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Economical and ecological comparison of granular activated carbon (GAC) adsorber refill strategies

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Abstract

Technical constraints can leave a considerable freedom in the design of a technology, production or service strategy. Choosing between economical or ecological decision criteria then characteristically leads to controversial solutions of ideal systems. For the adaptation of granular-activated carbon (GAC) fixed beds, various technical factors determine the adsorber volume required to achieve a desired service life. In considering carbon replacement and recycling, a variety of refill strategies are available that differ in terms of refill interval, respective adsorber volume, and time-dependent use of virgin, as well as recycled GAC. Focusing on the treatment of contaminant groundwater, we compare cost-optimal reactor configurations and refill strategies to the ecologically best alternatives. Costs and consumption of GAC are quantified within a technical–economical framework. The emissions from GAC production out of hard coal, transport and recycling are equally derived through a life cycle impact assessment. It is shown how high discount rates lead to a preference of small fixed-bed volumes, and accordingly, a high number of refills. For fixed discount rates, the investigation reveals that both the economical as well as ecological assessment of refill strategies are especially sensitive to the relative valuation of virgin and recycled GAC. Since recycling results in economic and ecological benefits, optimized systems thus may differ only slightly.

Keywords: Granular activated carbon (GAC); Sorption; Reactivation; Recycling; Economic assessment; Life cycle assessment (LCA); Life cycle impact assessment (LCA); Groundwater treatment

1. Introduction

The use of granular-activated carbon (GAC) is a common method for the decontamination of polluted water. In municipal and industrial wastewater treatment plants, or groundwater clean-up facilities, water passes through fixed-bed adsorbers, which retain preferably lipophilic compounds such as a broad range of organic chemicals. The volume of water that can be properly treated by a certain amount of GAC is limited, depending on the specific sorption capacity of the GAC type in use. The sorbent has to be exchanged when contaminant concentrations exceed thresholds at the reactor outlet.

Several methods and tools have been proposed to estimate the service life of GAC adsorbers (Rosen, 1952, 1954; Crittenden et al., 1986; Kilduff et al., 1998; Heijman and Hopman, 1999; USACE, 2001; Wigton and Kilduff, 2004). Depending on the physico-chemical

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boundary conditions during water treatment, the performance of the specific GAC type and its price, as well as the economically optimal refill intervals and their respective GAC volumes can be derived. In this study, a concept is presented to address this issue by using an existing adsorption model within an economic analysis in order to support the planning and design of fixed-bed adsorbers. The investigation highlights a typical GAC type used for treatment of synthetic organic chemicals. Decision parameters for the system design are examined by a sensitivity analysis in order to identify relevant design criteria and qualify the general validity of the observed relationships.

From the ecological point of view, a critical question is whether clean-up measures though passing particular environmental amendments result in an overall benefit for the presented environmental situation. While valuing the overall environmental benefit of (ground-) water, clean up is beyond the scope of this paper, we ask how the negative environmental impact by manufacturing and providing GAC can be minimized. Based on the outcome of life cycle analyses of virgin and reactivated GAC, refill strategies which have been identified to be cost-effective are also qualified in terms of their ecological impact.

2. Life cycle assessment of GAC

2.1. Framework

Life cycle assessment (LCA) has evolved as *the* method for analyzing the environmental aspects of a product from raw material extraction through production, use, disposal and/or recycling. The broad range of different LCA realizations is oriented at the ISO 14040 series of standards (ISO, 1997, 2000), which provide the basic conceptual outline and subdivide the methodic elements based on these standards. LCA reports emissions on a chosen functional unit basis such as the production and consumption of mass units of GAC (Rebitzer et al., 2004). After the definition of processes during production, usage and service of goods, an inventory is established in order to structure all inputs and outputs of materials and energy during each life cycle period. During the successive life cycle impact assessment (LCIA), the flows of materials and energy are assigned to environmental impact categories. The interpretation of the results can be carried out in relation to individual types of impact categories as well as the total environmental burden (e.g., Volkwein and Klöpffer, 1996; Ross and Evans, 2002).

Within this study, the LCA methodology was used to evaluate a selected type of GAC. For the set up of the inventory, we used the software tool UMBERTO (Schmidt and Häuslein, 1997) from among a variety of different methods and tools that map life cycles of water treatment facilities and measurements (e.g., Beinat et al., 1997; Tillman et al., 1998). It comprises detailed and recently updated databases and models for calculation and visualization of material and energy flow systems.

The outcome of the LCIA is utilized to characterize GAC production, use and recycling with respect to energy consumption, ecological, as well as human health consequences. Estimates of the environmental impact per GAC mass are derived separately for the following common categories (ZAG, 2003):

- depletion of energy resources (DER): indicator in crude oil equivalents representing the energy consumption of fossil fuels with removal from the environment,
- global warming potential (GWP): emissions are evaluated according to their potential to cause global warming compared to CO_2 over a time horizon of 100 years,
- photochemical ozone creation potential (POCP): NO_x corrected emissions of substances with potential to form ozone,
- acidification potential (AP): indicator signifying acid emissions,
- human toxicity potential (HTP): cancer-risk potential of emissions,
- terrestrial eutrophication potential (TEP): adverse ecosystem effects by nutrient enrichment of soils in phosphate equivalents.

The estimated indicator values for these six categories are employed for the environmental evaluation of the GAC refill strategies analyzed below. Due to the lack of reliable data sources, further relevant categories such as those denoting stratospheric ozone depletion or land use (Pennington et al., 2004) are not considered. Equivalent to examining the terrestrial eutrophication potential, an impact category which reflects the adverse growth of aquatic biomass due to nutrient enrichment could be included. However, since this aquatic eutrophication potential is particularly controlled by wastewater production, and the amount of wastewater that accrues during GAC life cycle is relatively low, it is neglected here.

2.2. GAC life cycle

GAC types can differ strongly in their physico-chemical properties. Numerous carbon-rich raw materials are available as precursors, e.g. coal, nutshells or olive waste cakes, which are processed by specified manufacturing techniques (Bansal et al., 1988; Marsh, 2001). Since a comprehensive LCA of distinct GAC types is beyond the scope of this paper, we focus on

GAC produced out of hard coal which is prevalently used in Central Europe. Manufacturers' information of, among others, CarboTech (Henning and Degel, 2001) and Chemviron (2004) served as the basis for the setup of the inventory.

The main processes during the production of this GAC type are wet grinding of coal, mixing with binding agent, creation of briquettes, oxidation, drying, carbonization, activation, crushing, sieving and packaging. The crucial step is the activation procedure, a selective high-temperature treatment of the carboniferous precursor resulting in a highly porous material. Steaming with water vapor and CO_2 yields partial coal gasification at temperatures between 800 and 1000 °C. During this procedure, 60% of the original weight is lost. The demand of raw material is specified as 3 tons hard coal per 1 ton GAC. In order to describe the power consumption, an energy figure of 1600 kWh is presumed. For 1 ton GAC, 12 tons of water vapor are required, which are heated by burning 330 m^3 natural gas.

A conventional practice to save money, resources and obviate liabilities associated with GAC disposal at off-site facilities is the recycling of used GAC. In some cases, however, recycling may not be practicable, especially if GAC is contaminated with poly-chlorinated biphenyls (PCBs), dioxins, and heavy metals (USACE, 2001). In some cases, on-site recycling facilities are used. Reactivable GAC, in this study, is treated off-site at similar conditions to those during virgin GAC production. After drying at 100 °C, the GAC is heated to over 700 °C to degrade sorbed contaminants. Residual components clogging the micropores are then gasified through reacting with vapor at temperatures between 800 and 1000 °C. The weight losses during reactivation vary between 5% and 15% (Faust and Aly, 1987). A mean value of 10% is assumed here.

The emissions caused during transport of materials are highly dependent on the local conditions and might vary considerably. The transport distances are oriented at the current situation in Germany within this study. The system boundaries, transport procedures and inventory data are documented in Borken et al. (1999). According to Kohlenwirtschaft (2000), coal mining is expected to take place in Central Europe (65.4%), Eastern Europe (12.5%), South Africa (10.2%), Columbia/Canada/USA (7.8%) and Australia (4.1%). The distance between manufacturing/reactivation and treatment facility is set at 400 km. This lumped value is rather arbitrary, but a preliminary sensitivity analysis showed only a minor influence of the GAC transport assumptions (ZAG, 2003).

2.3. Estimation of indicator values

The indicator values are supposed to be directly proportional to the number of functional units produced, reflecting a general concept in LCA with linear relationships between human activities and environmental impact (Heijungs et al., 1992; Azapagic and Clift, 1999). Table 1 lists the calculated indicator values for the categories given in the respective emission equivalents for GAC production and transport. Recycling of GAC particularly means avoiding emissions resulting from mining and processing of raw coal. Furthermore, since the required amount of resources is comparably low, recycling yields relative savings between 25% and 70% for the categories DER, POCP, AP, TEP and of 90% savings for the GWP. Since activation and reactivation processes are comparable and both are the relevant production steps of carcinogenic emissions, the calculated HTP indicator value of recycled GAC reaches not less than 75% of virgin GAC.

A striking feature is the high emissions of CO_2 equivalents for virgin GAC, which subsume 11 times the mass of the final product. This especially denotes the high net loss of raw coal during the production process. The CO_2 equivalents spent for recycling reach only a tenth of this, reflecting the minor role of energy consumption during heating.

3. Economic evaluation of GAC

The cost of virgin GAC is dependent on type and usage. In retrospect, unit prices per kg have decreased during the last decades complicating predictions of future price development. Static prices are assumed for the presented study, which are staggered depending on

Table 1
Indicator values for selected impact categories for LCA of virgin and recycled GAC

Category	Abbr.	Virgin	Recycled	Transport	Unit
Depletion of energy resources	DER	0.90	0.33	3.5E−02	kg COE/kg GAC
Global warming potential	GWP	11.0	1.17	1.1E−01	kg CO_2/kg GAC
Photochemical ozone creation potential	POCP	1.2E−03	5.4E−04	2.4E−04	kg C_2H_4/kg GAC
Acidification potential	AP	5.8E−03	1.8E−03	6.6E−04	kg SO_2/kg GAC
Terrestrial eutrophication potential	TEP	5.2E−04	3.0E−04	1.3E−04	kg PO_4^{3-}/kg GAC
Human toxicity potential	HTP	4.2E−08	3.2E−08	1.5E−08	kg As/kg GAC

the mass of GAC required for one fixed bed reactor fill:

$$\mathrm{GACC_{unit}} = aM^{\alpha}_{\mathrm{GAC}}, \tag{1}$$

where $\mathrm{GACC_{unit}}$ is the unit cost of one fixed bed fill (€/kg), a the (regression) unit price factor (€/kg$^{\alpha+1}$), M_{GAC} the GAC mass (kg), α the regression exponent ([−1,0]).

The cost of one fixed bed GACC is given by

$$\mathrm{GACC} = aM^{\alpha+1}_{\mathrm{GAC}}. \tag{2}$$

This concept of expressing reduced prices at growing purchase quantities by exponential approximations is an efficient technique used in numerous formulations and has been successfully tested for water treatment issues by Clark (1987) and Bayer (2003). Fig. 1 shows the unit costs of GAC that have been derived on the basis of a price survey for a number of manufacturers ($a = 3.5$€/kg$^{\alpha+1}$, $\alpha = -0.1$). The costs for reactivated GAC are expressed according to Eqs. (1) and (2), with savings of 50% compared to virgin GAC ($a = 1.75$€/kg$^{\alpha+1}$). The savings may vary depending on types of contaminants, GAC and special contracts with service companies (LUA NRW, 1998; USACE, 2001).

Total costs of long-term measurements are calculated by discounting future costs to net present values and summarizing present and discounted values. According to NRC (1997) the total expenditures $\mathrm{GACC_{tot}}$ (€) are derived by

$$\mathrm{GACC_{tot}} = \sum_t \frac{\mathrm{GACC}_t(1+p)^t}{(1+i)^t}, \tag{3}$$

where GACC_t (€) is the total cash disbursements for GAC in year t. Assuming that t_{GAC} is the service life of the fixed bed, then $t = 0,\ t_{\mathrm{GAC}},\ 2t_{\mathrm{GAC}}, \ldots,\ T - t_{\mathrm{GAC}}$. Parameter T defines the total number of years of expected expenditures, which equals the operation time. The variable p (−) represents the inflation rate and i (−) is the discount rate.

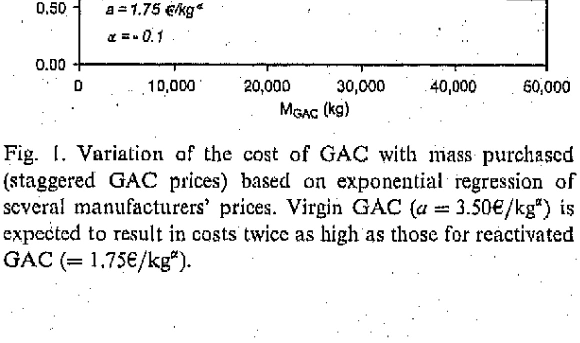

Fig. 1. Variation of the cost of GAC with mass purchased (staggered GAC prices) based on exponential regression of several manufacturers' prices. Virgin GAC ($a = 3.50$€/kg$^{\alpha}$) is expected to result in costs twice as high as those for reactivated GAC (= 1.75€/kg$^{\alpha}$).

4. Calculation of GAC consumption

4.1. General formulation

The adsorption of contaminants is described after Rosen's approach (1952, 1954), which assumes one (dominant) contaminant, plug flow and non-equilibrium sorption by contaminant diffusion into GAC particle pores. The service life t_{GAC} is derived by relating influent and target concentrations (C_{w}, C_{MCL}):

$$t_{\mathrm{GAC}} = \frac{M_{\mathrm{GAC}} n_{\mathrm{e}}}{Q\rho_{\mathrm{GAC}}} - \frac{M_{\mathrm{GAC}}}{Q\rho_{\mathrm{GAC}}}[K_{\mathrm{d,i}}\rho_{\mathrm{s}}(1-n_{\mathrm{e}})] \times \left[2\,\mathrm{arcerfc}\frac{2C_{\mathrm{MCL}}}{C_{\mathrm{w}}}\frac{r^2 Q\rho_{\mathrm{GAC}}}{15\mathrm{Dh_{app}}K_{\mathrm{d}}\rho_{\mathrm{s}}(1-n_{\mathrm{e}})M_{\mathrm{GAC}}} - 1\right], \tag{4}$$

where M_{GAC} is the fixed bed mass of GAC (kg), n_{e} the macroporosity of GAC, ρ_{GAC} the GAC bulk density (kg/m^3), ρ_{s} the GAC particle density (g/cm^3), r_{particle} the effective radius of particles (cm), Q the water flow rate (m^3/h), $\mathrm{Dh_{app}}$ the apparent diffusion coefficient (m^2/s).

The distribution coefficient K_{d} (cm^3/g) specifies the sorptivity of a substance assuming a linear isotherm (Schwarzenbach et al., 1993). It is derived from non-linear, Freundlich isotherm parameters (K_{F}, n_{F}) by

$$K_{\mathrm{d}} = K_{\mathrm{F}} C_{\mathrm{w}}^{(n_{\mathrm{F}}-1)}. \tag{5}$$

4.2. Specific system properties

From the broad range of different GAC types, we selected Filtrasorb TL 830 (Chemviron), which was tested by Tiehm et al. (2000) and Kraft and Grathwohl (2003) for the treatment of groundwater at the SAFIRA site in Bitterfeld/Germany (Merkel et al., 2000). They expose the material properties of Filtrasorb TL 830 and the relevant sorption parameters of a number of chlorinated hydrocarbons. For the subsequent analysis, perchloroethylene (PCE), trichloroethylene (TCE), *cis*-dichloroethylene (*cis*-DCE) and vinyl chloride (VC) are considered as contaminants in the water that has to be purified. The input parameters for the calculation of the GAC service life (Eqs. (4, 5)) are subsumed in Tables 2 and 3.

Fig. 2 depicts the calculated mass M_{GAC} for PCE- and *cis*-DCE-contaminated water assuming a service life of 1 year. The significantly lower sorptivity of *cis*-DCE (Table 2) results in likewise higher amounts of GAC than required in the case of PCE contamination. For example, at *cis*-DCE concentrations of

1000 mg/m^3 and a flow rate of 50 m^3/h, about 30 tons of GAC have to be supplied, while for PCE only one-tenth (ca. 3 tons) is required. Fig. 2 reflects further characteristics of Eq. (4): the required GAC masses are directly proportional to the flow rate, but rise non-linearly with the concentration. An increase of concentration results in a relatively minor growth of M_{GAC}, indicating a relatively better exploitation of GAC.

In order to analyze the influence of the required service life of the fixed bed fill, the influent contaminant concentrations are fixed at 1000 mg/m^3. The operation time is assumed to be 10 years. Independent of the contaminant type, required total GAC mass decreases slightly with increasing lifetime, i.e. decreasing number of (re-)fills (Fig. 3). This can be attributed to the sigmoid shape of the contaminant front propagating through the reactor, which causes a certain proportion of the GAC at the very end of the reactor to be incompletely loaded. As this proportion is independent of the reactor volume, its relative importance declines with decreasing number of refills.

5. Identification of cost-effective refill strategies and their environmental impact

For a first economic analysis of refill strategies, the rate of price increase is set equal to the discount rate. This means the total costs for supplying GAC can be summarized without temporal discounts. Apart from this, staggered prices (Eq. (1), $\alpha = -0.1$), i.e. a price reduction for volume purchases, are considered. The primary objective is to minimize total costs by selecting the optimal refill strategy. The ideal, most cost-efficient adaptation of a fixed-bed reactor depends on several decision factors that will be discussed subsequently.

Two factors are identified as antagonists for the resulting optimal number of refills. On the one hand, the required total GAC mass decreases with increasing reactor volume (see previous section), thus favoring

Table 2
Material properties of Filtrasorb TL 830 (Chemviron) after Kraft and Grathwohl (2003)

Material property TL 830	Abbrev.	
Macroporosity of GAC	n_e	0.53
GAC bulk density	ρ_{GAC}	0.4 kg/m^3
GAC particle density	ρ_s	1.2 g/cm^3
Effective radius of particles	$r_{Particle}$	0.1 cm

Table 3
Freundlich isotherm parameters of chlorinated hydrocarbons for Filtrasorb TL 830 (Chemviron) after Tiehm et al. (2000) and Mertz et al. (1999)

Contaminant	Abbrev.	Units	PCE	TCE	*cis*-DCE	VC
Maximum contaminant concentration value	C_{MCL}	mg/m^3	10	10	10	3
Freundlich constant	K_F	$[mg/l:(l/mg)^{n_F}]$	106.2	48.4	12.7	2.4
Freundlich exponent	n_F	—	0.52	0.59	0.53	0.62
Apparent diffusion coefficient	Dh_{app}	m^2/s	1.0E−12	1.0E−12	1.0E−12	1.0E−12

Concentration thresholds are oriented at European and American standards. The apparent diffusion coefficient is assumed to be constant for all contaminants.

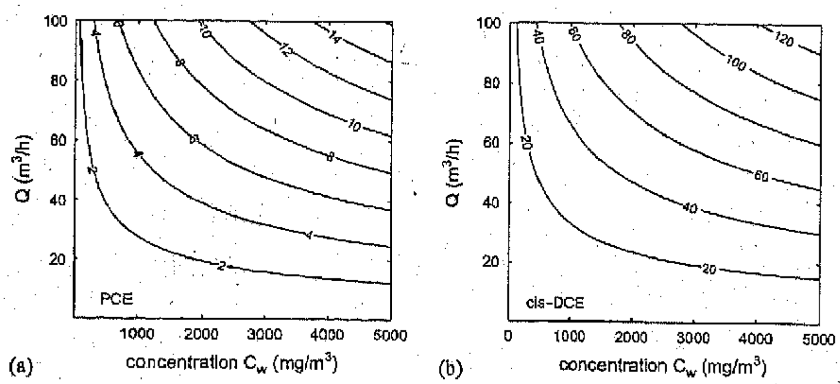

Fig. 2. Required mass of GAC (tons) for fixed-bed reactors for a service life of $t_{GAC} = 1$ year as a function of water flow rate Q and concentration of contaminant (a: PCE, b: *cis*-DCE).

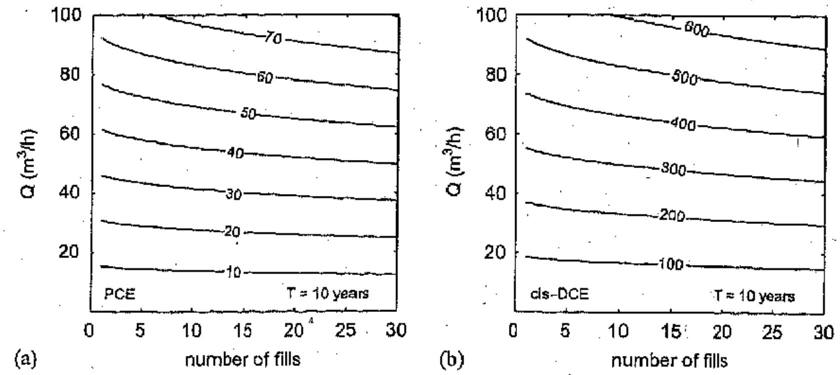

Fig. 3. Required total mass of GAC (tons) for fixed-bed reactors assuming constant contaminant concentrations in the influent water of $C_w = 1000\,mg/m^3$ (a: PCE, b: cis-DCE). The total operation time is set to $T = 10$ years, the service life t_{GAC} is given by the respective number of refills of a reactor.

large reactors. On the other hand, smaller GAC units yield benefits from both economic and ecological perspectives since the proportion of recycled GAC (which is cheaper and results in lower emissions than virgin GAC) increases with the number of refills. Hence, the relative valuation of fresh and virgin GAC in terms of economical or ecological criteria plays a central role for the ideal system adaptation.

Neglecting costs associated with the GAC exchange, the cost-optimal number of refills depends on the relative weighting of the prices of virgin and recycled GAC. For a cost ratio of 0.5, totally seven fills, i.e. a service life of the reactor equal to 17 months is optimal ($T = 10$ years, see Fig. 4). Assuming contaminant concentrations of $1000\,mg/m^3$, the calculated consumption of crude oil equivalents through production of GAC is three times higher than that by recycling (see Table 1). As a result, the optimal strategy in terms of this indicator value differs from the economically optimized strategy. The emission isolines of Fig. 5 delineate the lowest crude oil equivalents if the reactor material is changed every 10 months.

It should be noted that optimal refill intervals are independent of the water flow rate Q as there exists a linear relationship between water flow rate Q and GAC mass required (Fig. 2). Comparison of Figs. 4a and b (5a and b) shows that the contaminant type also does not change the optimal service life.

Fig. 6 depicts the trade-offs between number of fills and indicator values of the supply of virgin, recycled and total GAC. The optimal number of refills rises in the order of HTP < TEP < POCP < DER < AP < GWP reflecting the different ratios of indicator values for virgin and recycled GAC (Table 1). Note that for every reactor fill the indicator values for transport of (virgin and recycled) GAC are added. It is shown that increasing the number of fills above the optimal value means only a slight climb of emissions for all categories inspected (exception HTP). This is in accordance to the observations for economically optimized strategies demonstrated in Fig. 4. The prevailing reason for this is that the relative total mass of recycled GAC changes most between strategies with a small number of refills.

In contrast to a staggered price profile which tends to favor large reactor units, discounting in the case of interest rates surmounting the price increase rate (positive net interest rate) reduces the optimal service life. Figs. 7a and b show the influence of both factors on the ideal refill strategy. Expressing optimal service life as a function of the ratio C_w/C_{MCL}, we obtain design curves that are valid for any contaminant independent of the specific target concentrations at the outlet. Consequently, the individual net interest rates which reflect the financial situation and subjective planning of a company, have a strong impact on the refill strategy. The higher the interest rate, the higher the benefit from the future investments i.e. from shorter refill intervals. Within the considered range of $i = 2$–15%, the resulting cost optimal refill interval t_{GAC} changes by approximately 1 year (~1.7 years for $i = 2\%$, ~0.7 years for $i = 15\%$). It is noteworthy that influent and target contaminant concentration apparently exert only little influence on t_{GAC} compared to the financial factors discussed here.

A comparison of Figs. 7a and b further reveals the role of rebates on high purchase amounts (exponent in Eq. (1)). Without staggered prices ($\alpha = 0$), i.e. assuming unit costs independent from the purchase amount, the ideal service life is significantly shorter than in the case of a staggered price profile ($\alpha = -0.1$), indicating that benefits from price reductions support big reactors and long service lives, respectively. Note that in individual cases, optimal refill strategies will obviously differ from those depicted here, as specific price lists and contracts

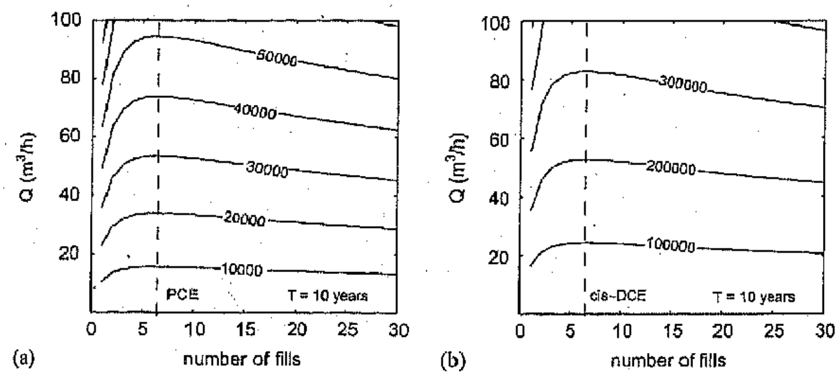

Fig. 4. Calculated total costs (€) for supply with virgin and recycled GAC for a total operation time of 10 years (without discounting, i = p). Influent concentration of PCE (a) or *cis*-DCE (b) is $C_w = 1000\,mg/m^3$. Dashed lines mark minimum cost strategy with 7 fills.

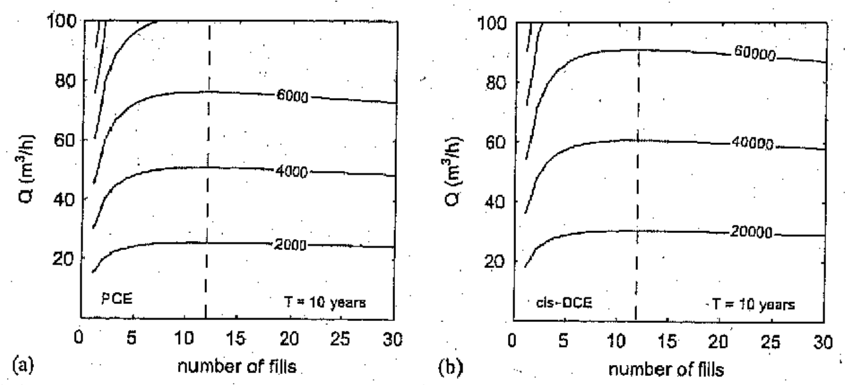

Fig. 5. Total crude oil equivalents (in thousands) for supply with virgin and recycled GAC for a total operation time of 10 years. Influent concentration of PCE (a) or *cis*-DCE (b) is $C_w = 1000\,mg/m^3$. Dashed lines mark minimum emission strategy with 12 fills.

with GAC suppliers apply. Additionally, particular changes of the results could be expected when trends of GAC prices over time are taken into consideration.

Fig. 8 illustrates the optimal service lives t_{GAC} if ecologic indicators are taken as design criteria. The results reflect the order among the indicators mentioned above, which is governed by the ratio of valuation between virgin and recycled GAC. The optimal refill interval t_{GAC} typically ranges between 4 and 24 months, indicating a remarkable influence of indicator-specific issues. An exception represents the human toxicity potential, for which the relative savings through recycling are the least.

Economically and ecologically optimal GAC lifetimes found here mostly correspond to common practice, which is virtually based on technico-economic considerations only. Keller et al. (2000) discusses bed lifetimes of 2–7 months for contaminant groundwater treatment, which are within the lower range of 2–17 months derived for cost-optimal strategies within our study. Compared to this, US EPA (2004) analyzed the cost-efficiency of pump-and-treat systems at leaking underground storage tank sites and estimate benefits from increasing common GAC life-times.

6. Conclusions

A model-based methodology is presented that is capable of determining optimal refill strategies for GAC reactors with respect to economic or ecological criteria. The results show that the particular refill strategy is of minor importance with respect to the total mass of GAC required to hinder contaminant breakthrough within a certain time period. The required mass is governed by the sorption capacity of GAC contaminant-specific sorption isotherm properties, and influent concentrations.

The refill strategy is a crucial factor for economic as well as ecologic objectives. This is due to the fact that the proportion of total recycled GAC mass depends on the number of fills. As recycled GAC is both cheaper and

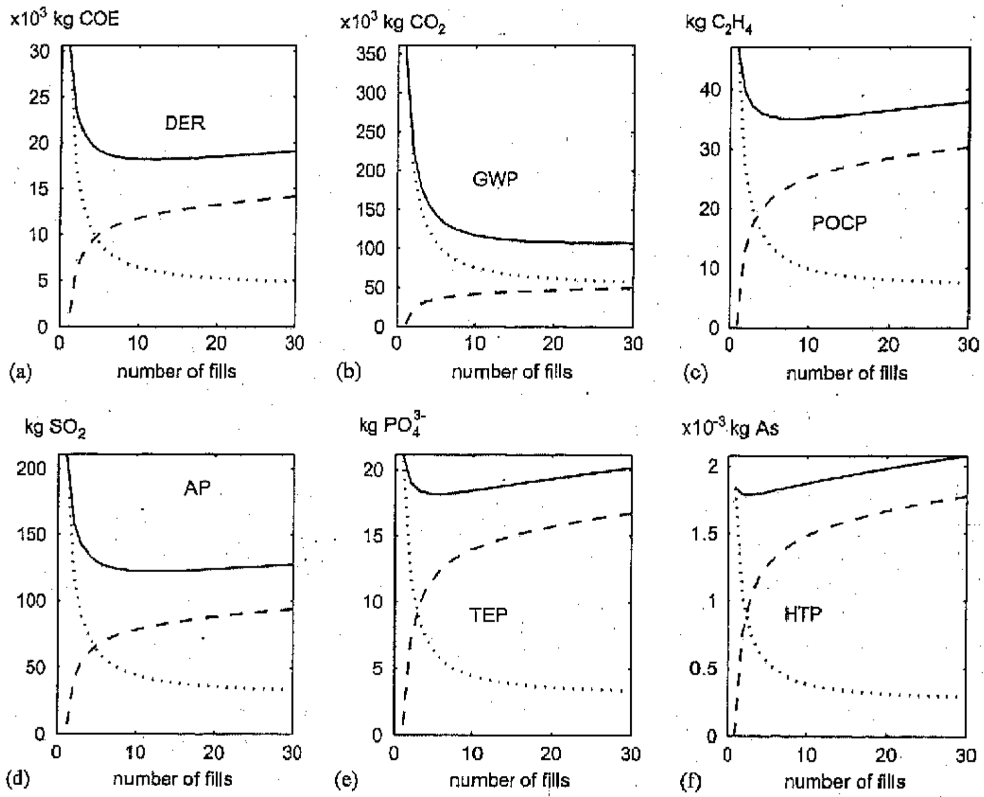

Fig. 6. Emission equivalents in five categories for fixed-bed adsorbers of variable service life (total operation time $T = 10$ years, flow rate $Q = 50\,\mathrm{m^3/h}$, PCE concentration $C_{PCE} = 1000\,\mathrm{mg/m^3}$). Dotted lines represent virgin GAC, dashed lines reactivated GAC and solid lines total GAC.

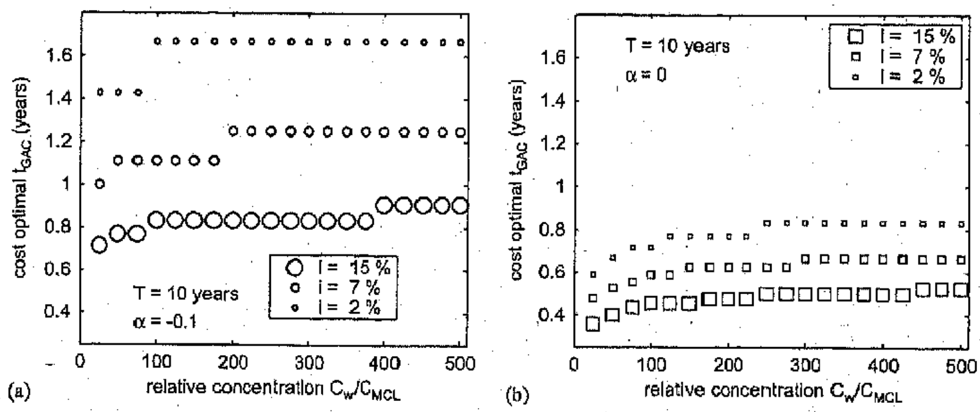

Fig. 7. (a) Cost-optimal service lives of fixed-bed reactors as a function of discount rates (rate of price increase $p = 2\%$). Circles show results for staggered prices with discounts on high purchase amounts ($\alpha = -0.1$). Solutions are valid for any flow rate and contaminant at given ratio between influent concentration (C_w) and target concentration at outlet (C_{MCL}). (b) Cost-optimal service lives of fixed-bed reactors as a function of discount rates (rate of price increase $p = 2\%$). Squares show results for staggered prices without discounts on high purchase amounts ($\alpha = 0$). Solutions are valid for any flow rate and contaminant at given ratio between influent concentration (C_w) and target concentration at outlet (C_{MCL}).

environmentally more favorable compared to virgin GAC, costs and ecological indicator values vary significantly among the refill strategies. One can derive an optimal strategy, which depends on the relative economic or ecologic valuation of virgin and recycled GAC. Optimal refill strategies are shown to be

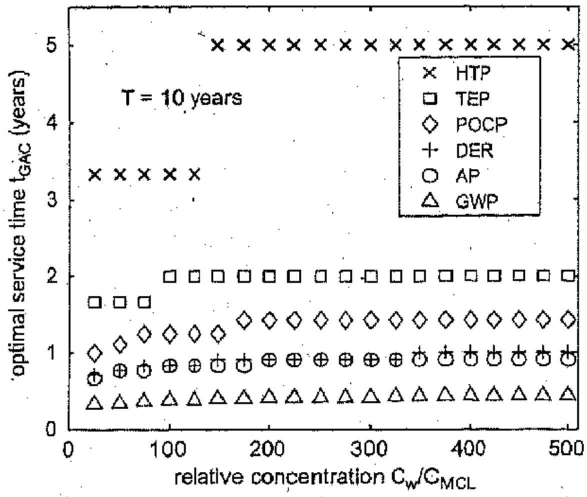

Fig. 8. Optimal service lives of fixed-bed reactors with respect to six emission categories. Solutions are valid for any flow rate and contaminant at given ratio between influent concentration (C_w) and target concentration at outlet (C_{MCL}). The total operation time is set $T = 10$ years.

independent from the water flow rate and approximately constant over a broad contaminant concentration range. Therefore, fairly general relationships between optimal carbon service life and economic and ecologic factors were found. Typical curves for economically optimized refill strategies are presented that are independent of absolute cost values. It is illustrated how discounts affected by the interest rate support shorter refill intervals, whereas discounts on purchase amounts favor longer periods.

Since GAC is used in various applications, it is not feasible to cover all possible design criterions, and therefore individual, case-specific factors may play an additional role. Applications for GAC range from small-scale water purification to huge filtration systems for municipal water supply and groundwater treatment. Here, the focus was set on capacious water treatment units that are common for groundwater treatment technologies. For this application, further site-specific issues exclusively related to the consumed GAC mass have to be taken into account but can hardly be approached generally. Increasing GAC mass per fill means an increase of container size or numbers of vessels, which could be additional decision factors. Vice versa, decreasing the change-out frequency could be economically favorable due to lower labor costs. Furthermore, very long GAC lifetimes of several years may be restricted by biofouling or precipitations.

The life cycle assessment for Filtrasorb TL 830, a coal-derived type of GAC, provides an example of a calculation for the ecologically optimal lifetimes of the fixed-bed reactor. With respect to the depletion of energy resources, the global warming potential, the photochemical ozone creation potential, the terrestrial eutrophication potential and the acidification potential, optimal service lives varying between 6 months and 2 years are obtained. For the human toxicity potential, a lower discrepancy between the indicator values of virgin and recycled GAC are presumed, which yields optimal service lives about three times higher than calculated for the other categories. In view of this, the overall ecologically optimal system depends on the subjective weighting of the impact categories.

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