells are placed more closely together at a smaller site. The results also indicate that SEE generates lower environmental impacts and resource depletion per unit volume remediated than the other three techniques, whereas RFH generates the highest impacts and the results for ISTD and ET-DSP™ are intermediate. SEE, however, is not applicable to lower-permeability sites that can be addressed using the other in situ thermal remediation technologies (Kingston et al. 2010). As mentioned previously, the inventory for ISTD is more conservative in terms of well distance than the other technologies. However, due to the relatively limited impact from well materials (except in toxic impact categories) it would not change the internal ranking of technologies if for instance the well distance were doubled. Furthermore, it should be noted that, as RFH was not assessed for the large site, the comparison of RFH with other technologies was only done for the small site which showed higher impact and resource use per m^3 soil treated than the remaining technologies.

The results of the life cycle assessments show that the toxic impacts are generally higher than the nontoxic impacts in terms of PE. When comparing the normalized toxic and nontoxic impacts, it should be kept in mind that the assessment of toxic impacts is associated with a much higher degree of uncertainty in inventory data, impact assessment and data normalization due to the large number of chemicals included in the assessment and the associated data gaps (Sleeswijk et al. 2008). Furthermore, the current characterization factors for metals in USEtox™ are interim as they disregard metal speciation. As a consequence of these issues, normalized toxic impacts may be overestimated.

Evaluation of Improvement Options

The life cycle assessment determined that the on-site energy consumption, vapor cap concrete, activated carbon and steel and stainless steel are the main contributors to environmental impacts and resource depletion. Based on this finding, options for improving the environmental profiles of the thermal remediation technologies have been identified and evaluated using life cycle assessment.

Improvement Options Related to Energy Use

The environmental impact of the energy consumption may either be reduced by changing to another energy source

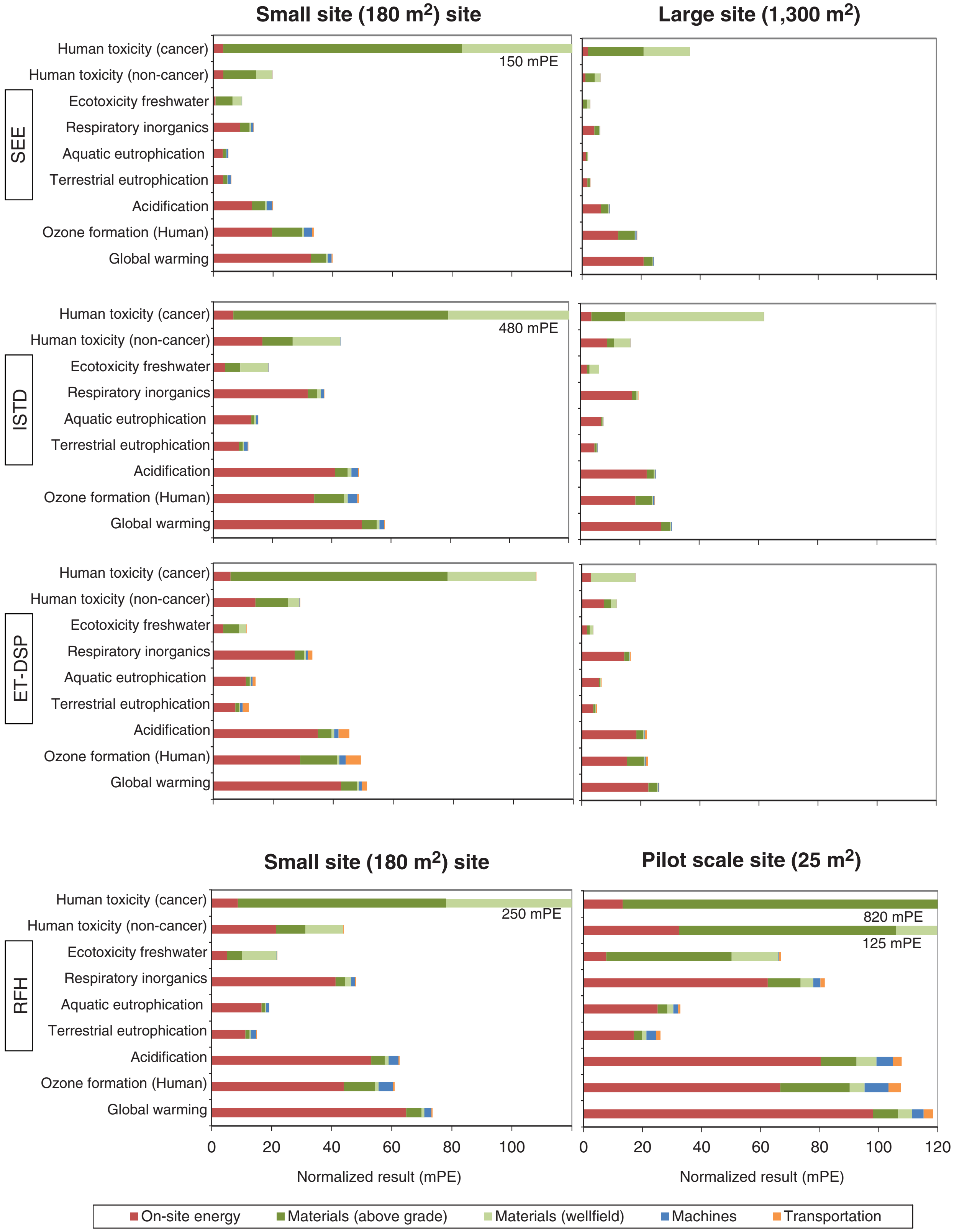


Figure 2. Environmental impacts (in mPE) per m³ of soil remediated using SEE, ISTD, ET-DSP™ at a smaller (180 m²) and a larger contaminated site (1300 m²), and RFH at a smaller (180 m²) site and a pilot scale site (25 m²) respectively.

or using more energy efficient equipment. In the baseline scenario for ISTD, ET-DSP™, and RFH, the applied electricity is low-voltage electricity from the Danish grid (average production mix of 38% coal, 21% natural gas, 14% wind, 4% biomass, 3% oil and 19% import from Sweden, Germany, and Norway) whereas SEE employs a natural gas-fired steam boiler. A continuous application of energy to the subsurface is employed in all baseline scenarios representing the normal practice for in situ thermal remediation. However, we have examined a scenario, where heating is

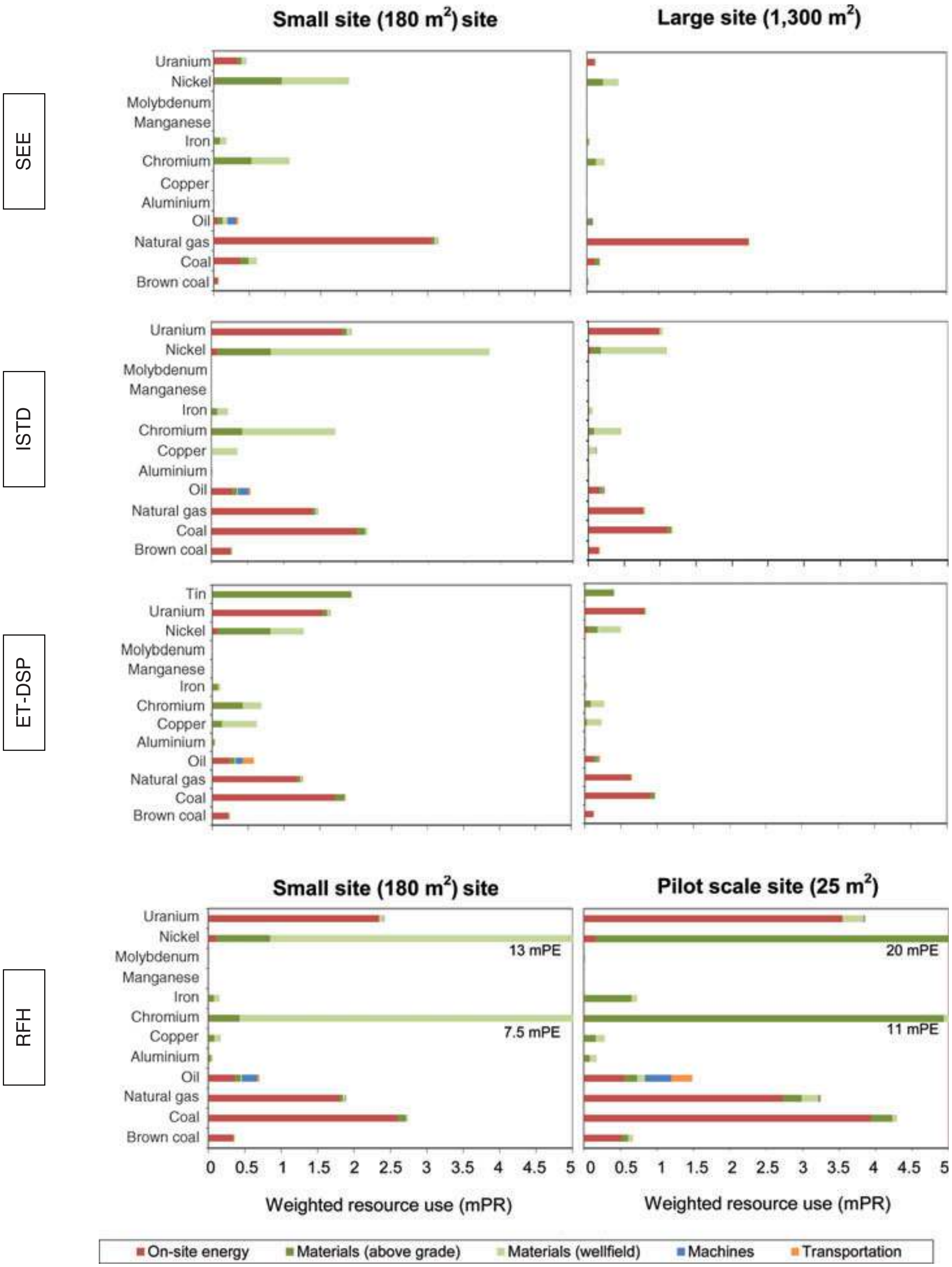


Figure 3. Resource depletion (in mPR) per m^3 of soil remediated using SEE, ISTD, ET-DSP™ at a smaller (180 m^2) and a larger contaminated site (1300 m^2), and RFH at a smaller (180 m^2) site and a pilot scale site (25 m^2).

mainly applied at off peak periods at night on weekdays (12 h/d from 8 p.m. to 8 a.m.). In the daytime, the energy input for heating is reduced by 80% in order to scale down electricity consumption during the peak demand period. This discontinuous heating strategy causes an increased operation time for ISTD and ET-DSP™ of 9% and 18% respectively, and an increased energy consumption of 3% and 6%, respectively. However, by heating at night outside the peak demand period, it can be expected that the demand on the Danish coal-fired power plants is reduced and that the excess wind power in the grid at night can be utilized. An exact composition of the electricity mix over time in

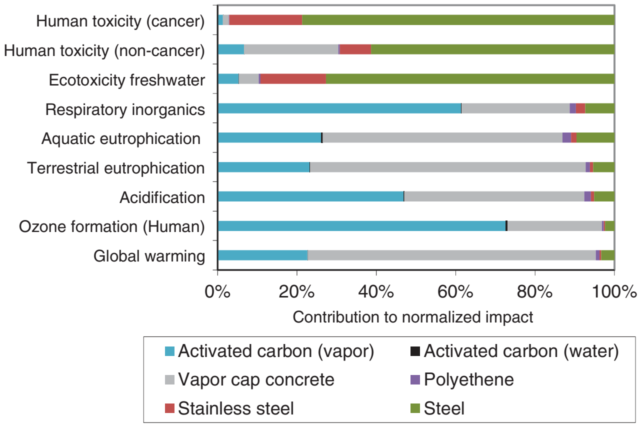


Figure 4. Detailed result for the subcategory above grade materials showing the contribution in percent to the environmental impacts from materials used above grade. The result for SEE (large site) is shown, but it differs only slightly from the other technologies.

the Danish grid is not available. Under the assumption that there is 6 h of wind power available in the grid at night, the comparison shows that a reduction of 10% for ISTD and 8% for ET-DSP™ in the environmental impacts and resource depletion associated with the electricity consumption can be achieved by heating outside peak demand periods (see Figure 5).

Another option for reducing the environmental impact of electricity consumption would be to ensure that the energy comes from a renewable source. For the actual ISTD remediation project at the large site, certified hydropower from Norway was purchased, but this only ensures that the purchased amount of hydropower is allocated to the project thus reducing the amount of renewable energy available in the grid to other customers. It does not ensure that the amount of hydropower is increased in the Danish electricity mix. Furthermore, due to the very small premium on this product and the fact that the hydropower potential is already fully utilized in the Nordic countries it is debatable (see Dyck-Madsen 2009) if the purchase of this type of certified hydropower will provide any environmental improvement. However, there are other renewable energy products available, for example, wind power, which may have a larger benefit.

The SEE technology uses a natural gas-fired steam generator. In Figure S1 (see supporting information), a life cycle assessment comparison of different steam generators is presented. This shows that changing from a noncondensing to a condensing steam boiler will reduce environmental impacts and resource depletion by an average of 7% due to the higher efficiency of this boiler type. It also demonstrates that changing to light fuel oil instead of natural gas will increase the environmental impacts and resource depletion.

Improvement Options Related to Material Use

In the baseline scenarios, the vapor cap is assumed to be a 40 cm layer of foam (i.e., lightweight) concrete with a density of 400 kg/m^3 similar to what was actually used at the two case sites. The vapor cap concrete gives a high contribution to environmental impacts especially due to the cement production. Four alternative vapor cap compositions with the same insulating properties were evaluated. These are 26 cm foam concrete with a density of 300 kg/m^3 and three concrete sandwich constructions. The concrete sandwich construction consisted of a thin (5 cm) layer of spray concrete on the top and bottom and filled with either 10 cm of expanded polystyrene (EPS), 21 cm of Leca® (lightweight expanded clay aggregate) beads or 30 cm of sea shells. Use of a foam concrete with a density of 300 kg/m^3 gives a reduction of approximately 50% in all environmental impacts and resource depletion compared to the baseline vapor cap. With a concrete sandwich construction, an even higher reduction of up to 65 to 75% of all impacts can be obtained. The vapor cap construction with the sea shells has slightly lower impacts than the other concrete sandwich constructions, but the availability of this product may be limited. The comparison presented in Figure 6 assumes (see Table S10) that at end-of-life, EPS is incinerated with an energy credit, Leca® beads are returned to the factory and reused in Leca® block production and sea shells are reused locally as draining materials. Foam concrete and concrete is

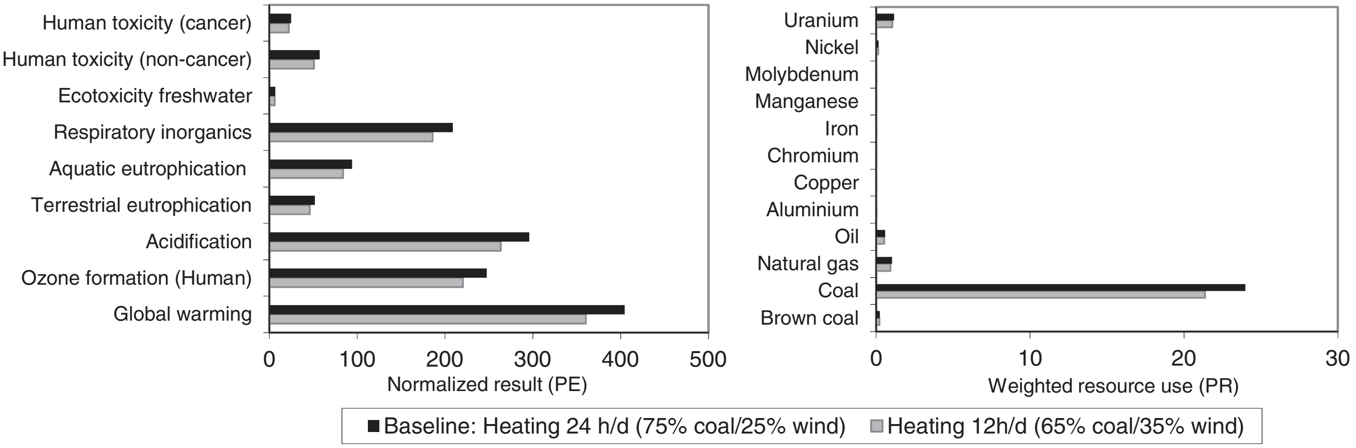


Figure 5. Comparison of ISTD scenario with heating 24 h/d and a scenario with the main heating at night on weekdays assuming that there are 6 h of wind power available in the grid at night and that the electricity in the remaining period is coal-based.

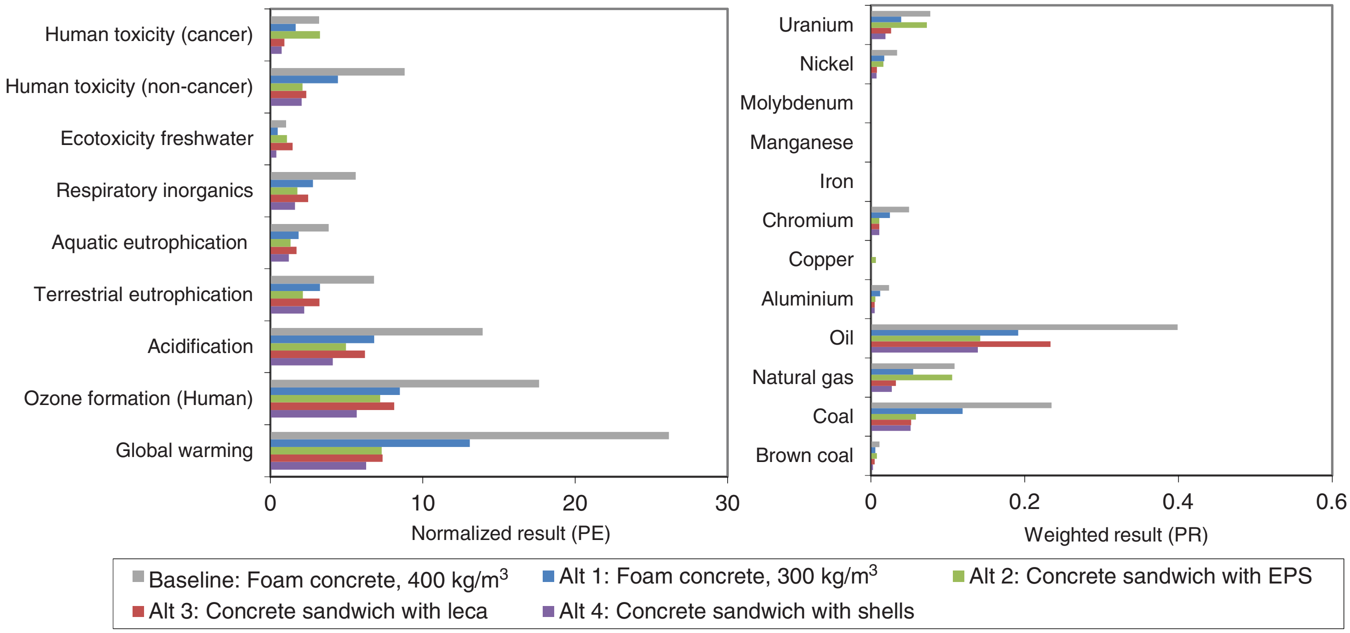


Figure 6. Comparison of life cycle impacts and resource depletion of alternative vapor cap constructions.

crushed and used in place of gravel, for example, for road fill. It should be noted that EPS may not be able to withstand the elevated temperatures, but it is included as a representative for this type of insulation material as more thermo resistant materials were not available in the life cycle assessment databases.

Activated carbon made from coconut shells is a potential substitution for the hard coal based activated carbon usually used for remediation projects. Furthermore, the results indicate that changing to a biobased activated carbon made from coconut shells can potentially reduce the impacts from activated carbon treatment. Large reductions are indicated for impacts on ozone formation, global warming, respiratory impacts, and hard coal depletion (see also Figure S2).

The baseline results show that the stainless steel used for well field installations made a high contribution to nickel and chromium depletion. For SEE, it may be possible to substitute the steel and stainless steel in the steam injection wells with fiberglass. This will reduce the amount of material needed due to the lower density of fiberglass. It would furthermore reduce the toxic impacts of the well materials by 87 to 98% as well as reduce nickel and chromium depletion by 99%. At the same time, however, small increases are seen in other impacts (global warming, ozone formation, and acidification) (see Figure 7). For ISTD, an alternative stainless steel alloy with a much lower content of nickel and a moderately lower content of chromium may be used for the heater rods and the liners. In addition, the high nickel content in the cold pins may be changed to an alloy with a lower nickel content augmented with copper. The combined effect of changing the stainless steel alloys and the nickel alloy is an 80% reduction in nickel depletion and a 2% reduction in chromium depletion (see Figure 8). The amount of steel needed for the heater rods increases when the low alloy stainless steel is used in order to ensure the same structural properties, therefore the reduction in chromium depletion is relatively small.

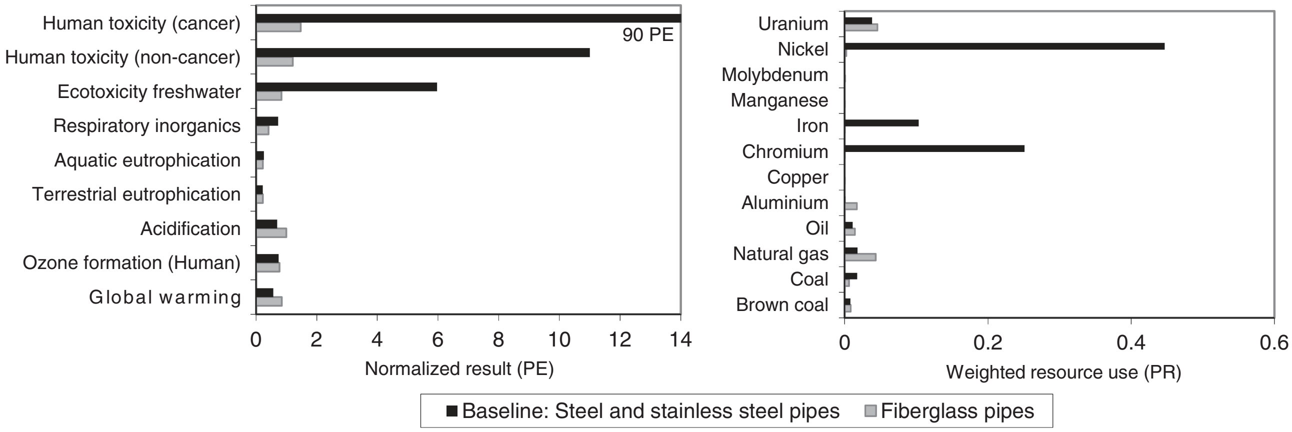


Figure 7. LCA comparison (environmental impacts and resource use) of injection well materials for SEE.

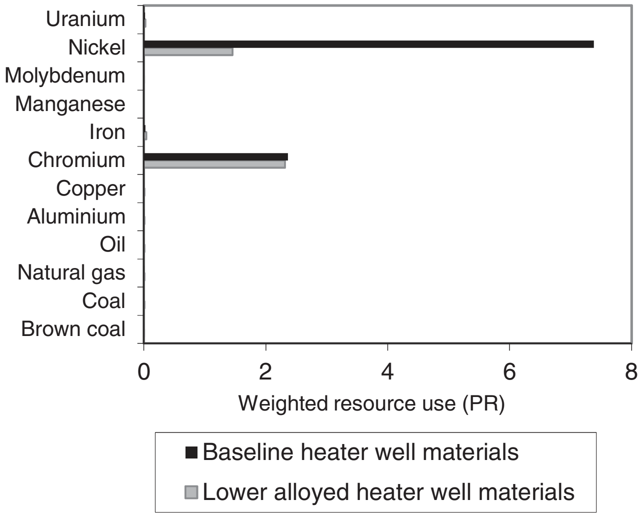


Figure 8. LCA comparison (resource depletion) of baseline heater well materials and an alternative scenario with low alloy stainless steel and cold pins with lower nickel content for ISTD.

Overview of Improvement Options Identified for In Situ Thermal Remediation and Combined Improvement Potential

Table 4 gives an overview of the improvement options identified for SEE, ISTD, and ET-DSP™ and the combined reduction potential in environmental impacts and resource depletion by introducing all improvement initiatives at the large site. The reduction potential is quantified as the reduction (in %) of the sum of person equivalents (PE) and person reserves (PR) of environmental impacts and resource depletion respectively. The combined reduction potential ranges from 10 to 21% for environmental impacts and 8 to 20% for resource depletion depending on the considered technology (see Table 4). As previously mentioned, the human toxic and ecotoxic impacts are generally higher and more uncertain than the nontoxic remaining impacts and therefore a bias is introduced when the sum of PE is considered. If toxic impacts are disregarded, the reduction potential for environmental impacts would increase for ISTD and ET-DSP™ to 17% and 18%, respectively. The pie charts in the last column of Table 4 show the distribution of the reduction potential for the individual improvement options. For SEE, each of the four identified improvement options contribute almost equally to the reduction in environmental impacts, whereas the use of a condensing boiler is the option with the highest improvement potential (50% of total reduction potential) for reducing the resource depletion.

For both ISTD and ET-DSP™, a change to heating mainly 12 h at night is the main improvement option leading to approximately 50% of the reduction in environmental impacts. The remaining reduction potential is shared almost equally by optimization of vapor cap construction and a change to bio-based activated carbon. For ET-DSP™, optimization of transportation is also included as a potential improvement option as in the baseline scenario, specialized equipment and personnel are imported from Canada. If local equipment and experts are available, this would reduce transportation impacts significantly. The change to low alloy stainless steel heater well materials for ISTD contribute 35% of the reduction potential for resource depletion, with 12 h heating during off-peak periods at night being the second most important contributor. For ET-DSP™, heating at off-peak periods is the main contributor to reduced resource depletion.

For RFH, the combined reduction potential was not quantified as the inventory was based on a pilot scale test. However, the general improvement options of heating during off-peak periods at night, using a concrete sandwich vapor cap and bio-based activated carbon also apply to this technology. In addition, further development of the RFH power generators will be beneficial for this technology as the efficiency is currently only 50%, i.e. 50% of the produced energy ends up in the subsurface. The next generation power generators are expected to have an efficiency of 80% (Hüttinger, personal communication, 2013). This is, however, still low compared to ISTD and ET-DSP™ where efficiencies are close to 100%.

It is clear from this investigation that the energy consumed on-site for heating is the main environmental impact driver for in situ thermal remediation technologies. Thus, the main improvement is obtained by reducing, changing or optimizing the energy consumption. The Danish electricity mix comprises approximately 20% energy from renewable sources (mainly wind and biomass). In other geographical locations with a larger share of renewable energy, the impacts from energy consumption will be lower and the improvement options for materials will become more important. In addition to the findings above, an important task is of course to conduct a detailed site investigation so that the contaminated source zone is delineated and the treatment zone is carefully identified in order ensure that only the necessary soil volume is remediated. However, in this assessment, the volume of the source treatment zone was assumed to be fixed and not to be a potential optimization parameter.

Uncertainties of LCA

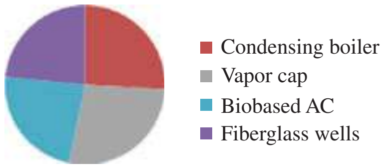
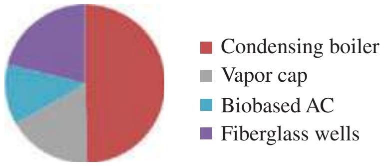
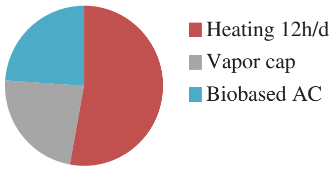
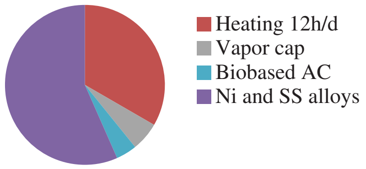
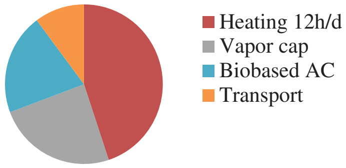
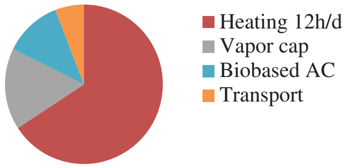
As indicated in Table 4, there are some uncertainties related to the identified improvement options. The actual improvement in changing to off-peak heating at night depends especially on the amount of wind energy available at night, which will vary a lot and is difficult to determine. Nevertheless, the certainty that this initiative creates a positive impact on the environmental profile is high, since it lowers the pressure on the coal-fired power plants during peak demand periods. The LCA inventory of the bio-based activated carbon stems from the literature (Sparrevik et al. 2011) and not from a reviewed LCA inventory database such as Ecoinvent, and therefore may be more uncertain.

Improvement Options in Relation to Size of Remediated Site

The LCA results showed that the environmental impacts per unit volume of remediated soil decreased by approximately 50% when comparing the large site to the small site. This is because of a relative lower heat loss at the larger site as well as the more efficient use of above grade equipment. In situ thermal remediation projects can be even larger than

Table 4

Summary of Identified Improvement Initiatives, the Certainty of the Improvement and the Combined Reduction Potential If All Initiatives Are Introduced at the Large Site

	Improvement Initiative	Certainty of Effect[1]	Combined Reduction Potential and Division Between Initiatives	
SEE	Condensing steam boiler	++	Environmental impacts: 21%	
	Concrete sandwich vapor cap	++		
	Bio-based activated carbon	+ (data quality)	Resource depletion: 9%	
	Change to fiberglass injection wells	+ +		
ISTD	Discontinued heating (12 h/day)	+ (amount of wind uncertain)	Environmental impacts: 10%	
	Concrete sandwich vapor cap	++		
	Bio-based activated carbon	+ (data quality)	Resource depletion: 20%	
	Substitution of heater well materials	+ (function/durability)		
ET-DSP™	Discontinued heating (12 h/day)	+ (amount of wind uncertain)	Environmental impacts: 13%	
	Concrete sandwich vapor cap	++		
	Bio-based activated carbon	+ (data quality)	Resource depletion: 8%	
	Use of local experts and equipment	++		

Note: The pie charts show the division of the improvement potential between the different initiatives.

[1] ++: High certainty of positive effect of initiative; +: Certainty of positive effect, but magnitude of improvement uncertain. The text in the parentheses explains the reason for the lower certainty.

the "large" project included in this study, and thus can have commensurately greater inherent efficiencies than the project studied. In the United States, sites of up to 70,000 and 300,000 m^2 are currently being designed and treated by ISTD and SEE. The fact that the heat loss and equipment use per volume of soil is lower for a larger site does not eliminate the need for environmental optimization of large systems. In contrast, the large energy and material usage at these sites make it even more important to assess the possibilities of reducing the environmental impacts. At a very large site, there may be a difference in practices applied, for example, it may be economically feasible to reactivate activated carbon directly on-site using steam, which will change the life cycle assessment of the activated carbon substantially, for example, reduce the amount of hard coal consumed, but increase the on-site energy use. However, to a large degree the design of the remediation will be similar and the improvement options identified in this study will apply.

Regional or Continental Differences in Environmental Impacts

Environmental impacts of remediation measures will to some degree depend on the geographical location of the contaminated site due to differences in production systems for electricity and consumed materials. The production processes for materials such as steel and plastics are based on a European LCA database. However, we expect these to be relatively similar to materials produced/used in the United States. To a large extent we therefore expect the baseline results to be relatively similar if the site were located in North America. With regard to energy use being the primary driver of impacts this will most likely also be the case in North America, unless the site were located in a state/region with a very large share of renewable energy in the electricity production mix. The specific findings related to energy consumption depend highly on the electricity production mix of the given country/state/region. Variable electricity mixes (i.e., different contents of renewable energy as well as different types of renewable and fossil energy types) can result in very large differences in the environmental impacts associated with energy use. Furthermore, the benefit of heating mainly at night depends on the electricity system and whether there is excess electricity available at night. Impacts related to transportation of equipment and personnel to and from the site will also be very site-specific. In the current case study, travel distances to from the site for personnel and equipment were rather small (90 km return trip). In North America and some European countries longer distances are very likely, which will increase the importance of this category.

Economical Implications and Implementation

The monetary implications were not part of the study as such, but they are of course an important driver for site owners and decisions makers. In general many of the changes proposed here are expected to be cost neutral or to give only marginal additional costs. With regard to changing the heating strategy to heating mainly at night, it is possible that this could give monetary savings as electricity, in some places, is cheaper at night. At the same time, the heating period is increased a bit, which will result in extra costs. Finally, it should be noted that engineering and implementation issues related to replacing the well field materials for ISTD have not yet been investigated in terms of function and durability. A full scale implementation of changes would include a comparison of environmental impacts, costs and technical feasibility, but this was beyond the scope of this paper.

Conclusions

The life cycle assessment showed that on-site energy consumption due to the energy requirements for heating the subsurface is the main environmental impact driver and source of resource depletion, followed by the impacts due to above grade materials and well field materials. SEE was found to be the thermal technology with the lowest environmental impacts and resource depletion per unit volume remediated, whereas RFH produced the highest environmental impacts. However, SEE is only applicable at locations with relatively high permeable geological conditions and therefore should not be compared directly to the other three technologies which are generally implemented at both low and medium permeability geological locations.

A number of options for reducing the environmental impacts and resource depletion have been identified: Heating outside peak demand periods for technologies applying electricity from the grid (ISTD, ET-DSP™ and RFH); use of a condensing steam boiler for SEE; use of a vapor cap with a minimum of concrete such as a concrete sandwich; use of bio-based activated carbon; use of fiberglass injection wells instead of stainless steel injection wells in SEE; and use of low alloy stainless steel and nickel types for heaters, liners and cold pins in ISTD. By introducing these changes, a 10% reduction in impacts from on-site energy consumption can be obtained, a 75% reduction of impacts related to the vapor cap and an 80 to 99% reduction in nickel depletion related to well materials. In combination, the identified improvement options will reduce the total impacts (in terms of PE) by 10 to 21% and the resource depletion (in terms of PR) by 8 to 20% for the four in situ thermal remediation technologies. As the energy consumption is the main contributor to most environmental impacts, the combined improvement potential is therefore to a high extent controlled by the reduction/improvement of the energy consumption. Finally, it should be noted that the benefit of heating mainly at night is dependent on the actual electricity production system in the given region of the analysis.

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Supporting Information

Supporting information is available in the online version of this article.

Table S1. Applied Normalization References for Environmental Impacts

Table S2. Applied Weighting Factors for Resource Depletion

Table S3. Unit Amounts and Reuse Rates for Well Field Materials used in ISTD, SEE, ETDSP™ and RFH

Table S4. Unit Amounts and Reuse Rates for above Grade Materials for ISTD, SEE, ET-DSP™ and RFH

Table S5. Overview of Transportation, Energy Usage, Material Usage, and Diesel Usage for Machines in the ISTD Scenarios

Table S6. Overview of Transportation, Energy Usage, Material Usage and Diesel Usage for Machines in the SEE Scenarios

Table S7. Overview of Transportation, Energy Usage, Material Usage and Diesel Usage for Machines in the ET-DSP™ Scenarios

Table S8. Overview of Transportation, Energy Usage, Material Usage and Diesel Usage for Machines in the RFH Scenarios

Table S9. Details for Applied LCA Data for Production of Electricity, Steam, Metal Alloys and Plastics

Table S10. Details for Applied LCA Data for Production of Grout, Concrete, Sand, Activated Carbon and LCA Data for Transportation and Construction Machines

Figure S1. LCA comparison of different steam boiler types.

Figure S2. LCA comparison of hard coal based activated carbon and bio-based activated carbon.

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