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# Environmental life-cycle comparisons of two polychlorinated biphenyl remediation technologies: Incineration and base catalyzed decomposition

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ABSTRACT

Remediation action is critical for the management of polychlorinated biphenyl (PCB) contaminated sites. Dozens of remediation technologies developed internationally could be divided in two general categories incineration and non-incineration. In this paper, life cycle assessment (LCA) was carried out to study the environmental impacts of these two kinds of remediation technologies in selected PCB contaminated sites, where Infrared High Temperature Incineration (IHTI) and Base Catalyzed Decomposition (BCD) were selected as representatives of incineration and non-incineration. A combined midpoint/damage approach was adopted by using SimaPro 7.2 and IMPACTA2002+ to assess the human toxicity, ecotoxicity, climate change impact, and resource consumption from the five subsystems of IHTI and BCD technologies, respectively. It was found that the major environmental impacts through the whole lifecycle arose from energy consumption in both IHTI and BCD processes. For IHTI, primary and secondary combustion subsystem contributes more than 50% of midpoint impacts concerning with carcinogens, respiratory inorganics, respiratory organics, terrestrial ecotoxity, terrestrial acidification/eutrophication and global warming. In BCD process, the rotary kiln reactor subsystem presents the highest contribution to almost all the midpoint impacts including global warming, non-renewable energy, non-carcinogens, terrestrial ecotoxity and respiratory inorganics. In the view of midpoint impacts, the characterization values for global warming from IHTI and BCD were about 432.35 and 38.5 kg $CO_2$-eq per ton PCB-containing soils, respectively. LCA results showed that the single score of BCD environmental impact was 1468.97 Pt while IHTI's score is 2785.15 Pt, which indicates BCD potentially has a lower environmental impact than IHTI technology in the PCB contaminated soil remediation process.



## 1. Introduction

Polychlorinated biphenyls (PCBs) are one of the first historically recognized persistent organic pollutants (POPs) and most widespread in the environment [1]. Owing to their desirable and excellent physical–chemical properties, a total of about 1.2 million tons of PCBs were produced and widely applied in industry as the coolants, lubricants in transformers, dielectric fluids in capacitors, pesticides and so on [2]. Although most countries stopped their PCB production by the late 1980s, PCBs still exist in old electric and transformer equipments. It was estimated that more than half of the PCBs was still in use or in storage, or deposited in landfills. Nearly one third was released to the general environment, and only few had been destroyed. PCBs released from evaporation, leakage, illegal recycling, improper disposal [3,4] and accidents posed high potential harmful affects to man through the bioaccumulation in organisms and the biomagnification in the food chain. Because of their persistence in the environment, PCB concentrations could hardly decrease in most of contaminated sites without remediation actions [5,6]. As a significant portion of PCBs ever produced remains in service, in storage or in landfills, the management of PCB contaminated sites and PCB-containing wastes will be a major concern in the future.

At present, high temperature incineration is widely used in developed countries to treat PCB wastes [7–9], which is well developed and generally a thermal oxidation and destruction technology. Most high temperature incineration plants have been built not only for the purpose of destroying PCBs, but also for the disposal of other hazardous wastes. Very high temperature, stringent operating conditions (maintenance at 1200 °C for 2-s residence time or 1600 °C for 1.5-s residence time) with limited feed rate of PCBs are required to achieve high destruction and removal efficiency (DRE) in a incineration process. When operating conditions do not meet the above requirements, PCBs could be evaporated out and highly toxic PCDDs/PCDFs (dioxins and furans) might be formed and released from the incinerators [5,10]. Some industrialized countries are just

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limiting the PCB incineration and trying to find alternative destruction technologies for their PCB-containing wastes [11].

Non-incineration processes generally operate at a low temperature and in a depleted or ambient oxygen atmosphere [12]. Though such technologies may also produce dioxins or furans, they need less equipment to remove these chemicals than the oxidizing process, for example high temperature rotary kiln. Base on their advantages, non-incineration demonstration and application is just being promoted by Global Environment Facility (GEF) as a preferred treatment for persistent organic pollutants, especially PCBs, in Slovakia, the Philippines, China and South Africa. Base Catalyzed Decomposition (BCD) [13], developed by EPA's Risk Reduction Engineering Laboratory in cooperation with the National Facilities Engineering Services Center (NFESC) to dispose liquids, soils, sludge and sediments contaminated with chlorinated organic compounds [14], is one of such non-incineration technology. BCD is a catalytic hydrogenation process in which atoms of chlorine are removed from molecules and replaced by hydrogen atoms. In a BCD process, contaminated soil is excavated and screened to remove large particles, then crushed and mixed with sodium bicarbonate and carrier oil which acts both as suspension medium and hydrogen donor. Several different combinations of reagents can be used in the mixture process, all of which utilize a basic (caustic) reagent such as sodium hydroxide or sodium bicarbonate, usually in combination with liquid carriers/reagents as well as catalytic materials. The addition of alkali often enhances the stripping of chlorinated hydrocarbons from difficult matrices. Then, the mixture is heated to about 200–400 °C in a rotary reactor. Under these conditions, significant fractions of the POPs are destroyed in the desorption process, especially in the presence of alkali. And hydrogen splits off from the carrier/donor oil and hydrogenates the bonded chlorine during the operation. The soil left behind is removed from the reactor and can be returned to the site. The oil and salt containing sludge could be disposed as fuel in a cement kiln. The volatilized contaminants are captured, condensed and treated separately. The concentration of PCBs in the vaporized phase that has been treated by BCD process was reported to be as high as 45,000 ppm, and could be reduced to less than 2 ppm.

A major question regarding the choice of PCB treatment technologies remains. It is not clear which technology is the "best", nor can it be said that one best technology exists for all cases. At most of the time, evaluation criteria for remediation technologies involve destruction and removal efficiency (DRE) and treatment cost. However, the environmental impact of the whole treatment process should be considered with high priority in the selection of a remediation technology. Several methods were developed for assessing the environmental impact, which reveals a wide diversity of approaches from the point of view of objectives, concepts and potential users. For example, environmental risk mapping (ERM) approach generally deals with a single environmental impact, such as the risk of nitrate leaching [15] or pesticide transportation [16]. Multi-agent system (MAS), multiple linear programming approaches (LP) and analytic hierarchy process (AHP) was used to evaluate the environmental impacts from groundwater quantity management, chemical production optimization and construction of a sustainable farming system, respectively [17–19].

As far as we are aware, there has until now been no systematic study that objectively correlate environmental impacts and benefits of various PCB treatment technologies. Life cycle assessment (LCA) is an internationally standardized methodology for systematic and quantitative evaluation of environmental impacts [20] of functionally equivalent products or services through all stages of their life cycles, which was widely used in soil and groundwater remediation to evaluate the negative and positive impacts concerned [21,22]. Related studies showed that LCA was an effective tool to identify environmental impacts and improve remediation technology in the trichloroethene, heavy metal and polycyclic aromatic hydrocarbon contaminated sites [23–25].

This study presents LCAs for (i) an infrared incineration technology disposal plant, and (ii) a BCD technology treatment plant for PCB contaminated wastes. The LCA framework was prescribed by ISO 14040.

## 2. Process descriptions

The flow diagrams of two selected PCB remediation technologies are shown in Fig. 1. Infrared High Temperature Incineration (IHTI) is a mobile thermal processing system that using electrically powered silicon carbide rods to heat organic wastes up to 1010 °C to destroy organic pollutants. It was used for the treatment of 34,000 tons of PCB contaminated soil at the Rose Township Dump Superfund Site in 1992–1993 [26]. For BCD process, PCBs are firstly separated from the soil by thermal desorption, then they are treated in a chemical dechlorination process, which transforms PCBs, dioxins and furans into non-toxic compounds. BCD technology was ever used to treat a total of 81,600 tons of PCB contaminated soil in the Warren County PCB Landfill site, Warren County, North Carolina.

The input data of energy and materials consumption for IHTI were obtained from the report of on-site incineration at Rose Township Dump Superfund site. In the IHTI plant, PCB contaminants excavated from the stack pile are firstly screened to remove debris greater than 1 inch in diameter using a portable three-tiered screen. Screened soils are blended with fuel oil to raise its heat content to 1167.4 kJ/kg. Mixed soils are sent to the primary combustion chamber (PCC), where the contaminated material could be heated at temperatures up to about 1000 °C at a residence time greater than 15 min. Ash and off-gas discharged from the PCC then enter the secondary combustion chamber (SCC) for further destruction, where the temperature is up to about 1100–1300 °C. Excess combustion air is provided in the secondary combustion chamber by a blower. Ash and off-gas from the SCC are quenched with a water spray that reduces its temperature to less than 120 °C. The off-gas from the quench is then routed to a low energy venturi scrubber to remove particulates. Water is injected into the venturi scrubber, and the pH in the venturi scrubber is controlled by the addition of a 10% caustic solution. The off-gas is then sent to a packed column chemical scrubber to remove acid gas. To improve the removal efficiency, the off-gas is then sent to a high energy venturi scrubber to remove particulates and heavy metals. After passing the low and high energy scrubber, the gas passed through a high efficiency munter chevron mist eliminator, and then to an exhaust stack with an inside diameter of 80 cm and a height of 11 m. Two induced draft fans maintain a negative pressure in the system.

The input data for BCD were mainly obtained from the actual remediation case in a technology transfer report: Production Base Catalyzed Decomposition Process Guam, Mariana Islands [27]. In the BCD process, PCB contaminated soil is firstly crushed, mixed with sodium bicarbonate in a pug mill, and fed into an indirectly fired Rotary Kiln Reactor (RKR), which is a standardized calciner with a carbon steel inner shell. In the RKR, the PCBs and naturally occurring organics are driven off from the soil at temperature up to 400 °C. The bicarbonate could catalyze BCD process by decomposing the PCBs and causing them to be desorbed at reduced temperatures. The air capture system started in the calciner where steam is injected as the sweep gas to carry out the desorbed PCBs. The oxygen content in the calciner is too low to support combustion, so there is no danger of combustion occurring and creating an overpressure that would result in releasing of contaminants from the calciner. The RKR off-gas passes through a cyclone to remove larger dust particles, and then into a wet electrostatic precipitator

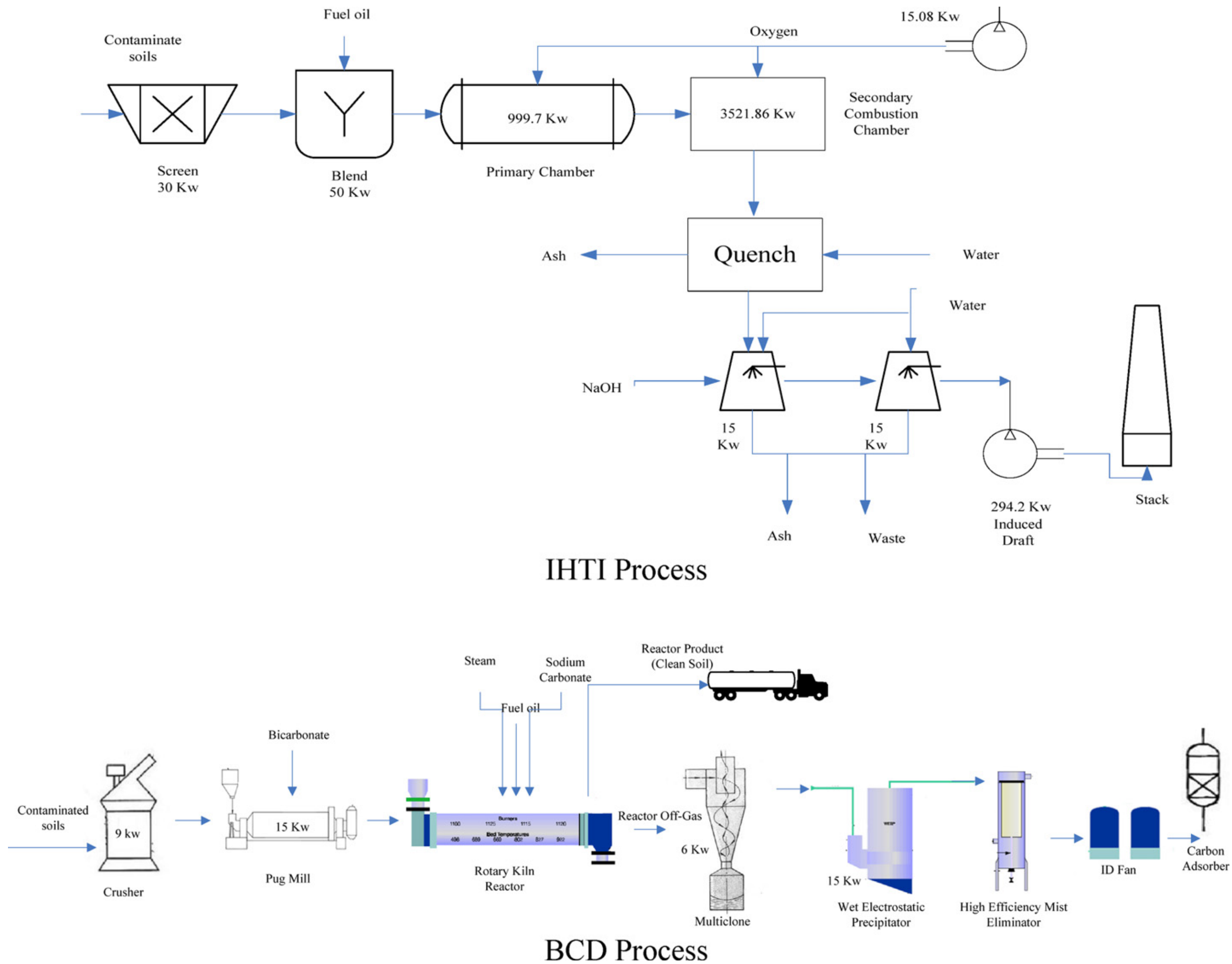


**Fig. 1.** The process flow diagrams of incineration and BCD technologies.

(WESP) where almost all the contaminants are removed. Additional steam is injected into the WESP as necessary to maintain a low oxygen level in the gas. Low oxygen levels ensure that dioxins are not formed. In the WESP, the gas passes through a shell-and-tube heat exchanger where the steam is condensed. In addition to maintaining low oxygen levels, another great advantage of using steam as an inert gas is that it can be easily removed from the gas. Gas leaves the condenser at about 26.7 °C. For final purification, the off-gas was chilled to 4.4–10 °C and passes through a high efficiency mist eliminator (HEME) and a carbon absorber. Because the WESP removes most of the PCBs and other condensable organics, the HEME and carbon absorber could have a very long life. A final post-treatment stage is undertaken to dispose of the dust and wastewater generated.

## 3. Life cycle assessment

LCA (also known as life cycle analysis and cradle-to-grave analysis) is a technique to assess the impacts that a product or process making on the environment throughout its life span. The procedures of LCA are part of the ISO 14000 environmental management standards, which is carried out in four distinct phases [28–31]: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and (4) interpretation. In this study, we performed LCA of two PCB remediation technologies using SimaPro 7.2 and Impact 2002+ method developed by PRé Consultants to model products and systems from a life cycle perspective [32].

### 3.1. Goal and scope definition

The goal of this life cycle assessment was to compare environmental impacts of IHTI and BCD technologies for PCB treatment and detect high environmental impact processes for the purpose of improving their environmental performance and reducing substances consumption. The functional unit was the treatment of 10,000 tons of PCB contaminated soil from 800 to 1000 ppm to less than 5 ppm used as the basis for compiling the life cycle inventory of IHTI and BCD. The system boundary of LCA included both the first-order and second-order impacts, covering all the direct emissions and disposal and resources required for upstream electricity generation and chemicals manufacture. As IHTI and BCD have different PCB treatment capacities, we define no timeframe for the LCA in order to capture both long-term and short-term impacts.

Both of the life cycle stages for the IHTI and BCD system were grouped into five major subsystems: pre-treatment, treatment process, off-gas treatment, wastewater treatment and wastes treatment. Here, only operation phases were considered when analyzing

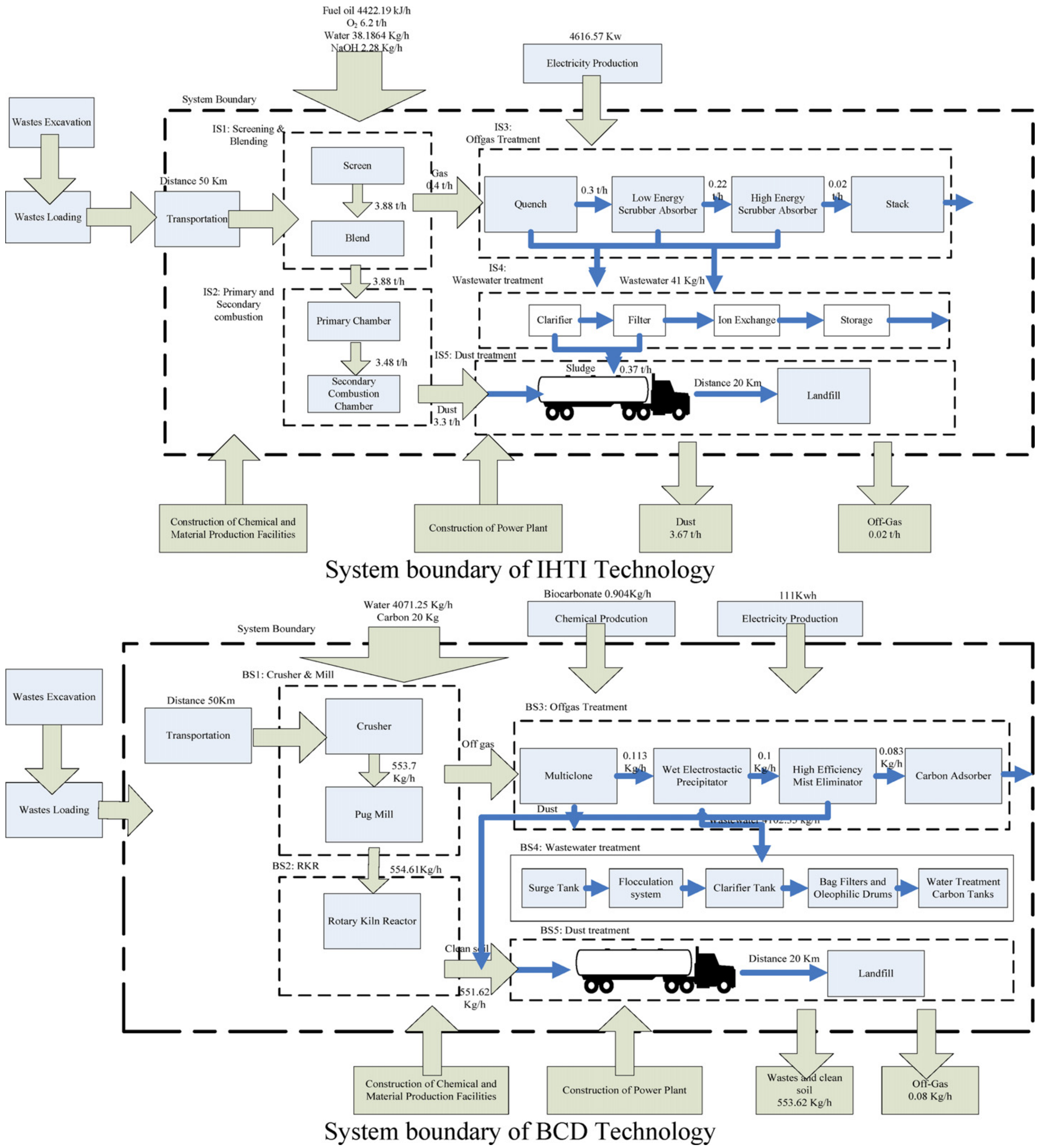


**Fig. 2.** System boundaries and process chain under study.

technologies. Impacts associated with the process of production of capital goods were excluded from this study taking into account the lack of data for the IHTI and BCD infrastructures. Also, several studies have shown the environmental impacts from the production of capital goods are insignificant in comparison to their operation stage [33,34].

The basic structure of these two technologies evaluated is similar and a detailed description of them is presented in Fig. 2.

#### 3.1.1. *System boundary of the incineration technology*

The pre-treatment subsystem of IHTI (IS1) includes the screening and blending processes. Energy carrier production and chemical production were not included in this subsystem. The PCB-containing soils are excavated from the contaminated site and transported to the ex-site treatment location. After pre-treatment, the PCB-containing soils are incinerated in the primary and secondary combustion chambers, which make up the incineration

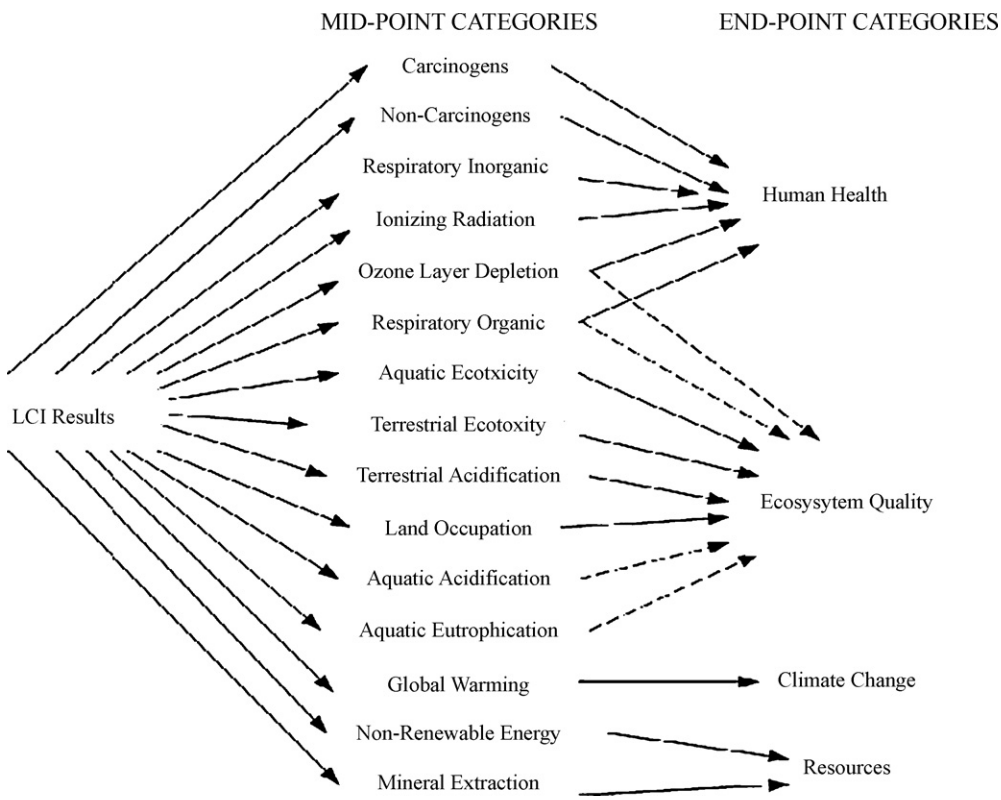


**Fig. 3.** Overall scheme of the IMPACT 2002+ framework.

subsystem (IS2). Off-gas and dust are generated after the IS2. The off-gas treatment subsystem (IS3) includes quench, low energy scrubber absorber, high energy scrubber absorber and stack. The off-gas is then emitted to the environment after IS3. Wastewater generated by the quencher and scrubbers is treated on the site with a wastewater treatment subsystem (IS4) consisting of clarification, filtration and ion exchange. The dusts generated in the incineration and sludge produced in the wastewater treatment are transported to the landfill, which were included in the dust treatment subsystem (IS5). Electricity consumption was especially important in most of the processes and was considered as a key environmental issue in all of the five subsystems. The transportation of PCB-containing soils from contaminated site to the ex-site treatment place was included in subsystem IS1. The average transport distance is assumed to be 50 km. Transportation of the dust to landfill was also included in IS5, while the average transport distance was set as 20 km.

*3.1.2. System boundary of the BCD technology*

The life cycle stages for the BCD technology were also grouped into five subsystems (as shown in Fig. 2). The pre-treatment subsystem (BS1) includes the crusher and pug mill processes. After pre-treatment, the PCB-containing soils are degraded in the rotary kiln reactor, which is the major BCD treatment subsystem (BS2). Off-gas and clean soil are generated after BS2. The off-gas treatment subsystem (BS3) includes the multiclone, wet electrostatic precipitator, high efficiency mist eliminator and carbon absorber. Then the off-gas is emitted to the air after BS3. Wastewater is mainly generated from the wet electrostatic precipitator and the high efficiency mist eliminator. The wastewater treatment subsystem (BS4) is a conventional process utilizing flocculation and clarification followed by filters and oleophilic media to remove oil, and finally carbon adsorption treatment. The clean soil and wastes generated in BS2 and BS3 are transported to a landfill, which makes up the dust treatment subsystem (BS5). The transportation of PCB-containing soils from contaminated site to the ex-site treatment place was also included in BS1. The average transport distance was assumed to be 50 km. Transportation of clean soil and wastes to landfill were included in BS5. The average transport distance was set as 20 km. Because transportation distances and transportation method were same for both BCD and Incineration, environment impacts generated from transportation were almost same.

## 3.2. Life cycle inventory

In the inventory analysis phase, inputs (energy and chemicals used) and outputs (emissions to the environment) associated with the BCD and IHTI treatment processes were listed in detail. In the impact assessment stage, inputs and outputs were interpreted in terms of their environmental impacts. The foreground life cycle inventory (LCI) data for these two technologies were compiled directly from the remediation reports of Navy Facilities Engineering Service Center and Rose Township Dump Superfund site [35]. The background life cycle inventory data (e.g., life cycle inventory of 1 kWh electricity, 1 kg of fuel oil, 1 kg of activated carbon) were provided by the Ecoinvent Database [36] based on average technology data, as implemented in SimaPro 7.2. These data are entirely European-based and were adopted without alteration for this study.

## 3.3. Life cycle impact assessment

The life cycle impact assessment (LCIA) methodology adopted for this study was IMPACT 2002+, as implemented in SimaPro 7.2 [37]. This methodology proposes a feasible implementation of a combined midpoint/end-point approach by linking all types of LCI results via 15 midpoint impacts to four end-point damages. Fig. 3 shows the overall scheme of the IMPACT 2002+ framework. The

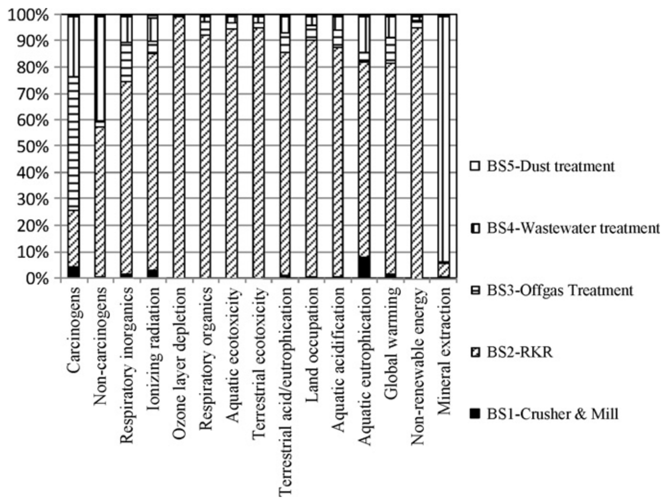


**Fig. 4.** The percent contribution of different subsystems of BCD technologies to each midpoint impact category.

solid arrows symbolize that relevant impact pathways are known or assumed to exist. Dotted arrows indicate that these uncertain impact pathways between midpoint and end-point levels are not modeled quantitatively.

The environmental modeling in IMPACT 2002+ was entirely based on European conditions and was adopted without change for this study, so the conclusions are strictly limited to this context. Fig. 4 shows the relative contributions of different subsystems to each midpoint impact in BCD technology. It could be found that BS2 presents the highest contribution to almost all midpoint categories excluding mineral extraction and carcinogens. BS3 and BS4 also make significant contributions to carcinogenic and non-carcinogenic impacts, respectively. It is necessary to remark that BS4 contributes to more than 90% of total mineral extraction. In the midpoint of carcinogens, BS2 and BS4 generate roughly equivalent proportions, following BS3 process. BS5 shows a very low level contributes to almost all the midpoint impacts, except the aquatic eutrophication effect. It was mainly caused by emissions of organic compounds generated by the final disposal process.

Fig. 5 shows the percent contribution of different subsystems of IHTI technology to each midpoint category. When compared with the BCD technology, the IHTI process showed different characteristics in its five subsystems. For all of the midpoint impacts, IS2 shows a very high contribution to almost 50% of all the categories except ionizing radiation, aquatic ecotoxicity, aquatic eutrophication and mineral extraction. IS3 presents a significant contribution to aquatic ecotoxicity (86%), ionizing radiation (57%) and mineral extraction (35%). IS4 contributes about 31% to ozone layer depletion. IS4 also generates high contribution to the midpoint impacts of aquatic ecotoxicity and aquatic entrophication.

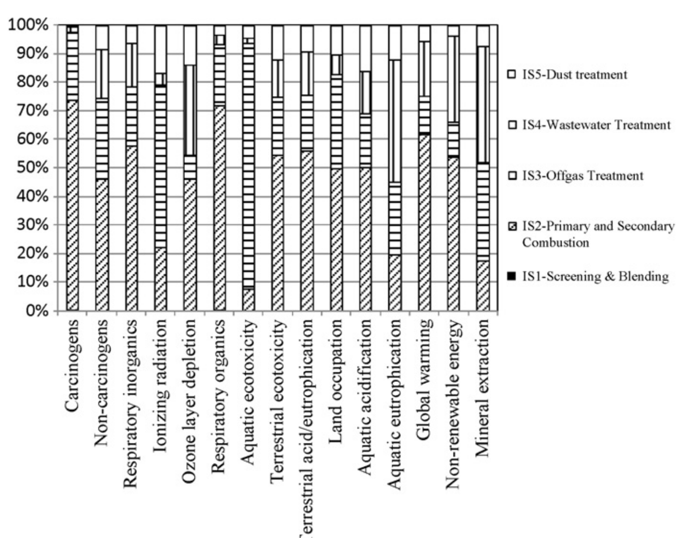


**Fig. 5.** The percent contribution of different subsystems of IHTI technologies to each midpoint impact category.

To identify the major environmental impacts in all of the ten subsystems, the energy, electricity and chemicals consumption were also analyzed in this study, which contribute to both the midpoint and end-point impacts. Fig. 6 shows the LCIA results of selected midpoint impacts for all of the ten subsystems. The results were expressed in terms of common reference substances for each environmental midpoint impact (e.g., kg $CO_2$-eq for global warming, kg $C_2H_3Cl$-eq for carcinogens). A positive values indicate an adverse environmental impact. The higher the value, the worse the impact. Both of the midpoint and end-point environmental impacts were calculated according to the IMPACT2002+ method.

*3.3.1. Non-renewable energy*

The midpoint impact of non-renewable energy was commonly expressed in MJ-total primary. Characterization factors for non-renewable energy consumption, in terms of the total primary energy extracted, were calculated by the upper heating values taken from Ecoinvent Database [37].

It could be found that the non-renewable energy midpoint impact was mainly caused by BS2, IS2 and IS4. For BCD technology (shown in Fig. 4), the fuel oil and diesel consumed in BS2 to provide the reducing condition contributed mostly to this midpoint impact. In BS2 process, diesel was injected to heat the RKR to about to 400 °C to drive off PCBs from the contaminated soils. The diesel consumed in this stage was about 50.47 gallon/h. The characterization factor for the diesel was 1.1683 MJ-total primary/MJ, so Non-renewable energy of diesel was about 43,139,361 MJ-total primary. At same time, the characterization factor for the fuel oil was 42 MJ-total primary/kg, so effect from the fuel oil is 89,769,619 MJ-total primary.

For IHTI technology, electricity used in IS2 and activated carbon to treat wastewater in IS4 were the major contributors to non-renewable energy consumption. The non-renewable energy consumption of electricity and heat are 41,129,257 and 43,071,448 MJ-total primary, respectively. The activated carbon consumption shows a little higher impact, which was about 50,581,197 MJ-total primary.

*3.3.2. Carcinogens and non-carcinogens*

The midpoint impacts of carcinogens and non-carcinogens could be classified to estimate the cumulative toxicological risk and potential impacts associated with a specified mass of a chemical emitted into the environment. These were also determined with IMPACT 2002+ model in SimaPro 7.2, which models risks and potential impacts per emission for several thousand chemicals [38]. Chloroethylene ($C_2H_3Cl$) emitted into environment was used as the reference substance for both carcinogenic and non-carcinogenic effects. Moreover, the chemical of benzo(a)pyrene was defined as the main source of these two midpoint impacts, which contributes highly to carcinogenic and non-carcinogenic impacts for the two technologies. The characterization factor of carcinogens is 52,029 kg $C_2H_3Cl$/kg benzo(a)pyrene, while that of non-carcinogens is 22.14 kg $C_2H_3Cl$/kg benzo(a)pyrene.

For BCD technology, non-carcinogenic impact was mainly caused by the off-gas and wastewater treatment processes. The rotary kiln reactor process' contribution to non-carcinogens is about 25,263.37 kg $C_2H_3Cl$. Furthermore, $Al(OH)_3$ used in

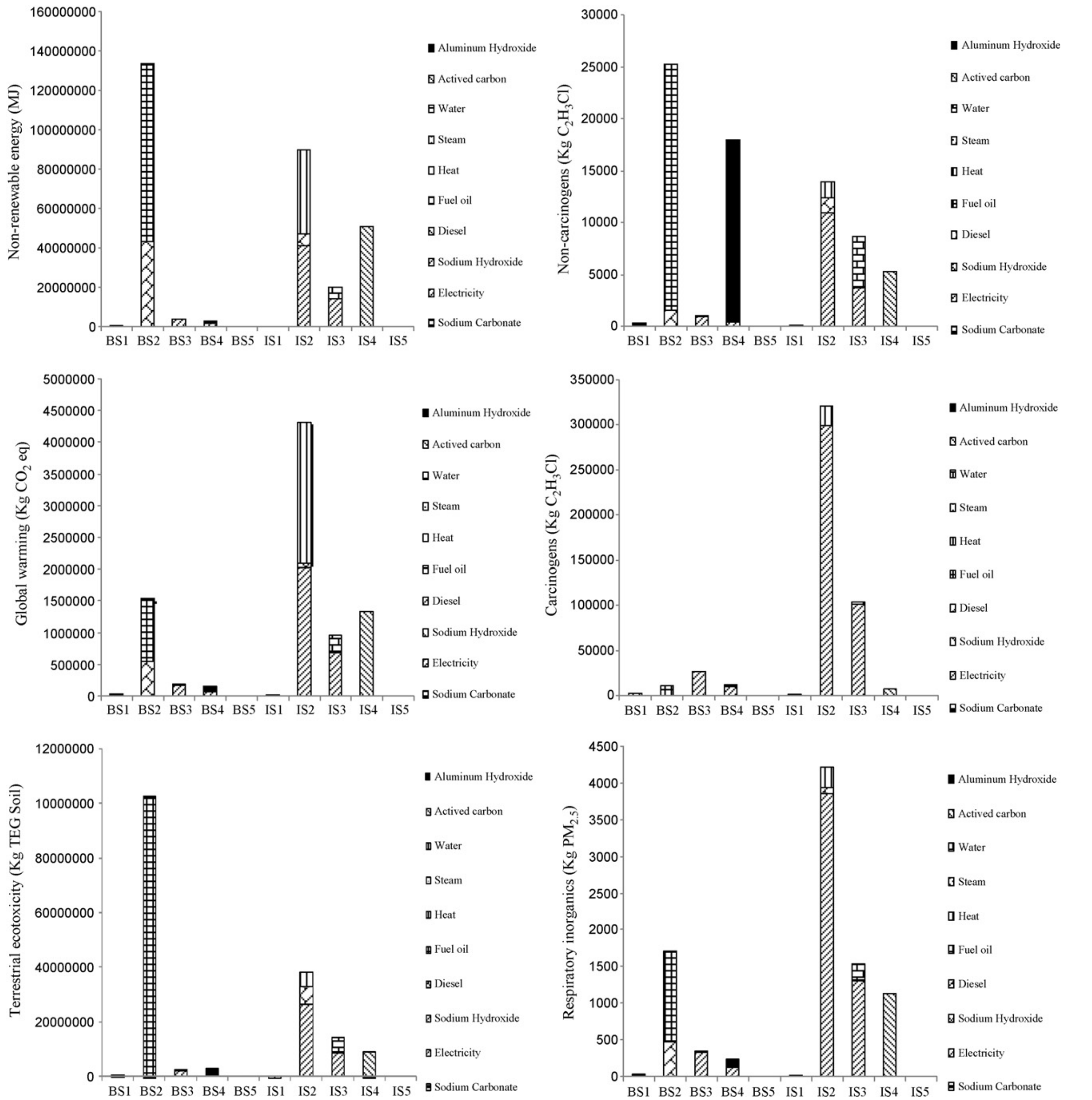


**Fig. 6.** Selected midpoint life cycle impact assessment results. The results are expressed in terms of a reference unit for each environmental impact category (e.g., kg $CO_2$-eq for global warming, kg $C_2H_3Cl$-eq for carcinogens). Values indicate an adverse environmental impact. The higher the value, the worse is the impact.

wastewater treatment process was another major source to non-carcinogens, which was mainly generated from the production of $Al(OH)_3$. For IHTI technology, primary and second combustion contributes a lot to this midpoint impact. The characterization value of electricity consumed was about 10,891.36 kg $C_2H_3Cl$.

For carcinogenic impact, the total carcinogenic effect in IHTI technology was much higher than that of BCD technology. Off-gas treatment process in BCD contributes highest to this midpoint impact and its carcinogenic characterization value is about 26,142.57 kg $C_2H_3Cl$. The carcinogenic impacts of BS2 and BS4 are nearly same. For IHTI technology, carcinogenic impacts are mainly caused by IS2 and IS3 processes. Carcinogenic characterization value of IS2 is about 321,149.5 kg $C_2H_3Cl$, which is mainly caused by its high electricity consumption.

### 3.3.3. Global warming

The characterization factors for global warming midpoint impact (kg-$CO_2$ into air/kg-emi) were taken from the IPCC list [39]. Characterization factors were given for emissions into air only. The $CO_2$ generated during non-renewable energy consumption was considered to be the highest contributor to this midpoint impact. Electricity production followed by heat consumption in IS2 was observed as the major responsibility for global warming. The characterization factors of electricity and heat are 0.61 kg-$CO_2$/kWh and 0.06 kg-$CO_2$/MJ, respectively. The total electricity used in IS2 was about 2,577,536 kWh, while the heat consumed was as high as 32,683,247 MJ. Production of chemicals (specifically, NaOH used in IS4) was also identified as an important contributor. The global warming of NaOH is about 1,328,240 kg-$CO_2$. Furthermore, the

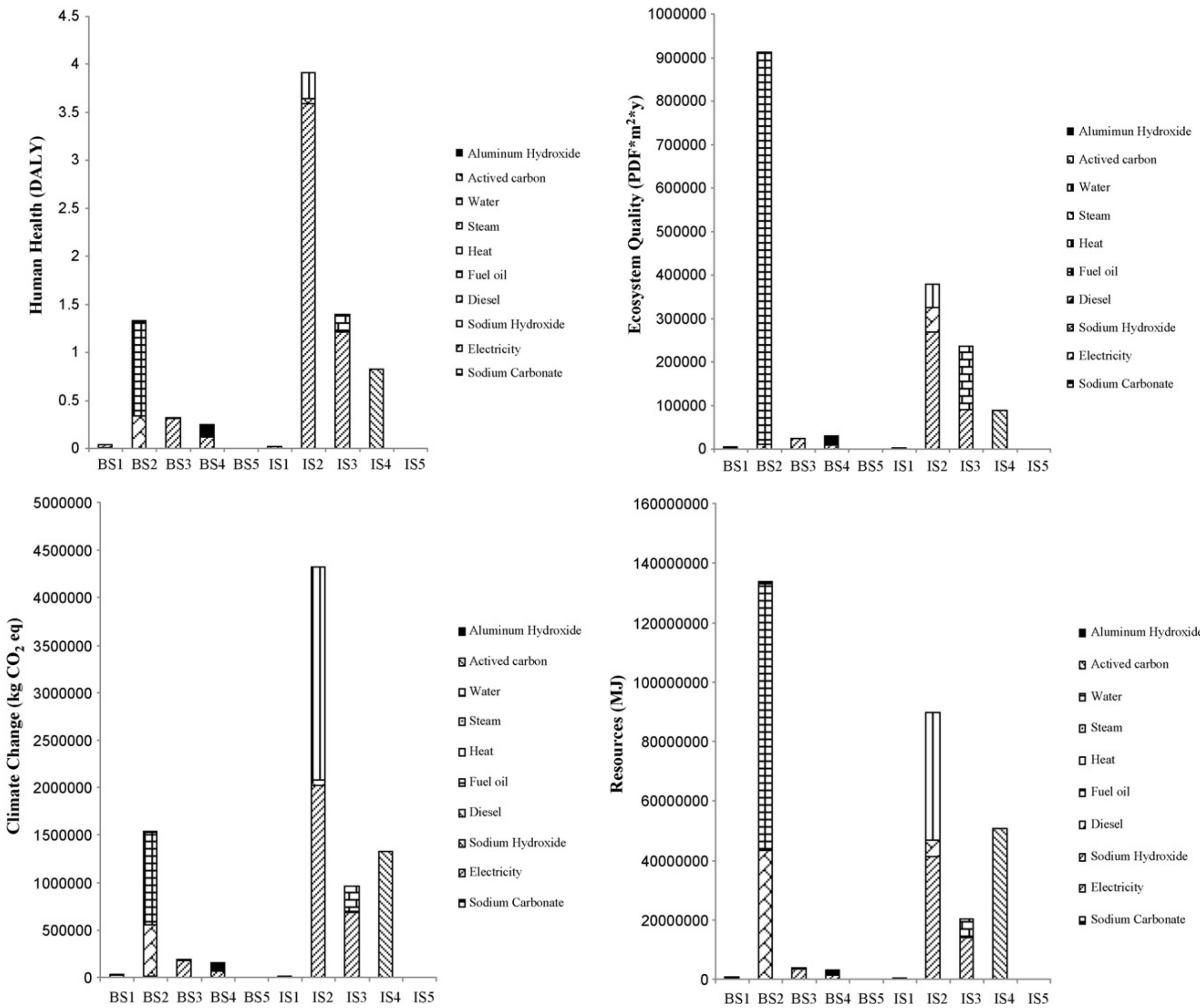


**Fig. 7.** Endpoint life cycle impact assessment results. The results are expressed in terms of "DALY" (disability-affected life years) for human health, "PDF*m$^2$*y" (potentially disappeared fraction of species, integrated over an area and time) for ecosystem quality, kg $CO_2$-eq emissions for climate change, and primary energy usages (MJ) for resources consumption.

production of heat steam contributed to about 30% of total global warming.

### 3.3.4. Terrestrial ecotoxicity

For the midpoint impact of terrestrial ecotoxicity, it was estimated that substances show ecotoxic effects only by exposition through the aqueous phase in soil. So the terrestrial ecotoxicity potentials were calculated in a similar way as aquatic ecotoxicity potentials. Characterization factors are given for emissions into air, water and soil. This midpoint was obtained by dividing the damage factor of the considered substance by the damage factor of the reference substance (kg triethylene (TEG) into soil/kg-emi). The characterization of terrestrial ecotoxicity is about 116,096.01 kg TEG into soil/kg. In this study, BS2, IS2 and IS3 contributed a lot to this midpoint impact. The fuel oil consumption in BS2 and electricity in IS2 were the major contributors to about 85% of total terrestrial ecotoxicity. According to the IMPCAT 2002+ method, fuel oil and electricity presented to characterization factors were about 47.4 g/kg fuel oil and $4.65 \times 10^{-5}$ kg/kg electricity, respectively. So terrestrial ecotoxicity from fuel oil in BS2 and electricity in IS2 were $1.02 \times 10^8$ and $0.26 \times 10^8$ kg TEG into soil. The IS3 process contributed about 13% of the total terrestrial ecotoxicity in IHTI technology.

### 3.3.5. Respiratory inorganics

Respiratory inorganics effects were taken directly from Eco-indicator 99 [40]. This midpoint has been obtained by dividing the damage factor of the substance considered by the damage factor of the reference substance ($PM_{2.5}$ into air). $PM_{2.5}$ are all particles less than 2.5 μm. IS2 and IS3 processes contributed to about 60% and 20% of the total respiratory inorganics effect respectively due to large volume inorganic particles generated during the incineration process. Electricity used in IS2 and IS3 contributed to about 5168.23 $PM_{2.5}$ into air totally. The fuel oil and diesel consumed in BS2 also showed a high contribution to this midpoint impact (roughly 10% of the total impact). The characterization factors of fuel oil and diesel are 48.6 g $PM_{2.5}$/kg fuel oil and 0.58 kg $PM_{2.5}$/TJ diesel, so respiratory inorganics of these two substances are 1212.44 and 469.18 kg $PM_{2.5}$ into air respectively. The IS4 and BS4 contributed to 10% and 5% of total impact, respectively.

As shown in the scheme of IMPACT 2002+ (Fig. 3), all fifteen midpoint categories can be grouped into four end-point categories. Those four end-point categories were also calculated by respectively damage factors under the IMPACT 2002+. Fig. 7 shows the four end-point life cycle impacts of the ten subsystems in BCD and IHTI.

Further, we also compared the different end-point environmental damages between IHTI and BCD technologies. These results were

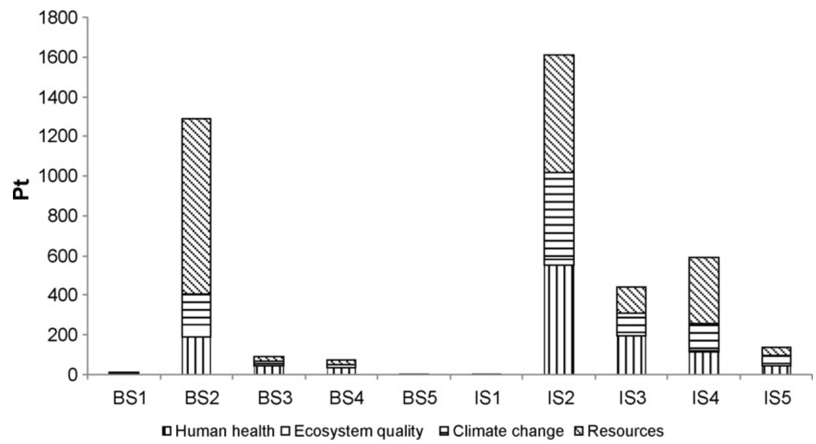


**Fig. 8.** Comparison of normalized endpoint scores of subsystems of two technologies.

normalized by comparing them against the environmental profile of an "average European", which is embedded in the IMPACT 2002+ LCIA methodology in SimaPro 7.2. The results of end-point damage were also shown in dimensionless units, together with a summed total score. The relative contribution of each subsystem to mid-point and end-point categories was also normalized by comparing against the environmental impacts caused by the average person in the European Union society. All end-point impacts were summarized to a single score for each of the two technologies. Fig. 8 shows comparison of normalized end-point scores of subsystems of the IHTI and BCD technologies.

In general, normalized score shows the environmental impacts generated during all subsystems and could be used as an important baseline for technology selection. The normalized results could be also provided for environmental officers and factory managers as a theoretical basis for the remediation technology optimization [31]. LCA enables us to identify environmental performances of each treatment subsystems, and decide which technology should be a better option from the environmental points. However, results are always calculated based on the user-defined systems and closely depending on the type of data used in the conduct of the study, which may result in uncertainties because of data availability, system boundaries and the choice of LCA method. The uncertainty was also performed and shown in Fig. 8 as a potential measure of the 'goodness' of LCA results [23]. The error bars in Fig. 9 indicated the 95% confidence interval for each result, which reflected the uncertainty in the background inventory data.

### 3.4. Life cycle assessment interpretation

#### 3.4.1. Incineration technology

To interpret the environmental impacts precisely, we compared the five subsystems of IHTI technology. The midpoint and end-point impacts were mostly generated by IS2, IS3 and IS4 (shown in Figs. 6 and 7). Nearly 85% of the total life cycle impacts arose from energy consumption in the operation phase.

It is important to note the global warming and the carcinogen are most important midpoint impacts from the five subsystems. The LCA results showed that about 432.35 kg $CO_2$-eq for the global warming is produced for the treatment of one ton of PCB-containing soil, which was mainly caused by the electricity production and consumption to keep high temperature to treat the PCBs. The value is very close to Kim's result, who used LCA to evaluate analysis of food waste disposal options from the perspective of global warming and the results indicated that about 410 kg $CO_2$-eq/f.u. was discharged through incineration of dry feed [41]. Additionally, volatile and semivolatile organics could be generated under the incompletely combustion. Some reports showed that toxic volatile and

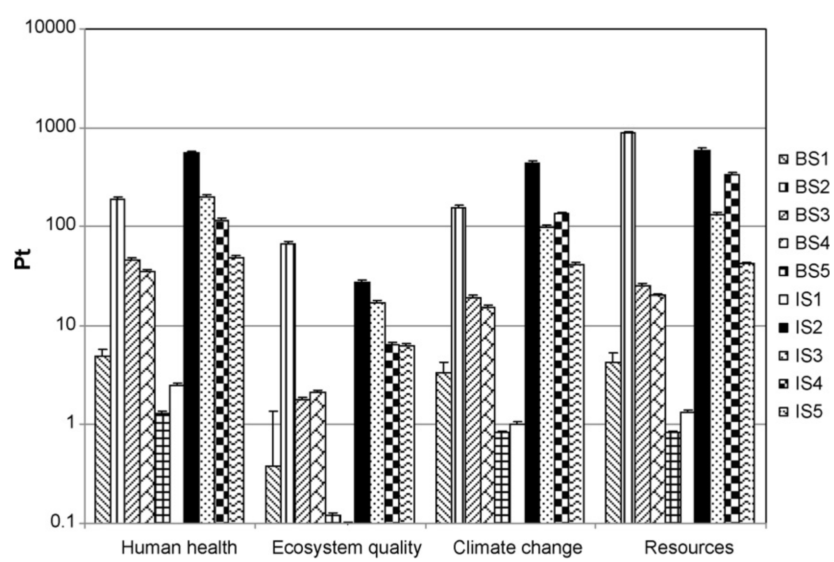


**Fig. 9.** Uncertainty analysis ranges of normalized endpoint scores under IHTI and BC.

semi volatile substances could be detected in the primary and secondary combustion chamber, e.g., the concentration of naphthalene was more than 1,640,000 μg/kg. Furthermore, 2.3.7.8-substituted polychlorinated dibenzodioxins and furans (PCDD/Fs) could be detected in the fly ash and bottom ash from the incineration [4,9]. The carcinogenic and non-carcinogenic impacts were almost 33.5 kg $C_2H_3Cl$-eq per ton PCB-containing soils. These were mainly caused by dusts and off-gas generated during the quench stage containing residue PCBs and particulates. In the off-gas treatment process, large volume of water was used to cool the off-gas and absorbers, which caused higher environmental impacts from the non-renewable energy consumption. The non-renewable energy impact was 8988 MJ-total primary per ton. The contribution of off-gas treatment to the midpoint of global warming was higher than other subsystems. According to the LCA results, the heat consumption contributes also higher to the terrestrial ecotoxicity. The production of chemicals represented about 15% to terrestrial ecotoxicity effect.

According to the results end-point impact analysis (Fig. 7), it could be found that the improvement of primary and secondary combustion efficiency could ease the negative impacts of human health and climate change from IHTI. Furthermore, the improvement of the off-gas treatment could effectively reduce the impacts of carcinogens, respiratory inorganics and non-renewable energy by decreasing in substance consumption, such as cooling water and activated carbon.

### 3.4.2. BCD technology

The LCA results showed that BCD technology for PCB-containing soils generated lower environmental impacts than Incineration technology. During the BCD technology, the most important midpoint environmental impact arises from the energy consumption in BS2 (shown in Fig. 6). The fuel oil and diesel consumption in the rotary kiln reactor contributes highly to the negative impacts of non-renewable energy consumption, non-carcinogens, global warming, terrestrial ecotoxicity and respiratory inorganics. The global warming impact was about 38.5 kg $CO_2$-eq per ton, which was less than that of IHTI technology. And the non-renewable energy impact was about 688.56 MJ-total primary per ton PCB contaminated soil. The respiratory inorganics category was about 2295 kg $PM_{2.5}$-eq to 10,000 tons of PCB-containing soils.

The carcinogenic impact was about 9.58 kg $C_2H_3Cl$-eq per ton totally, which was mainly from the electricity consumption in off-gas and wastewater treatment and the fuel oil consumption in the rotary kiln reactor. We can adjust the spray method of HEME in off-gas treatment process to reduce the water consumption and improve the absorption efficiency of off-gas to lower the environmental impacts of respiratory inorganics and carcinogens.

Also, the end-point damages of BCD technology were mainly from fuel oil and diesel consumption in BS2 (Fig. 7). Especially in end-point damages of ecosystem quality and resources, contributions of rest subsystems could be neglected when comparing to BS2's contribution. The optimization of BS2 process by using high effective alternatives of hydrogen donor and improving heat efficiency is the key factor to reduce the environmental impacts of BCD technology. As soils after disposing was clean, so the environmental impacts generated from the landfill stage were so low that they can be ignored. Only the transportation of clean soils to the landfill generated little environmental impacts.

### 3.4.3. Comparison of the two technologies

Though the results of midpoint environmental impacts are complicated, we can compare the two technologies by the end-point impacts. Based on the single score, we can preliminarily conclude that the environmental impacts of BCD are less than that of incineration. The total single score of BCD is 1468.97 Pt while incineration's score is 2785.15 Pt (shown in Fig. 8). The negative impacts from resource damage contribute almost half of the total score both in BCD and IHTI. Moreover, our LCA results showed that resource consumption from non-renewable energy should be concerned especially in the rotary kiln reactor process of BCD technology, which contributes much higher than the primary and secondary combustion, off-gas treatment and wastewater treatment processes of ITHI technology. The LCA comparisons of these two technologies could be served for environmental officers and factory managers as a theoretical basis on which a remediation technology can be chosen. If a new PCB remediation plant would be built in a developing country, where there is no exiting high temperature incinerators, BCD technology might be a better choice due to lower environmental impacts. The negative environmental impacts could be also reduce for existing incineration facilities, however, by increasing the combustion efficiency, reducing energy consumption and decreasing exhaust emissions in the off-gas treatment.

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