Estimated Greenhouse Gas Emissions from PFAS Treatment of Maine Drinking Water

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ABSTRACT

State law requires the adoption of a maximum contaminant level (MCL) for PFAS contamination in drinking water by June 1, 2024. While discussion of mitigation options has included the degree of risk reduction and the cost of treatment, indirect environmental effects are missing from the conversation. Until other technologies are developed, water treatment in Maine will likely rely on the established, energy-intensive method of PFAS adsorption (binding) to granular activated carbon. We conducted an inventory of greenhouse gas emissions associated with water treatment using this treatment media to fill gaps in the discussion. We found that greenhouse gas emissions for water treatment to bring PFAS down to the current interim standard are substantial, raising the footprint of an average user by 6.7–18 percent. We use this information to discuss implications for policymaking.

INTRODUCTION

Per- and poly-fluoroalkyl substances (PFAS) have been a significant technological advancement for consumer and industrial material applications since the 1950s (Buck et al. 2011; Kissa 2001). This family of thousands of chemicals, with *nonstick* (repelling water, dirt, and oil) and *surfactant* (soap-like) properties, has been used extensively in products ranging from firefighting foams to waterproof clothing, cookware, and food packaging (Kwiatkowski et al. 2020). These properties mean PFAS are highly soluble in water (ITRC 2020) and are retained in soils (Campos Pereira et al. 2018). PFAS can also be transported over long ranges through the air after they are emitted from industrial stacks (Ahrens et al. 2012). The chemicals are typically present at elevated concentrations near where they have been released (e.g., industrial stacks, firefighting-training areas, landfills, wastewater treatment plants, and biosolids application areas), but are also detectable far from known emissions. PFAS are now found across the environment globally (ITRC 2020), which is of great concern due to the human and ecological health impacts of PFAS and their ability to persist in the environment (Sunderland et al. 2019).

People can be exposed to PFAS both directly and indirectly. PFAS can be taken up in crops irrigated with PFAS-contaminated water (Stahl et al. 2009) and crops grown in soils amended with PFAS-laden biosolids (Blaine et al. 2013). Some PFAS accumulate in animals (Death et al. 2021; Houde et al. 2011), resulting in higher tissue concentrations in the animals than in their food. This bioaccumulation can lead to human exposure through the food chain when people eat PFAS-contaminated meat or drink contaminated milk or water (Domingo and Nadal 2019). Other people are exposed to PFAS through food packaging, consumer products, and house dust derived from these products (ITRC 2020). As a result, PFAS are generally found in blood samples collected from people across the country (CDC 2018). While large quantities of PFAS have been produced since the mid-1950s, researchers have only begun investigating their effects on people in the last few decades. Potential human health effects from PFAS exposure include impaired immune function, thyroid disease, liver disease, liver cancer, increased cholesterol, kidney disease, kidney cancer, and adverse reproductive and developmental outcomes (Fenton et al. 2021).

Given our growing understanding of the distribution of PFAS in the environment and their negative impacts on human health, the state of Maine established a PFAS Task Force on March 6, 2019. This task force, comprised of stakeholders in state government, industry partners, and water/waste management, reviewed the available Maine-specific data on PFAS. The task force made recommendations for providing safe drinking water, protecting the food supply, characterizing PFAS distribution in the environment, phasing out PFAS use, and educating the public. The task force also identified the significant financial cost for implementing the recommendations and suggested methods for future funding (Maine PFAS Task Force 2020). The report by the task force was followed by Maine SP 64 – LD 129, which required testing for PFAS across the state, including drinking water sources. This resolve also established an

PFAS Currently Regulated in Maine Drinking Water

Full Name	Acronym
Perfluorooctanoic acid	PFOA
Perfluorooctane sulfonate	PFOS
Perfluorononanoic acid	PFNA
Perfluorohexane sulfonate	PFHxS
Perfluoroheptanoic acid	PFHpA
Perfluorodecanoic acid	PFDA

interim drinking water standard of 0.020 micrograms per liter (or 20 parts per trillion) for the sum of six individual PFAS listed in Table 1. The six PFAS include two of the most studied (PFOA and PFOS) and others with similar chemical structures that have been detected in Maine's water and soil. The legislation required that the Department of Health and Human Services (DHHS) enact rulemaking in 2022 to establish a drinking water maximum contaminant level (MCL) as a final rule on or before June 1, 2024.

The interim drinking water standard for PFAS of 0.020 micrograms per liter (or 20 parts per trillion) is a relatively stringent value compared to many other contaminants. For instance, the MCLs for lead and benzene are more than 100 times higher than the PFAS interim drinking water standard, partly due to the potential for PFAS to accumulate and persist in humans. Other relatively toxic and bioaccumulating contaminants, such as benzo(a)pyrene and dioxin, have MCL values closer to the interim PFAS standard.[1]

The rulemaking process for PFAS is likely to incorporate information on toxicity, emerging data on the distribution of PFAS in the environment, and costs for investigation and treatment based on currently available technologies. This information is available to Maine regulators in conference presentations, academic journal articles, and through information sharing with federal and state regulators. Considerations of the environmental footprint of PFAS mitigation, however, are largely missing from state and national discussions of the issue. Greenhouse gas (GHG) emissions could be high due to the available treatments and the low cleanup levels that will likely be required. For instance, the most developed technology for treating water contaminated with PFAS uses granular activated carbon. This material is sourced either directly from coal or generated by high-temperature treatment of biomass. In addition, there is not currently a granular activated carbon manufacturer in the state, so it must be delivered to Maine by freight. Finally, granular activated carbon would be an add-on to many water treatment systems because it is not effective for typical Maine drinking water contaminants like arsenic. These factors combined may mean substantial GHG emissions for new treatment.

Maine's climate plan (Maine Climate Council 2020: 6) recognized that "climate change represents the greatest threat of our age" and that GHG emissions in Maine must be aggressively reduced across public, private, and government sectors. PFAS mitigation may actually increase GHG emissions in the state, but the degree of this increase has not been assessed. To address this gap in knowledge, we conducted a GHG emissions inventory to (1) assess potential emissions associated with drinking water treatment for an example private residential and public water supply, (2) estimate the range of emissions associated with different levels of treatment (higher and lower standards), and (3) identify dominant factors in potential emissions for possible opportunities to decrease them.

METHODS

We conducted an environmental footprint analysis, focusing on GHG emissions, to better understand the implications of different potential PFAS drinking water quality standards in Maine. The analysis included impacts during production, transportation, use, and disposal of water treatment materials. GHG emissions will likely be the greatest environmental impact for water treatment systems for residential well water and centralized water systems in the state. As Maine's PFAS mitigation efforts eventually begin to focus on decreasing PFAS presence in the broader environment, other indirect environmental effects (e.g., groundwater extraction and treatment via *pump-and-treat* remedial systems) may have similar or greater environmental impact. With current and near-future mitigation efforts focusing on drinking water treatment, however, a GHG emissions estimate is likely most useful for decision makers.

We simulated two water treatment scenarios: (1) point-of-entry PFAS removal from private (single household) residential drinking water, and (2) PFAS removal from municipal drinking water, both sourced from groundwater. These scenarios represent a large proportion of drinking water users in Maine. For instance, more than half of Maine homes obtain drinking water from private, residential wells, and approximately one-third of public water supplies are from groundwater.[2] In both scenarios, we used the six currently regulated PFAS in Maine (Table 1) in the

TABLE 2: **Total GHG Emissions Estimates**

Scenario	Activated carbon type	Target sum-of-six PFAS concentrations (μ/L)	Annual GHG emissions (metric tons CO_2 eq)	Annual per user GHG emissions (metric tons CO_2 eq)
Private residential water treatment	Coal-based	0.002	67	17
		0.010	18	4.4
		0.020	**10.7**	**2.7**
		0.040	6.3	1.6
		0.200	1.9	0.47
	Coconut-based	0.002	16.3	4.1
		0.010	6.4	1.6
		0.020	**4.6**	**1.1**
		0.040	3.2	0.8
		0.200	1.4	0.34
Municipal water treatment	Coal-based	0.002	250,000	13
		0.010	67,000	3.5
		0.020	**40,000**	**2.1**
		0.040	23,000	1.2
		0.200	3,200	0.17
	Coconut-based	0.002	100,000	5.4
		0.010	31,000	1.6
		0.020	**20,000**	**1.0**
		0.040	12,000	0.63
		0.200	1,900	0.10

Note: Maine interim standard of 0.020 micrograms per liter (μ/L) is in bold.

simulation. We used available data from the state to determine base-case scenarios for PFAS concentrations in untreated groundwater. We then used engineering assumptions and calculations to simulate PFAS removal from this untreated groundwater using adsorption (binding) to granular activated carbon treatment systems. We varied the amount of PFAS removal to match the current interim drinking water standard, as well as lower and higher target PFAS concentrations. The various components of the treatment system were multiplied by emissions factors to estimate GHG quantities for each scenario.

A fuller description of the methods is available in the appendix (https://digitalcommons.library.umaine.edu /mpr/vol31/iss1/4). Treatment scenarios were for evaluation purposes and do not represent a specific exposure or treatment system.

RESULTS

Emission estimates to reach the Maine PFAS interim drinking water standard range from 4.6 metric tons carbon dioxide (CO_2) equivalent for the private residential water treatment scenario to 40,000 metric tons CO_2 equivalent for the municipal water treatment (Table 2, Figure 1). The wide range is attributable to the quantity of water treated in the two scenarios, with the private residential water treatment for a household of four people vs the municipal scenario treatment for a population of approximately 19,000 people. For reference, 1 metric ton CO_2 equivalent corresponds to the emissions of a typical passenger vehicle for 2.6 months.[3]

The right column in Table 2, and right axis of Figure 1, report per user estimates of annual GHG emissions. In the private residential water treatment scenario, the total emissions are divided by four users to obtain the per user estimate. For the municipal water treatment scenario, the per user emissions are calculated based on 19,000 users. For the target PFAS concentration set to the interim water quality standard, per user emissions range from 1.0 to 2.7 metric tons CO_2 equivalent, or approximately 6.7–18 percent of the US per capita GHG emissions (15 metric tons CO_2 equivalent).[4] Thus, treating water to the interim drinking water standard will likely lead to a substantial increase in a given user's carbon footprint. The extent of PFAS contamination in drinking water across Maine has not been characterized yet. If drinking water is widely affected by PFAS, then treatment to the interim standard for risk reduction could mean a significant addition to the state's emissions, working against Maine's goals for reductions in GHG emissions.

Increasing or decreasing the target PFAS concentration from the interim standard will likely have an effect on emissions (Table 2, Figure 1). Generally, raising the target PFAS concentration has a smaller effect than lowering the target.[5] The greater change to emissions when decreasing the standard is because adsorption becomes less efficient at lower

FIGURE 1:   Total Greenhouse Gas Emissions (Bar Charts) and Components (Pie Charts)
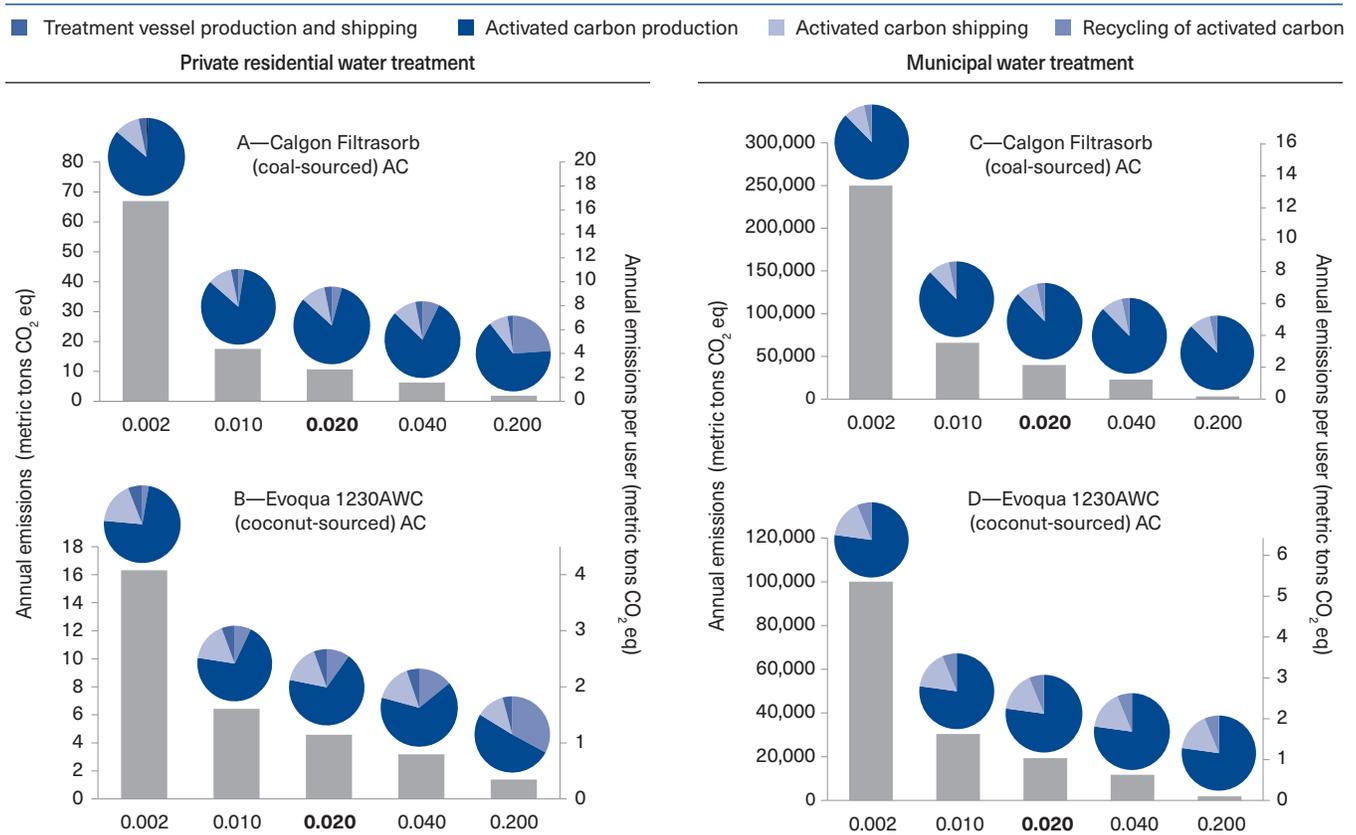
Note: The current interim drinking water standard of 0.020 micrograms per liter (μg/L) is in bold. Treatment vessel production comprises less than 0.05 percent of emissions in all municipal water treatment scenarios, and this component is not visible on those pie charts.

concentrations, which increases the quantity of activated carbon needed. We estimate the most stringent target PFAS concentration of 0.002 micrograms per liter will increase GHG emissions by more than 27 percent per user. While much more stringent than the interim drinking water standard, the 0.002 micrograms per liter value is still 500 times higher than the USEPA's recent health advisories for PFOA and 100 times higher than the advisory for PFOS.[6]
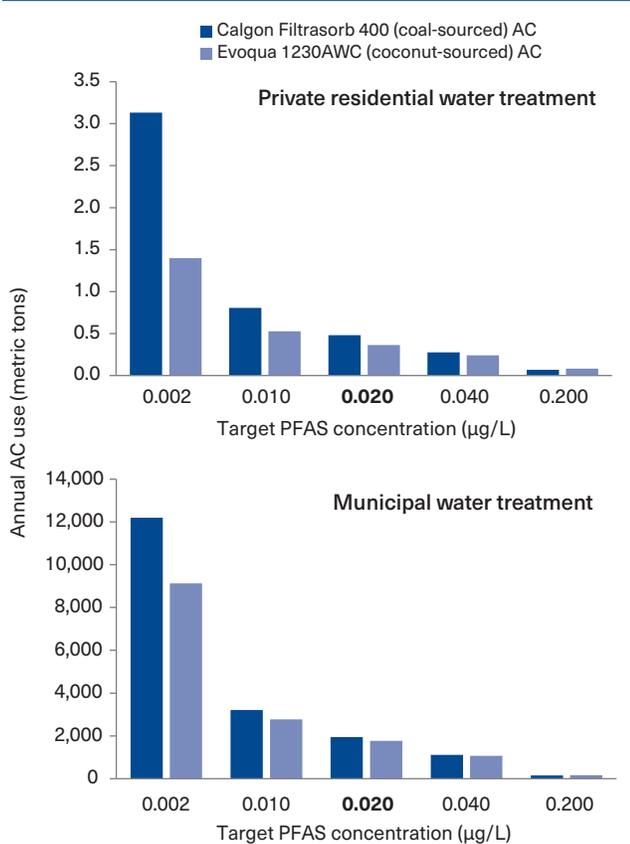
Figure 1 displays the components of each treatment scenario. In all scenarios, activated carbon production contributes at least 50 percent of the total GHG emissions due to the energy-intensive process of generating activated carbon. For treatment to the lowest target PFAS concentration, activated carbon production accounts for 74–88 percent of the estimated GHG emissions.

The second darkest wedges of the Figure 1 pie charts represent the emissions associated with the vessels that hold

the activated carbon (fiberglass for the private residential water treatment scenario and steel for the municipal scenario). Creating and shipping these vessels to treatment facilities generate GHG emissions. As a proportion of the total, for the private residential water treatment scenario, these *startup* emissions constitute 4–10 percent of the total emissions at the interim drinking water standard. However, for municipal water treatment, they constitute less than 0.05 percent of total emissions in all scenarios. On an absolute scale, the startup emissions for municipal water treatment are not small (2.7 metric tons CO_2 equivalent), but on a per user basis they are small due to the benefit of scale from centralized water treatment.

Our results suggest that treating drinking water to low concentrations will result in significant emissions associated with activated carbon production (plus shipping and recycling) due to a combination of the high emissions factor for

Note: (μg/L = micrograms per liter)

could have lower emissions for an actual treatment system for PFAS currently regulated in Maine.

To look at the amount of activated carbon required to treat individual PFAS, we used an equal initial concentration for each of the six PFAS in our municipal water treatment scenario (see Appendix). Figure 3 shows the proportion of the total activated carbon usage at the interim drinking water standard and half that standard. Based on its chemical characteristics, PFHxS is a poor match for sorption onto activated carbon (Smith et al. 2016), and it requires a large share of activated carbon in all scenarios. Our findings suggest that treating a broad range of PFAS with activated carbon will mean that much of the media will be spent removing the more poorly adsorbing compounds or that some form of water pretreatment would be needed.

POLICY DIRECTIONS

This study provides a preliminary estimate of GHG emissions associated with PFAS treatment for residential well and municipal well treatment scenarios in Maine. The sources of the GHG emissions include vessels for activated carbon installation, production of activated carbon, shipment of equipment and treatment media, and recycling of the activated carbon. Although some residential systems use activated carbon, it is mainly used for improving taste and odor. Activated carbon is not effective for removing typical Maine drinking water contaminants such as arsenic, and most municipal water treatment systems do not use it. So, the simulations we outline would be add-ons to existing systems, with additional environmental impacts from GHG emissions.

The treatment scenarios in this study include the current interim drinking water standard for the sum-of-six PFAS, as well as four alternative (two higher, two lower) target concentrations. While the simulations use multiple simplifying approaches and are not intended for design of any particular system, the results fill an important information gap for policy making. The results suggest that, if the current interim standard is applied to drinking water, there will be a substantial increase in per user GHG emissions because activated carbon requires large quantities of energy to produce. This information will allow policymakers to consider the potential effect on GHG emissions in addition to potential risk reduction and financial costs as they develop appropriate target PFAS concentrations for drinking water. Five policy considerations follow.

each kilogram of activated carbon (see Appendix Table 3) and the significant quantities of treatment media required (Figure 2). At the lowest target water concentration, for instance, the private residential scenario would use at least 1.0 metric tons of activated carbon and the municipal scenario would use at least 8,000 metric tons per year.

Across most scenarios, the quantities of activated carbon are generally similar regardless of the source (coal vs biomass/coconut) of the media (Figure 2). Research generally reports that virgin activated carbon from coal performs better than virgin activated carbon from biomass/coconut (Cantoni et al. 2021).[7] For GHG emissions of coal-sourced activated carbon to be lower than coconut- or biomass-based activated carbon, the coal-sourced medium would need to be approximately two times more efficient at treatment. Therefore, we expect coconut- or other biomass-sourced activated carbon

Estimated Activated Carbon Usage for Individual PFAS in Municipal Water Treatment Scenarios
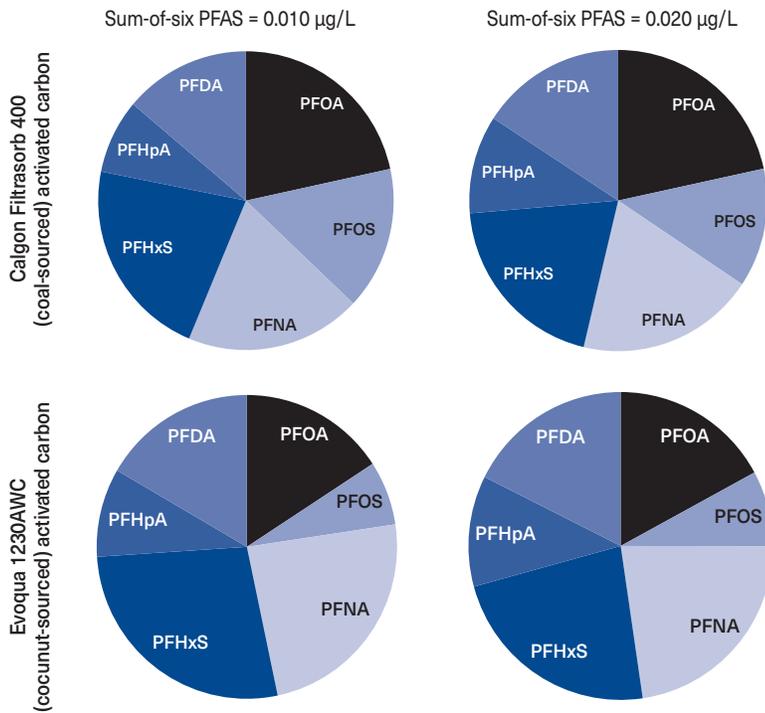
Alternative Target PFAS Concentrations

The sum-of-six approach adopted for the Maine interim drinking water standard is supported by several toxicological concepts including that (a) the six PFAS have similar human health effects, (b) these effects might be additive, and (c) multiple individual PFAS often occur together in contaminated water (MADEP 2019). Such a standard means that only one value for a given water sample must be evaluated. At face value, the most straightforward next step for future rulemaking is to retain this sum-of-six approach and revise the target concentration upward or downward, depending on how the various factors (risk reduction, financial cost, GHG emissions) are weighted.

More stringent drinking water standards mean higher GHG emissions due to the increased amount of activated carbon needed. These additional emissions and the increased financial cost for treatment can be significant, but could be justified by a reduction in risks to human health. However, it will be challenging to estimate risk reduction because of both the lack of available information about some compounds and the wide range of potential concentrations for individual constituents within one sum-of-six standard.[8] Thus, the uncertainty in estimating activated carbon usage at low concentrations may be compounded by uncertainty in how much the overall risk has been reduced. The sum-of-six approach may be relatively simple to implement as a rule, but understanding the actual benefits and costs for alternative target concentrations in this approach is more complicated.

Individual PFAS Constituent Targets

This study suggests that a large proportion of the activated carbon will be spent on PFHxS. Many toxicologists consider PFHxS to have lower toxicity than other regulated PFAS, such as PFOA (Dewitt et al. 2019; MDH 2020a, 2020b) although this is not a universal opinion (MADEP 2019). An alternative approach would be to set drinking water standards for individual PFAS constituents so that the highest-priority PFAS are treated. If Maine regulators are considering cost of treatment and GHG emissions in addition to risk reduction, there might be a case for setting a less stringent standard for PFHxS than for PFOA.[9]

If DHHS finds the toxicological arguments for a sum-of-six approach to be compelling, then it might be necessary to retain it for a proposed rule. But individual PFAS concentration targets could still be incorporated. For example, individual concentration targets for PFOA and PFOS could be specified along with a maximum allowable concentration for multiple PFAS combined.

Recycled Activated Carbon

The primary GHG emissions associated with PFAS water treatment is estimated to be production of the virgin activated carbon. There is, however, the possibility of using recycled activated carbon, which takes less energy to produce. In our simulation, the emissions attributed to the recycled activated carbon are 4–8 percent of the emissions attributed to virgin activated carbon (see Appendix Table 3). Even if the recycled activated carbon did not perform as well as the virgin activated carbon, it would still remove PFAS (Cantoni et al. 2021) and provide a significant reduction in GHG emissions. According to vendors of activated carbon,

however, availability of the material is a challenge for use on a large scale. State-level coordination between water treatment systems may be a way to establish common pools of recycled activated carbon. Then, as some treatment systems require less treatment media,[10] their recycled activated carbon could be made available to other systems. This pooling could decrease aggregate GHG emissions. Such coordination would need to enable competition between vendors, including possible future vendors that might establish in Maine. New local vendors of activated carbon would also decrease the emissions associated with transportation of the treatment media.

Information Sharing Between Treatment Facilities

Based on our research, the primary GHG emissions associated with PFAS treatment come from activated carbon use, so improving its adsorption efficiency could significantly decrease emissions. Given the large number of treatment applications that will be required to meet drinking water standards, there will be many opportunities to evaluate factors specific to Maine and to develop better understanding of actual activated carbon usage. The state should encourage and facilitate information sharing between treatment facilities and analyze the data to create best practices for the facilities. These best practices could improve adsorption efficiency at treatment sites across the state and lead to a reduction in GHG emissions associated with PFAS removal.

Periodic Reevaluation

Finally, just as the toxicological research on PFAS will continue to advance, so will technologies for treatment. The state will need to periodically reevaluate the risks and available technologies. Most research on new technologies for PFAS treatment focuses on the degree of PFAS removed from contaminated water. If it is clear, however, that policymakers are considering GHG emissions and other indirect environmental costs in the rulemaking process, then there may be increased motivation for technology developers to obtain and report this additional information. Periodic reevaluation of PFAS drinking water standards might benefit from an explicit statement that risk reduction, financial cost, *and* environmental cost are being incorporated. This is not to say that each component is of equal weight, but such a statement would be a signal that policymakers are taking a broad view for protection of human health and the environment.

SUMMARY AND CONCLUSION

Increased understanding of the human health risks from PFAS has prompted Maine to develop regulations for these chemicals in drinking water including upcoming rulemaking for an MCL. While the MCL may focus largely on reducing risk from ingestion and the cost of treatment, the state may also want to consider indirect environmental effects. Our evaluation indicates that GHG emissions will likely be an important indirect environmental effect from treatment. The most established treatment method uses activated carbon, which is energy intensive to produce and results in significant GHG emissions. Further, activated carbon suppliers are currently located outside of Maine, and transportation to Maine also generates GHG emissions. Finally, adsorption of PFAS to activated carbon becomes less efficient at lower target concentrations. Our research finds that these factors mean consumers of water treated to remove PFAS will have a significant increase in their per user GHG emissions. Treating water to reach very low PFAS concentrations in particular could result in substantial GHG emissions.

Given the potentially serious health effects from PFAS, Maine needs to act relatively quickly to develop an MCL, that is, before the treatment technologies have advanced to the point where GHG emissions are minimized. However, the rulemaking process can still incorporate information from our study on GHG emissions. Beyond considering the increased GHG emissions from a relatively low MCL (or decreased emissions from a relatively high MCL), policymakers might consider establishing individual PFAS concentration targets. The state could set less stringent standards for some PFAS compared to others so treatment can focus on the most toxic and best-adsorbing chemicals. Rulemaking might also state that periodic reevaluation of the MCL will consider the GHG emissions of treatment technologies. Such a statement could encourage developers to report this information and work toward developing lower-emissions approaches.

Finally, together with developing an MCL, the state (e.g., DEP) should consider coordinating the creation of a common pool of recycled treatment media. Such a pool could reduce the quantities of virgin activated carbon required. In addition, as treatment applications gather new information about PFAS removal, the state could facilitate information sharing and develop best practices. If the state

takes such an approach, it would demonstrate that rulemaking for an MCL is just one component of a PFAS policy. With the MCL likely affecting a wide range of drinking water users, the policy could also seek to improve treatment efficiency and minimize GHG emissions.

NOTES

1   MCLs: lead (15 µ/L), benzene (5 µ/L), benzo(a)pyrene (0.2 µ/L), and dioxin (0.00003 µ/L); https://www.epa.gov/risk/regional-screening-levels-rsls.

2   See https://data.mainepublichealth.gov/tracking/data-topics/privatewells and https://www.usgs.gov/centers/new-england-water-science-center/how-much-water-was-used-maine-2015.

3   https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle

4   https://data.worldbank.org/indicator/EN.ATM.CO2E.PC

5   For instance, in the private residential water treatment scenario with coconut-based activated carbon, doubling the target PFAS concentration from 0.020 µ/L to 0.040 µ/L means a decrease in annual per user emissions from 1.1 to 0.8 metric tons CO_2 equivalent, or a 27 percent decrease. This rate can be contrasted with cutting the standard in half to 0.010 µ/L, which increases per user emissions to 1.6 metric tons CO_2 equivalent, or a 45 percent increase. At the highest simulated target PFAS concentration, estimated annual per user GHG emissions range from 0.10 to 0.47 metric tons CO_2 equivalent. These rates are 0.67–3.1 percent of the US per capita value, suggesting that a less stringent standard could avoid significant emissions. At the lowest simulated target PFAS concentration of 0.002 µ/L, estimated annual per user emissions range from 4.1 to 17 metric tons CO_2 equivalent, or 27–110 percent of US per capita emissions.

6   US EPA advisories for PFOA (0.000004 µ/L) and PFOS (0.00002 µ/L).

7   Actual activated carbon performance for any particular treatment system will depend on a number of factors, including the PFAS mixture in the water, the dissolved organic matter content, the pH of the water, the water flow rate, the pore size of the activated carbon, the surface charge of the activated carbon, and the hydrophobicity of the activated carbon (Belkouteb et al. 2020; Crone et al. 2019; Siriwardena et al. 2019).

8   PFOA and PFOS are generally better characterized than are the others. Furthermore, a sum-of-six PFAS drinking water standard could alternatively mean people are ingesting a certain amount of either PFOA or PFHxS.

9   PFHxS is not a rare PFAS constituent. The initial PFHxS concentrations we used for simulating treatment were moderate values of 0.020 µ/L (private residential well) to 0.050 µ/L (municipal well). For the March 7, 2022, Maine sampling results database, 414 groundwater and surface water samples not designated as "treated" had concentrations greater than 0.050 µ/L. While this water was likely not used for consumption—and early sampling has prioritized areas with likely contamination—it is a preliminary indication that PFHxS may be a common constituent of water supplies with detectable PFAS. As PFHxS is relatively poorly sorbing, it may need substantial quantities of activated carbon and high GHG emissions will result from treatment to low levels.

10 e.g., highly contaminated water wells are decommissioned, other water sources become cleaner.

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