PFAS drinking water treatment trade-offs: comparing the health burden of GAC treatment to the health benefits of reduced PFAS exposure

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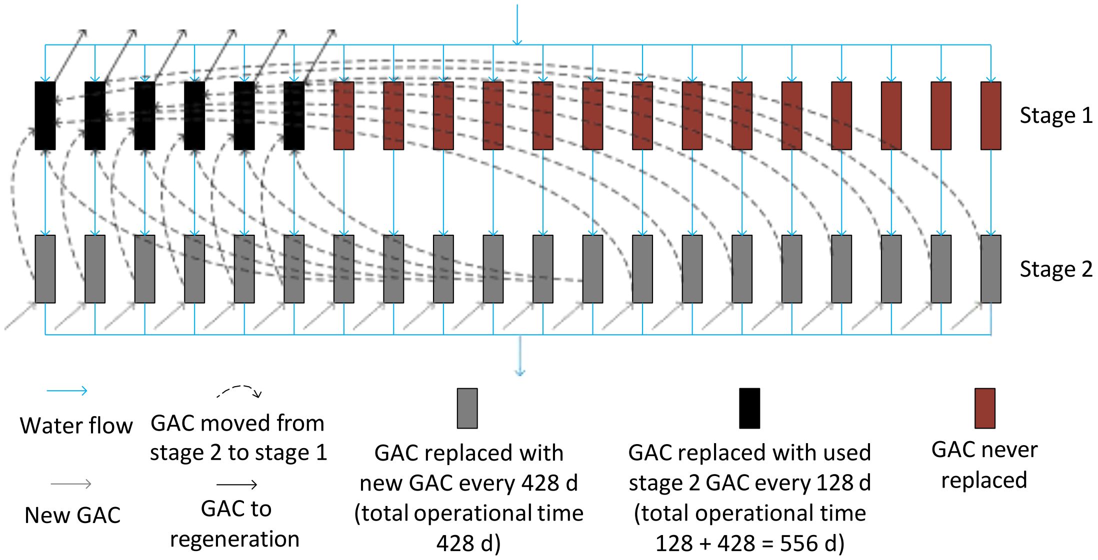
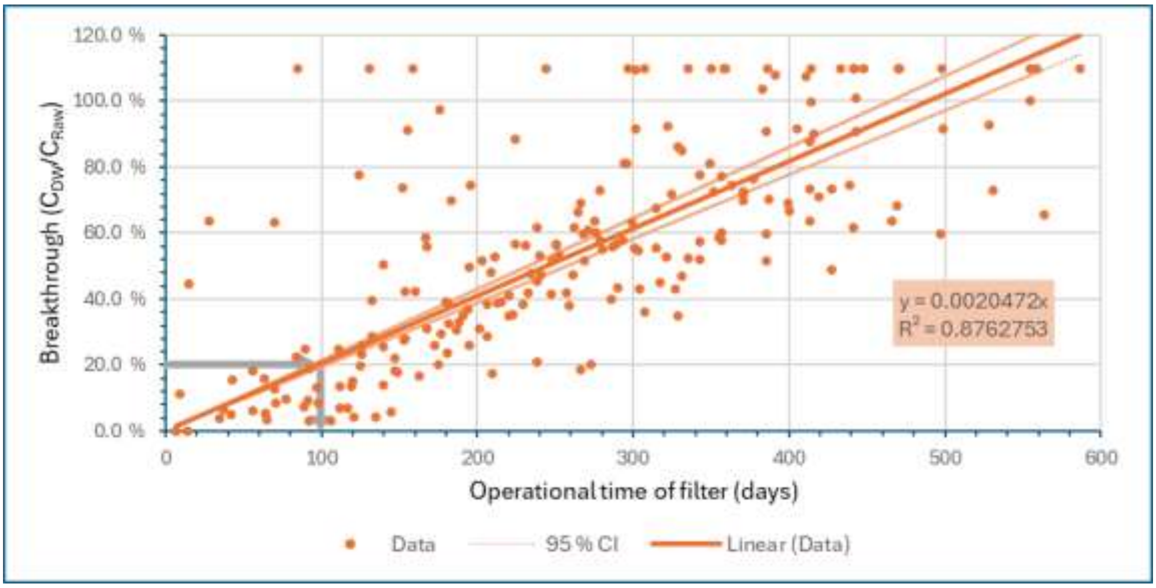
*SI Table 1: Full names and relative potency factors (RPF) of PFAS included in the calculation of PFOA-equivalent (PEQ) concentrations.[1,2] Compounds indicated with an * are included in the EFSA-4 tolerable weekly intake.*

Abbreviation	Full name	Relative potency factor (RPF)
PFOA*	Perfluorooctanoic acid	1
PFOS*	Perluorooctane sulfonic acid	2
PFNA*	Perfluorononanoic acid	10
PFHxS*	Perfluorohexane sulfonic acid	0.6
PFBA	Perfluorobutanoic acid	0.05
PFPeA	Perfluoropentanoic acid	0.05
PFHxA	Perfluorohexanoic acid	0.01
PFHpA	Perfluoroheptanoic acid	1
PFDA	Perfluorodecanoic acid	10
PFUnDA	Perfluoroundecanoic acid	4
PFDoDA	Perfluorododecanoic acid	4
PFTrDA	Perfluorotridecanoic acid	3
PFTeDA	Perfluorotetradecanoic acid	0.3
PFHxDA	Perfluorohexadecanoic acid	0.02
PFODA	Perfluorooctadecanoic acid	0.02
PFBS	Perfluorobutane sulfonic acid	0.001
PFPeS	Perfluoropentane sulfonic acid	0.6
PFHpS	Perfluoroheptane sulfonic acid	2
PFDS	Perfluorodecane sulfonic acid	2
HFPO-DA	Hexafluoropropylene oxide dimer acid	0.06
DONA	4,8-Dioxa-3H-perfluorononanoic acid	0.03
6:2 FTOH	6:2 fluorotelomer alcohol	0.02
8:2 FTOH	8:2 fluorotelomer alcohol	0.04

Concentrations in PEQ are calculated by summing the concentrations of individual PFAS multiplied with their RPF. For example, a water sample that contains 1 ng/L of each of the $EFSA_4$ compounds will have a PEQ concentration of 1·1 (PFOA) + 1·2 (PFOS) + 1·10 (PFNA) + 1·0.6 (PFHxS) = 13.6 ng PEQ/L.



SI Figure 1: Overview of GAC treatment process at the Leiduin drinking water treatment site from Waternet. Operational times shown are calculated based on the average reactivation frequency in 2024.



SI Figure 2: Breakthrough of PEQ, from raw water (C_{Raw}) to drinking water (C_{DW}) versus operational time of GAC filters, fit to a linear regression model. Note that the operational time used to determine the required reactivation frequency was twice the operational time found from the fitted equation: since multiple GAC filters are operated in parallel, this ensures that the average operational time over all filters is equal to the determined maximum.

SI Table 2: Inventory for Water Treatment Process (GAC focus) - Single Use Coal and Wood GAC

Inputs	**Amounts**	**Unit**	**Comments**
GAC:	(a) 931; (b) 2002; (c) 1774; (d) 2298		Coal-based GAC: Ecoinvent dataset 'Activated carbon, granular {RER}| activated carbon production, granular from hard coal | Cut-off, U' Wood-based GAC: Project data, as in SI table 6.
Tap Water	70726271	m^3	Tap water {Europe without Switzerland}| market for | Cut-off, U
Electricity	3823756	kWh	Electricity, medium voltage {NL}| market for | Cut-off, U. Estimation of WTP use data for GAC treatment.
Transport of Wood-GAC	(a) 32585; (b) 70070; (c) 62074; (d) 80430	tkm	Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, U. Distance of transport from GAC Activation to WTP – 35km.
Transport of Spent GAG	(a) 23250; (b) 50050; (c) 44350; (d) 57450	tkm	Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, U. Spent GAC to Incineration plant - 20 km.
Output			
Drinking water	70653937	m^3	Project defined, WTP data
Waste			
Spent WoodGAC, wet	(a) 1163.75; (b) 2502.5; (c) 2217; (d) 2873	ton	Hazardous waste, for incineration {Europe without Switzerland}| market for hazardous waste, for incineration | Cut-off, U, as in Ellis et al. 2023. Spent GAC is assumed to contain 25% moisture as in Vilen, 2022.

(a) 2024 GAC requirements
(b) average estimated GAC requirements
(c) minimum estimated GAC requirements
(d) maximum estimated GAC requirements

SI Table 3: Inventory for Water Treatment Process (GAC focus) - Reactivated Coal and Wood GAC .

Inputs	**Amounts**	**Unit**	**Comments**
Virgin GAC	(a) 116.4 (b) 250.3 (c) 221.7 (d) 287.3	ton	Coal-based GAC: Ecoinvent dataset 'Activated carbon, granular {RER}| activated carbon production, granular from hard coal | Cut-off, U' Wood-based GAC: Project defined, as in table SI 6.
Reactivated GAC	(a) 814.6; (b) 1751.8; (c) 1551.9; (d) 2010.8	ton	Coal-based GAC: Project defined, based on ecoinvent dataset 'Activated carbon, granular {RER}| treatment of spent activated carbon, granular from hard coal, reactivation | Cut-off, U' Wood-based GAC: Project defined, as in SI 7.
Tap Water	70726271	m^3	Tap water {Europe without Switzerland}| market for | Cut-off, U
Electricity	3823756	kWh	Electricity, medium voltage {NL}| market for | Cut-off, U
Transport	(a) 32585; (b) 70074; (c) 62076; (d)80434	tkm	Sum of transport need for virgin and reactivated GAC. Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, U. Distance of transport from GAC (re)activation to WTP – 35km.
Outputs	**Amounts**	**Unit**	**Database process**
Drinking water	70653937	m^3	Project defined
Spent GAC	(a) 1164; (b) 2503 (c) 2217; (d) 2873;	ton	Accounted as wet GAC, 25% moisture. Coal-based GAC: 'Activated carbon, granular {RER}| treatment of spent activated carbon, granular from hard coal, reactivation | Cut-off, U' Wood-based GAC: Project defined, as input for reactivation, as in SI 7,

(a) 2024 GAC requirements
(b) average estimated GAC requirements
(c) maximum estimated GAC requirements
(d) minimum estimated GAC requirements

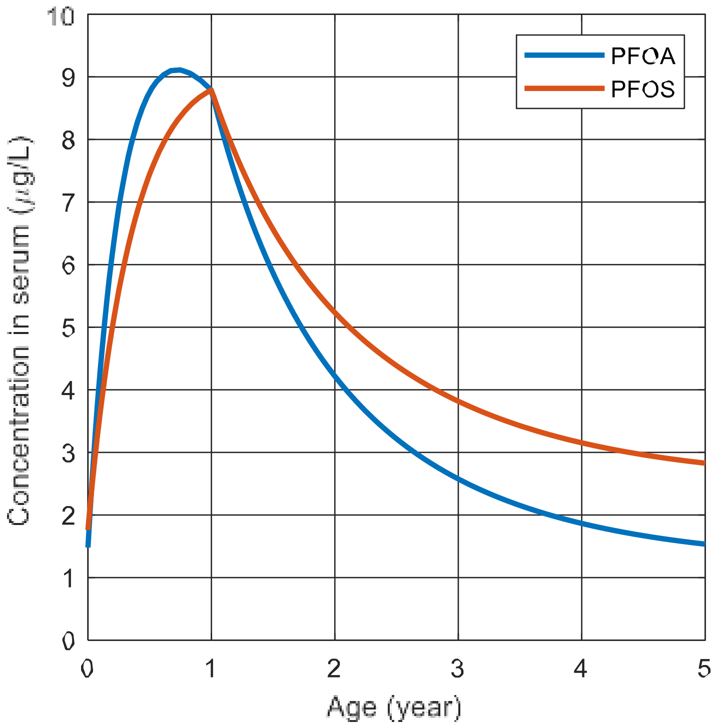
SI Table 4: Inventory for Wood GAC Production Process

Inputs	**Amounts**	**Unit**	**Comments**
Wood chips	8,44	kg	Bark chips, wet, measured as dry mass {GLO}| market for | Cut-off, U.
Electricity	1,7	kWh	Medium voltage, NL. Amount based on Vilen, 2022.
Nitrogen	0,15	kg	Nitrogen, liquid {RER}| market for | Cut-off, U. Amount based on Vilen, 2022 [31]
Tap water	2,11	kg	Tap water {Europe without Switzerland}| market for | Cut-off, S. Amount based on Vilen, 2022. [31]
Transport			
Truck	0,422	tkm	Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, U. Transport of wood chips to GAC production only, with an assumed distance of 50km, as in Vilen, 2022. [31]
Outputs			
Wood-based GAC	1	kg	Project defined stream.
Emissions			
Activation			
CO2	1,81E+00	kg	Based on Gu et al, 2018 [32] (originally per kg biochar feedstock, converted based on 2,11 kg wood biochar / kg wood-based GAC).
H2O	9,07E-02	kg	
N2	1,83E+00	kg	
O2	1,59E+00	kg	
H2	4,22E-03	kg	
CO	8,86E-03	kg	
CH4	8,44E-04	kg	
SO2	1,27E-03	kg	
HCl	1,39E-06	kg	
Nox	8,84E-05	kg	
N2O	1,39E-06	kg	
Acetaldehyde	1,16E-05	kg	
Benzene	8,36E-05	kg	
Formaldehyde	4,64E-08	kg	
Methanol	4,64E-06	kg	
Naphthalene	9,31E-06	kg	
Phenol	2,04E-06	kg	
Propanal	9,31E-08	kg	
Particulates	4,62E-02	kg	
Carbonization			
Acetaldehyde	9,65029E-06	kg	Taking emissions to air from ecoinvent dataset "wood pellets, burned in stirling heat and power co-generation unit, 3kW electric", with methane, carbon dioxide and carbon monoxide reduced by 43% as in Vilen, 2022 11 as described in main text.
Ammonia	0,000273688	kg	
Arsenic	1,58201E-07	kg	
Benzene	0,000143963	kg	
Benzene, ethyl-	4,74604E-06	kg	
Benzene, hexachloro-	1,13905E-12	kg	
Benzo(a)pyrene	7,91007E-08	kg	

Bromine	9,49209E-06	kg	
Cadmium	1,10741E-07	kg	
Calcium	0,000925478	kg	
Carbon dioxide, biogenic	8,711158032	kg	
Carbon monoxide, biogenic	0,002885594	kg	
Chlorine	2,84763E-05	kg	
Chromium	6,26478E-07	kg	
Chromium VI	6,32806E-09	kg	
Copper	3,48043E-06	kg	
Dinitrogen monoxide	0,000474604	kg	
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	4,90424E-12	kg	
Fluorine	7,91007E-06	kg	
Formaldehyde	2,05662E-05	kg	
Hydrocarbons, aliphatic, alkanes, unspecified	0,000143963	kg	
Hydrocarbons, aliphatic, unsaturated	0,000490424	kg	
Lead	3,95504E-06	kg	
Magnesium	5,69525E-05	kg	
Manganese	2,68942E-05	kg	
Mercury	4,74604E-08	kg	
Methane, biogenic	3,60699E-05	kg	
m-Xylene	1,89842E-05	kg	
Nickel	9,49209E-07	kg	
Nitrogen oxides	0,011074101	kg	
NMVOC, non-methane volatile organic compounds, unspecified origin	0,000363863	kg	
PAH, polycyclic aromatic hydrocarbons	1,75604E-06	kg	
Particulates, < 2.5 um	0,001582014	kg	
Phenol, pentachloro-	1,28143E-09	kg	
Phosphorus	4,74604E-05	kg	
Potassium	0,003701914	kg	
Sodium	0,000205662	kg	
Sulfur dioxide	0,000395504	kg	
Toluene	4,74604E-05	kg	
Zinc	4,74604E-05	kg	

SI Table 5: Inventory for Reactivated Wood GAC Production Process

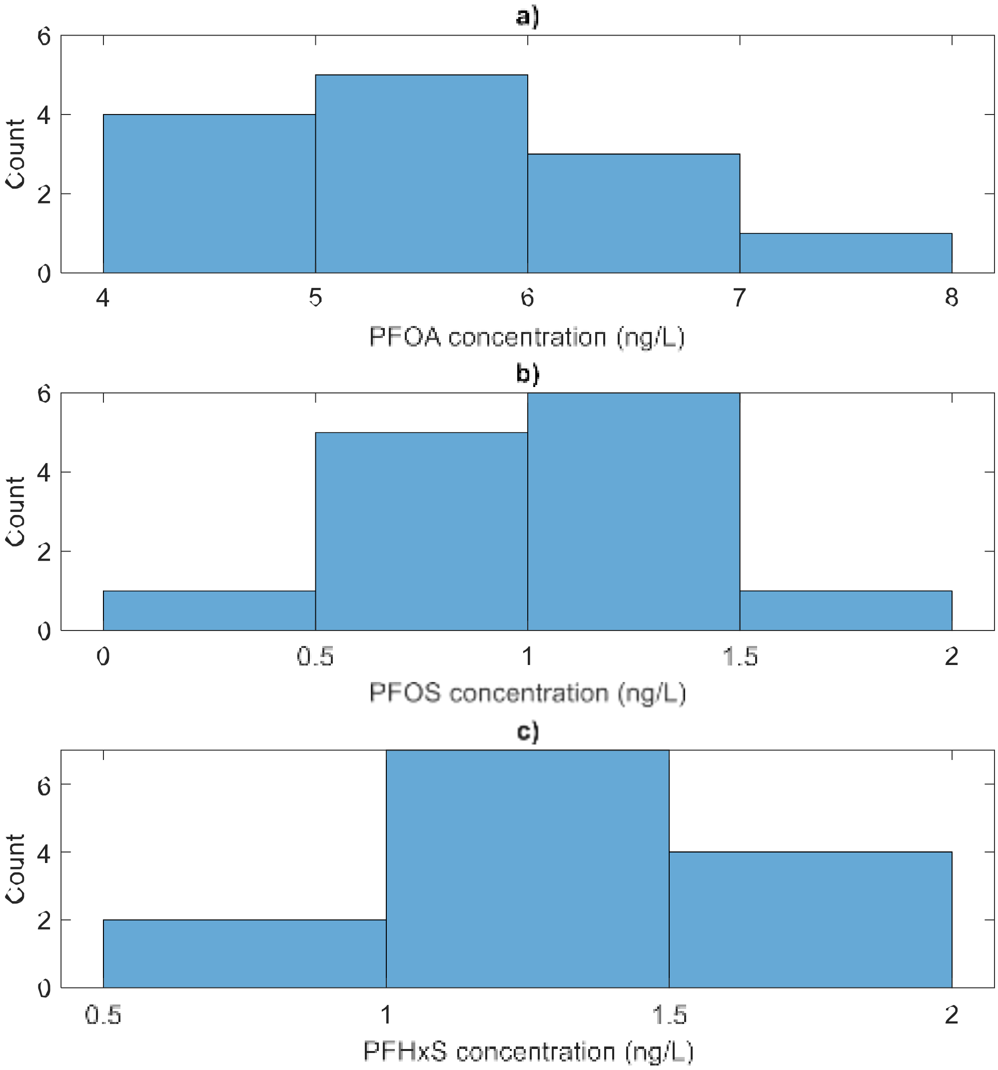
Inputs	**Amounts**	**Unit**	**Comments**
Spent GAC	1,00	kg	Wet, as output from drinking water process
Electricity	0,41	kWh	Medium voltage, NL
Nitrogen	0,04	kg	Liquid, RER
Tap water	0,55	kg	Europe without Swirzerland
Transport			
Truck	0,03	tkm	Transport, freight, lorry 16—32 t, RER. Same transport mode as Wood-GAC. Distance: 30km for return of spent GAC to Norit Activated Carbon for reactivation.
Outputs			
Reactivated Wood GAG	0,89	kg	1 enters, losses are 12,5% on final prod.
Emissions			
CO2	1,81E+00	kg	Based on activation of biochar as in Gu et al, 2018 (originally per kg biochar feedstock, converted based on 2,11 kg wood biochar / kg wood-based GAC). Biogenic CO, CO2 and CH4.
H2O	9,07E-02	kg	
N2	1,83E+00	kg	
O2	1,59E+00	kg	
H2	4,22E-03	kg	
CO	8,86E-03	kg	
CH4	8,44E-04	kg	
SO2	1,27E-03	kg	
HCl	1,39E-06	kg	
Nox	8,84E-05	kg	
N2O	1,39E-06	kg	
Acetaldehyde	1,16E-05	kg	
Benzene	8,36E-05	kg	
Formaldehyde	4,64E-08	kg	
Methanol	4,64E-06	kg	
Naphthalene	9,31E-06	kg	
Phenol	2,04E-06	kg	
Propanal	9,31E-08	kg	
Particulates	4,62E-02	kg	



SI Figure 3: Verification that MATLAB PBPK model is an accurate reproduction of EFSA's model: PFOA and PFOS serum concentrations until age 5 using the same parameters as in EFSA's original model, to compare with Figure M.1 (page 379; PFOA) and Figure M.3 (page 382, PFOS) from Schrenk et al., 2020. [3]

SI Table 6: Overview of data used in DALY calculation

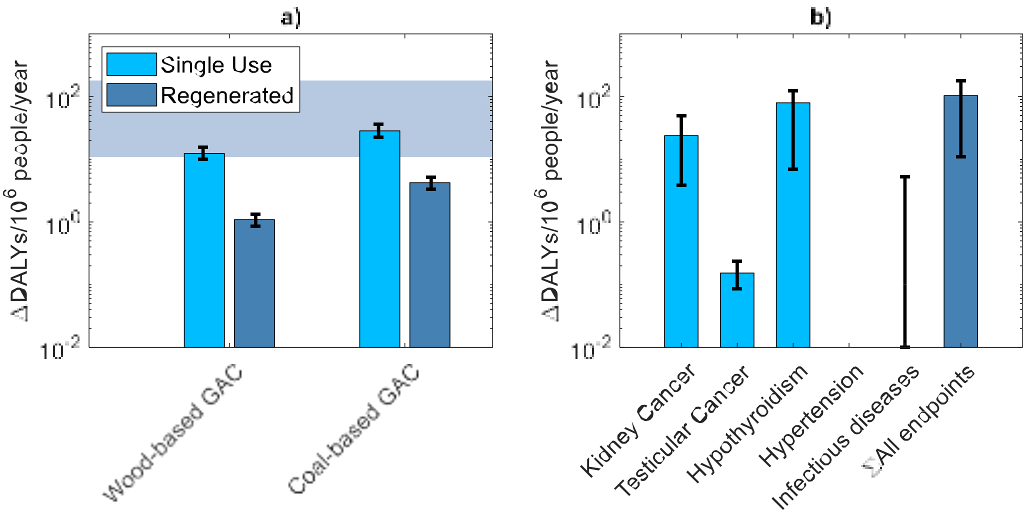
Endpoint	Population	P (per 10^6 people)[4]	W (DALYs/case)	I (cases/person/year)
Kidney cancer	Adults >20	792,000	9.1[5]	0.000194[6]
Testicular cancer	Males >18	403,000	1.8[7]	0.000064[6]
Hypothyroidism	Females 18-49	200,000	0.19[8,9]	0.002[10]
Hypertension	Adults > 20	792,000	0.12[11]	0.008[10]



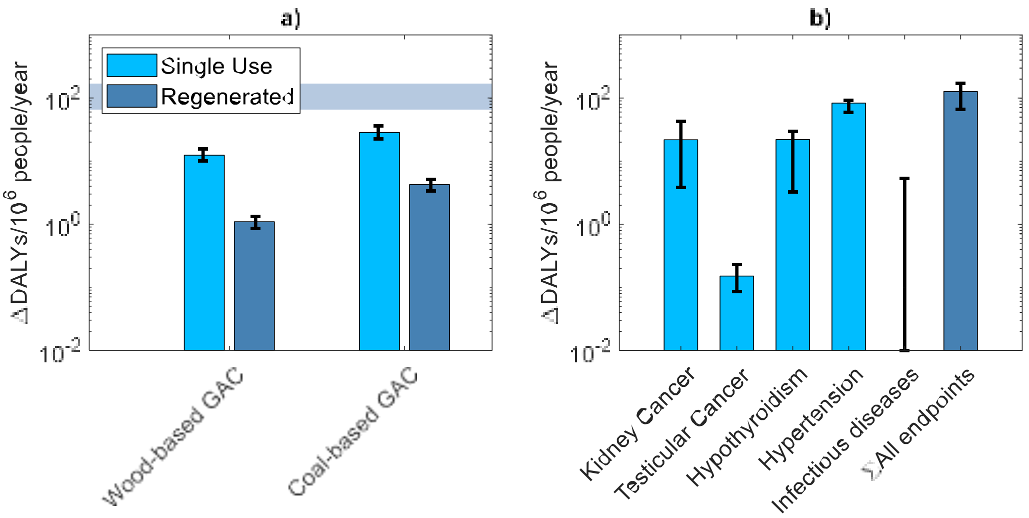
SI Figure 4: Distribution of 2024 drinking water concentrations of a) PFOA, b) PFOS and c) PFHxS. Total n = 13 for all.

SI Table 7: Health impacts (DALYs/10^6 p/year) from GAC treatment for each scenario, excluding DALYs related to water consumption. 2024 = reactivation frequency as in 2024 (current); Prosp. = prospective reactivation frequency

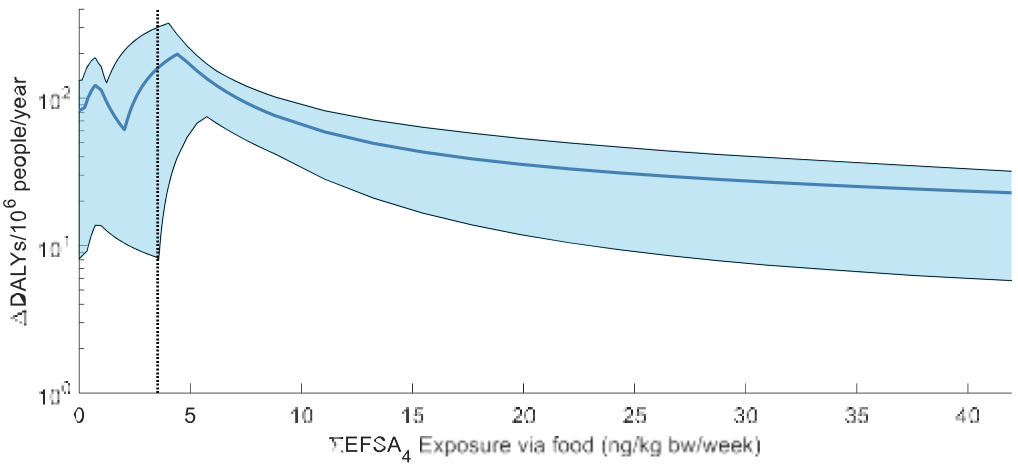
GAC type	**Single use wood**		**Single use coal**		**Reactivated coal**		**Reactivated wood**	
Scenario	2024	Prosp.	2024	Prosp.	2024	Prosp.	2024	Prosp.
Global warming	29	33	34	45	26	28	25	26
Fine particulate matter formation	31	38	37	50	29	31	28	29
Human carcinogenic toxicity	29	30	30	32	28	28	28	28
Human non-carcinogenic toxicity	8.7	9.1	10	13	8.3	8.7	8.0	8.1
Total	**98**	**110**	**110**	**140**	**92**	**96**	**89**	**90**



SI Figure 5: Repeated version of main text Figure 3, but with the dietary exposure set to the lower limit of the most recently estimated exposure of the Dutch population.



SI Figure 6: Repeated version of main text Figure 3, but with the dietary exposure set to the upper limit of the most recently estimated exposure of the Dutch population.



SI Figure 7: Sensitivity analysis over the effect of food exposure on the ΔDALYs between the scenario's with current and targeted drinking water concentrations. The blue line represents the best estimate, and the shaded region the uncertainty range (min-max, derived from 95 % CI over current drinking water concentrations and ERRs). The dotted vertical line is the food exposure at 80 % of the EFSA recommendation. Note that, in the dietary exposure, the ratio between PFOA/PFNA:PFOS/PFHxS is kept constant at the ratio assumed by EFSA (1:2.4).

SI Table 8: Serum/plasma concentrations at age 3 months in exclusively breastfed infants, comparison between measured and modelled results. The EFSA PBPK model assumes exclusive breastfeeding, as a worst-case scenario, so comparisons against plasma levels in breastfed infants are most realistic. Ranges represent the uncertainty from variation in current drinking water concentrations.

	Measured concentrations	**Modelled serum concentrations; current scenario**		
	Plasma conc. in exclusively breastfed infants[12]	EFSA food exposure[3]	LB food exposure 2022[13]	UB food exposure 2022[13]
PFOA/PFNA	4.04	11.7 (11.1-12.3)	6.1 (5.5-7.1)	16.4 (15.8-17.1)
PFOS/PFHxS	3.14	5.5 (5.3-5.8)	1.7 (1.5-1.8)	2.2 (2.1-2.4)
∑EFSA₄	7.18	17.2 (16.4-18.1)	7.8 (7.0-8.9)	18.6 (17.9-19.5)

SI Table 9: Plasma concentrations (ng/mL) at different ages for the different exposure scenario's. EFSA TDI: the tolerably daily intake of 0.63 ng/kg bw/d as calculated by EFSA; 2022 LB: the lower bound dietary exposure calculated by the RIVM for the Dutch population in 2022; 2022 UB: idem, but the upper bound.[13]

Exposure via food as:	80 % of EFSA TDI		2022 LB	2022 UB	80 % of EFSA TDI	2022 LB	2022 UB
Drink. water scenario	***EFSA TDI***	***Current DW conc.; mean (95 % CI)***			***Targeted DW conc.***		
	Blood plasma concentrations at birth (ng/mL)						
PFOA/ PFNA	1.5	2.4 (2.3-2.6)	1.3 (1.1-1.5)	3.4 (3.3-3.5)	1.6	0.5	2.6
PFOS/ PFHxS	1.8	1.7 (1.6-1.8)	0.5 (0.5-0.6)	0.7 (0.6-0.7)	1.5	0.3	0.5
∑EFSA₄	3.3	4.1 (3.9-4.4)	1.8 (1.6-2.1)	4.1 (3.9-4.2)	3.1	0.8	3.1
	Blood plasma concentrations at age 1 (ng/mL)						
PFOA/ PFNA	8.7	14.2 (13.5-14.9)	7.4 (6.7-8.7)	20.0 (19.2-20.7)	9.4	2.7	15.2
PFOS/ PFHxS	8.7	8.3 (8.1-8.7)	2.5 (2.3-2.7)	3.4 (3.1-3.6)	7.3	1.6	2.4
∑EFSA₄	17.4	22.5 (21.6-23.6)	9.9 (9.0-10.4)	23.4 (22.3-24.3)	16.7	4.3	17.6
	Blood plasma concentrations at age 35 (ng/mL)						
PFOA/ PFNA	2.0	3.3 (3.1-3.4)	1.7 (1.5-1.9)	4.6 (4.4-4.8)	2.2	0.6	3.5
PFOS/ PFHxS	4.9	4.7 (4.5-4.8)	1.4 (1.3-1.5)	1.9 (1.8-2.0)	4.1	0.9	1.3
∑EFSA₄	6.9	8.0 (7.6-8.2)	3.1 (2.9-3.4)	6.5 (6.2-6.8)	6.3	1.5	4.8

SI Table 10: Identified uncertainties per uncertainty type. Green highlight indicates the uncertainty was discussed in the main text.

Indeterminate	Epistemic	Ambiguity
Future PFAS concentrations in raw water	PFAS breakthrough with different types of GAC and raw water	Endpoints to consider in estimation of health benefits of lower PFAS exposure
Future PFAS regulations	Dose response relationships and DALY weights to relate PFAS serum concentration to health impacts	PFAS molecules to consider and how to account for the impact of the different PFAS molecules (e.g. equipotency, relative potency factors)
Type of treatment used (e.g. GAC, ion exchange, etc) and specific life cycle implications (e.g. transportation, waste management)	Concentrations of PFAS below the limit of quantification	LCA assessment method assumptions (e.g. time horizon of climate change impacts, climate change impacts on human health)
Future dietary exposure to PFAS and distribution across population	Inventory data for GAC production and reactivation, especially for wood GAC at commercial scale.	How to account for localization of health impact (e.g. local benefit from decreased PFAS exposure, global loss from global warming)
	Current dietary exposure to PFAS and distribution across population	

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