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Environmental and Cost Life Cycle Assessment of Disinfection Options for Municipal Drinking Water Treatment

Office of Research and Development
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ENVIRONMENTAL AND COST LIFE CYCLE ASSESSMENT OF DISINFECTION OPTIONS FOR MUNICIPAL DRINKING WATER TREATMENT

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ABSTRACT

EPA is evaluating water disinfection technologies in coordination with the Confluence Water Technology Innovation Cluster (WTIC) and EPA's National Risk Management Research Laboratory (NRMRL). EPA developed an environmental life cycle assessment (LCA) and cost analysis to evaluate the environmental outcomes and costs associated with innovative disinfection water treatment technologies. EPA is also interested in establishing an LCA and cost model framework that could be used to study other technologies or changes to drinking water and municipal wastewater treatment systems in the future. For each technology, there are associated differences in pathogen removal, disinfection by-product formation, treatment facility energy use and operating costs, input chemical requirements, and supply chain impacts.

This document summarizes the data collection, analysis, and results for a base case drinking water treatment (DWT) plant reference model and alternative disinfection technologies. The base case is modeled after the Greater Cincinnati Water Works (GCWW) Richard Miller Treatment Plant. The infrastructure and operational datasets collected through iterative inquires and onsite visit were used to develop the baseline life cycle model for the drinking water treatment system. Results of the base case analysis show global warming, energy demand, fossil depletion, acidification, human health cancer, human health criteria, and ecotoxicity impacts are largely driven by electricity consumption at the drinking water treatment plant and during distribution to the consumer. Labor and energy costs are the largest contributions to DWT plant costs. Disposal of sedimentation waste is the greatest contributor to eutrophication. Source water acquisition accounts for the majority of blue water use, with 1.2 m^3 of source water from the river required to deliver 1 m^3 of water to the consumer. Metal depletion impacts are primarily governed by chemical usage in the pre-disinfection and fluoridation stages as well as infrastructure requirements at the DWT plant and distribution network. Overall, the primary disinfection with gaseous chlorine life cycle stage only contributes zero to five percent to the total life cycle impacts of DWT for the results categories examined. LCA and cost results decrease slightly when excluding the adsorption step (0-15 percent).

EPA compared the base case results to four in-plant disinfection alternatives. The disinfection alternatives considered are in different stages of development. In-plant alternatives include disinfection by ultraviolet (UV) light (conventional mercury-vapor bulb system, LED UV, and plasma-bead UV) and oxidation/disinfection using ferrate ions. The in-plant alternatives would reduce the amount of chlorine required by the drinking water treatment plant among other benefits. The datasets for compiling the life cycle inventory of disinfection technologies were based on available industrial specifics and literature sources. Utilization of ferrate results in environmental, human health, and cost benefits for combined use in the pre-disinfection and primary disinfection stages, since ferrate acts as both a coagulant and disinfectant and only small dosages are required for treatment. Application of UV technology increases impacts during disinfection through increased electricity consumption and through new capital investment, but eliminates the formation of disinfection by-products and greatly reduces hazardous chlorine usage. LED UV is more energy efficient compared to conventional mercury-vapor UV; however, it is currently developed only for point-of-use applications, and not large-scale treatment facilities.

In addition, EPA considered point-of-use disinfection alternatives such as disposable membrane tap filters and small scale LED UV disinfection, which may be used in hospitals and other health care facilities to further reduce exposure to pathogens for immune-compromised individuals. Point-of-use disinfection alternatives for use at home were not considered. The point-of-use technologies are add-on technologies and are not compared to the base case results. For hospital point-of-use disinfection, the LED UV technology has the greater impacts overall compared to the disposable membrane tap filter. The LED UV system requires 0.0039 kWh per m^3 water treated for operation; whereas, the disposable membrane tap filter does not require electricity for generation.

In general, this analysis is provided to understand the potential impacts and trade-offs between different drinking water disinfection technologies within the framework of the entire drinking water supply system, and it is not intended to provide a recommendation on whether any technology is superior to other technologies. The open-source and process based models built in this study are flexible to incorporate future development of disinfection technologies and associated datasets.

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1. INTRODUCTION AND STUDY GOAL

This study investigates disinfection technologies that are currently under development in the Cincinnati Region in coordination with the Confluence Water Technology Innovation Cluster[1] and EPA's National Risk Management Research Laboratory. Each technology provides an alternative means of disinfecting drinking water and may address goals related to reducing disinfection by-products, improving microorganism and virus reduction, reducing life-cycle impacts, or reducing disinfection costs.

EPA collected data from the Greater Cincinnati Water Works (GCWW) Richard Miller Treatment Plant to develop a base case drinking water treatment (DWT) plant LCA model and cost analysis. The base case GCWW plant is a 106 million gallon per day (MGD) plant, which uses gaseous chlorine as the primary disinfectant. GCWW uses a granular activated carbon (GAC) system for removal of organics prior to chlorine addition. Additional details on the base case plant are provided in Sections 2.2 and 3.2. This study evaluated base case models with and without GAC. The goal for the base case LCA model and cost analysis is to:

1. Evaluate the base case environmental outcomes and costs to provide a baseline for comparison to alternative disinfection technologies.
2. Establish an LCA and cost model framework that could be used to study other technologies or changes to DWT systems.

This study addresses the following research questions[2]:

1. What are the net life cycle impacts associated with drinking water treatment from source water acquisition through distribution?
2. What are the contributions of each life cycle stage to the net result for each impact category?
3. How do the two different base-case drinking water treatment options compare to one another for each impact category?
4. How do the impacts and costs change as parameters associated with disinfection, energy use, and disinfection by-products (DBP) vary? What parameters associated with electricity use have the greatest effect on impacts and costs?

This study compared the results of the base case analysis to four in-plant disinfection alternatives and examined the additional impact of applying two point-of-use disinfection technologies for hospitals:

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[1]Confluence is a network of water technology researchers, businesses, utilities, and others in the southwest Ohio, northern Kentucky, and southeast Indiana region. The group was formed in 2011 with help from EPA and the U.S. Small Business Administration. See http://www.watercluster.org and http://www2.epa.gov/clusters-program for more information.

[2] This project requires the collection and use of existing data. EPA developed a Quality Assurance Project Plan (QAPP) which outlines the quality objectives for this project. The plan is entitled *Quality Assurance Project Plan for Systems-Based Sustainability and Emerging Risks Performance Assessment of Cincinnati Regional Water Technology Innovations: Comparative Life Cycle Assessment and Cost Analysis of Water Treatment Options*, and was prepared by Eastern Research Group, Inc. for U.S. EPA Sustainable Technology Division, National Risk Management Research Laboratory. The plan was approved February 2013.

- Conventional ultraviolet (UV) disinfection – UV radiation can effectively treat drinking water for viruses and bacteria. This study evaluated replacing chlorine disinfection with a conventional UV system. EPA worked with Aquionics to develop the conventional UV disinfection model. Recently GCWW installed a UV system to use in conjunction with traditional chlorine disinfection to improve removal of pathogens.
- LED UV disinfection – Use of a large-scale LED UV system. EPA worked with Aquionics to develop the LED UV disinfection model.
- Plasma-bead UV disinfection – Use of a new technology developed by Imaging Systems, which generates UV light for disinfection.
- Ferrate disinfection – Use of ferrate (FeO_4^{2-}), a strong oxidizer, for disinfection. Ferrate Treatment Technologies, LLC (FTT) has developed an on-site, skid-mounted method of producing ferrate for disinfection. Ferrate can also be used during pre-treatment as a coagulant.
- Point-of-use disinfection using disposable membrane tap filters and small scale LED UV disinfection.

Each technology has differences in pathogen removal, disinfection by-product formation, chemical and energy requirements, costs, and environmental benefits. EPA intends to answer the following research questions through the disinfection alternative analysis:

1. What are the net life cycle impacts associated with each disinfection alternative (in-plant and point-of-use add-on)?
2. For which life cycle stages do the results for the in-plant alternatives differ from the base case?
3. How do the overall plant costs change for each of the in-plant alternatives?
4. What are the costs and environmental impacts of additional reductions in pathogens for point-of-use add-ons in a health care facility?

The remainder of the report provides details on the analysis and is organized into the following sections:

- Section 2 defines the study scope.
- Section 3 provides details on the LCA methodology including a description of the unit processes included in the base case model.
- Section 4 describes the cost analysis.
- Section 5 presents base case results.
- Section 6 presents base case sensitivity results.
- Section 7 describes the in-plant alternative disinfection technologies, modifications to the LCA model and cost analysis, and results for each technology.
- Section 8 describes the point-of-use alternatives and compares costs of the alternative to additional pathogen reduction.
- Section 9 summarizes the study results.
- Section 10 provides the references for the study.

2. SCOPE

The base case DWT model includes source water acquisition, pre-disinfection, primary disinfection, and distribution. This study examined environmental impacts and changes in costs for different disinfection technologies; therefore, the base case established the reference case for comparison to alternative drinking water disinfection technologies.

2.1 Functional Unit

The functional unit, which provides the basis for comparison, used in this study is the delivery to the consumer of one cubic meter of water that meets or exceeds National Primary Drinking Water Regulations for microorganisms, disinfectants, disinfectant by-products, inorganics, organics, and radionuclides.[3] For the point-of-use technology analysis, the drinking water delivered to the consumer has a greater reduction in pathogens compared to the base case and in-plant disinfection technology alternatives analysis. Results for the point-of-use analysis are, therefore, not compared directly to results for the base case or in-plant alternative technologies as the end product delivered by these different pathways are not functionally equivalent.

2.2 System Boundaries

Figure 1 illustrates the system for the DWT base case model. The system boundaries start at acquisition of source water from a river and end at delivery of the treated drinking water to the consumer. Transportation requirements for all inputs to the processes within supply chains, such as transporting alum coagulant to the treatment plant, are also included as are all capital equipment and infrastructure requirements for the drinking water treatment plant and distribution network. Impacts for the following two base case model runs were evaluated:

- **Base Case 1:** Representative moderate-sized water treatment facility, including GAC adsorption.
- **Base Case 2**: Variation of the base case excluding GAC adsorption.

[3] U.S. EPA (2013) "National Primary Drinking Water Regulations" http://water.epa.gov/drink/contaminants/index.cfm

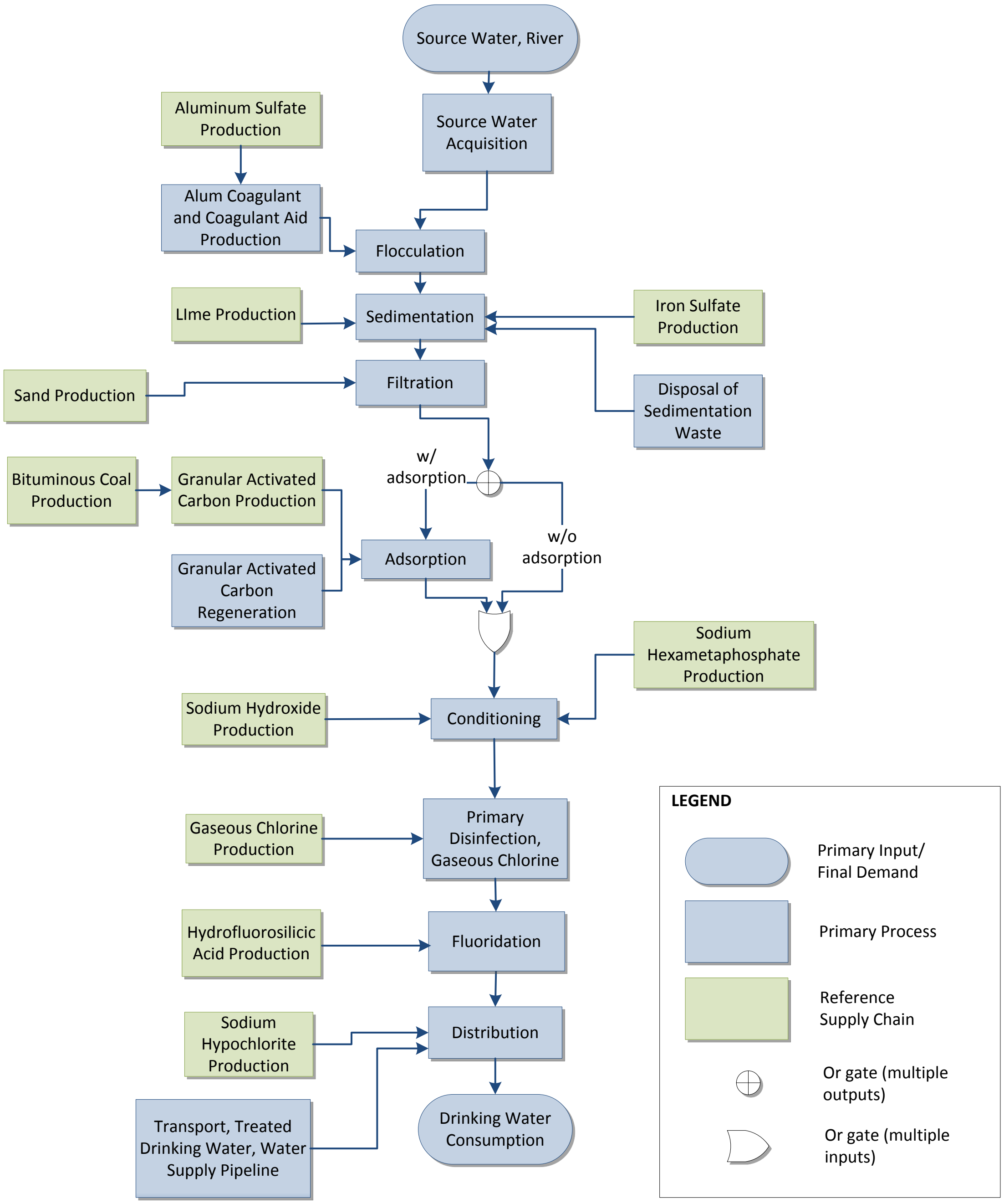


Figure 1. System boundaries of drinking water treatment base case options. Drinking water treatment operations along with infrastructure raw material extraction and construction are within the system boundaries. End-of-life of infrastructure is excluded due to lack of available data.

The GCWW Richard Miller Treatment Plant serves customers in Cincinnati and the surrounding towns in Ohio and Kentucky. The plant has 241,000 customers, of which 230,000 are residential customers. The remaining are either businesses or other non-residential customers. In terms of volume of water supplied, 16 percent of the treated water volume goes to wholesale customers, 48 percent of the treated water volume goes to residential customers, and 36 percent of the treated water volume goes to non-residential customers. GCWW was the first major municipal water provider to utilize granular activated carbon for adsorption of toxins.[4] While this adsorption process offers health benefits for consumers of GCWW water, it is not used in other areas and is not necessary for some other water sources. While GCWW was used as a reference for this study to allow the results to be based on actual operating conditions, the intent is that the results can be extrapolated to provide input to decisions made for other systems as well. For this reason, a second set of base case results without the GAC adsorption process are provided.

Table 1 shows the primary life cycle stages and unit processes included in Base Case 1 and 2.

Table 1. Primary unit process matrix for the two base case models.

Life Cycle Stage Reported	Unit Processes Covered	Base Case 1	Base Case 2
Source Water Acquisition	Source Water Acquisition	X	X
Drinking Water Treatment Plant, Energy and Infrastructure	Drinking Water Treatment Plant, Energy Usage	X	X
Pre-Disinfection	Flocculation	X	X
	Alum Coagulant	X	X
	Sedimentation	X	X
	Disposal, Sedimentation Waste	X	X
	Filtration	X	X
	Adsorption	X	
	GAC Production	X	
	GAC Regeneration	X	
Primary Disinfection	Primary Disinfection, Gaseous Chlorine	X	X
Distribution	Fluoridation	X	X
	Transport, Treated Drinking Water, Water Supply Pipeline	X	X
	Distribution Infrastructure, Drinking Water	X	X
Use	Drinking Water Consumption	X	X

2.3 Impacts and Flows Tracked

The full inventory of emissions generated in an LCA study is lengthy and diverse, making it difficult to interpret emissions profiles in a concise and meaningful manner. Life Cycle Impact

[4] Activated Carbon: Solutions for Improving Water Quality, Zaid K. Chowdhury, Garret P. Westerhoff, R. Scott Summers, Brian Leto, Kirk Nowack, American Water Works Association, 2012.

Assessment (LCIA) helps with interpretation of the emissions inventory. In the LCIA phase, the inventory of emissions is first classified into categories in which the emissions may contribute to impacts on human health or the environment. Within each impact category, the emissions are then normalized to a common reporting basis, using characterization factors that express the impact of each substance relative to a reference substance.

Table 2 shows the complete list of impacts examined for the base case model runs. This study addresses global, regional, and local impact categories. The LCIA method provided by the Tool for the Reduction and Assessment of Chemical and Environmental Impacts (TRACI), version 2.0, developed by the U.S. EPA specifically to model environmental and human health impacts in the U.S., is the primary LCIA method applied in this work.[5] Additionally, the ReCiPe LCIA method is used to characterize fossil fuel, blue water use (i.e. water depletion), and metal depletion.[6] Energy is tracked based on point of extraction using the cumulative energy demand method developed by Ecoinvent.[7] The blue water use impact category represents freshwater use from surface water or groundwater sources. The blue water use category includes indirect consumption of water from upstream processes, such as water withdrawals for electricity generation (e.g., evaporative water losses from coal power cooling water and establishment of hydroelectric dams).[8] Some flows specific to drinking water treatment, and not typically reported in LCA studies, are included in the results reported in the analysis:

- Cryptosporidium (Crypto) Exposure
- Total Trihalomethanes (TTHM) Exposure
- Chlorine Usage

These unique flows are tracked based on data reported by GCWW for specific life cycle stages, and do not cover all potential upstream exposure to cryptosporidium and TTHM or upstream use of chlorine. The purpose of tracking and displaying these aspects is to provide a more balanced, albeit cursory, analysis of other benefits associated with the disinfection technologies addressed by this study. These results are intended to be supplemented by additional studies focused on providing better resolution of these aspects for decision-making purposes within the context of a specific system. They are provided here for context.

[5] EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), see: http://www.epa.gov/nrmrl/std/sab/traci/.

[6] Goedkoop M.J., Heijungs R, Huijbregts M., De Schryver A.; Struijs J., Van Zelm R, ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level; First edition Report I: Characterisation; 6 January 2009, http://www.lcia-recipe.net

[7] Ecoinvent Cumulative Energy Demand (CED) Method implemented in ecoinvent data v2.2. 2010. Swiss Centre for Life Cycle Inventories.

[8] Pfister, S., Saner, D., Koehler, A. 2011. The environmental relevance of freshwater consumption in global power production. International Journal of Life Cycle Assessment, 16 (6): 580-591.

Table 2. Impact and flow results categories.

Category	Methodology	Unit	Description
Cost	Cost Analysis	$	Measures total cost in U.S. dollars.
Crypto Exposure	Individual Flow	oocyst	Measures exposure of consumer to cryptosporidium in delivered drinking water. Cryptosporidum levels reported in Distribution life cycle stage.
TTHM Exposure	Individual Flow	kg TTHM	Measures exposure of consumer to TTHM in delivered drinking water. TTHM levels reported in Distribution life cycle stage.
Chlorine Usage	Individual Flow	kg Cl_2	Measures gaseous chlorine usage for primary disinfection, which indicates on-site storage of this hazardous chemical.
Global Warming	TRACI 2.0	kg CO_2 eq	Represents the potential heat trapping capacity of greenhouse gases.
Energy Demand	ecoinvent	MJ eq	Measures the total energy use from point of extraction.
Fossil Depletion	ReCiPe	kg oil eq	Assesses the potential reduction of fossil fuel energy resources.
Acidification	TRACI 2.0	H+ moles eq	Quantifies the potential acidifying effect of substances on their environment.
Eutrophication	TRACI 2.0	kg N eq	Assesses potential impacts from excessive load of macro-nutrients to the environment.
Blue Water Use	Custom	m^3	Calculates consumptive use of fresh surface or groundwater.
Smog	TRACI 2.0	kg O_3 eq	Determines the potential formation of reactive substances (e.g. tropospheric ozone) that cause harm to human health and vegetation.
Ozone Depletion	TRACI 2.0	kg CFC-11 eq	Measures potential stratospheric ozone depletion.
Metal Depletion	ReCiPe	kg Fe eq	Assesses the potential reduction of metal resources.
Human Health, Cancer, Total	TRACI 2.0	CTU	A comparative toxic unit (CTU) for cancer characterizes the probable increase in cancer related morbidity (from inhalation or ingestion) for the total human population per unit mass of a chemical emitted.
Human Health, NonCancer, Total	TRACI 2.0	CTU	A CTU for noncancer characterizes the probable increase in noncancer related morbidity (from inhalation or ingestion) for the total human population per unit mass of a chemical emitted.
Human Health, Criteria	TRACI 2.0	kg PM10 eq	Assesses human exposure to elevated particulate matter less than 10 µm.
Ecotoxicity, Total	TRACI 2.0	CTU	Assesses potential fate, exposure, and effect of chemicals on the environment.

2.3.1 *Normalized and Weighted Results*

Normalization is an optional step in LCA that aids in understanding the significance of the impact assessment results. Normalization is conducted by dividing the impact category results by a normalized value. The normalized value is typically the environmental burdens of the region of interest either on an absolute or per capita basis. The results presented here are normalized to reflect person equivalents in the U.S. using TRACI v2.1 normalization factors.[9] Only impacts with TRACI normalization factors are shown. Some categories like blue water use and energy demand are excluded due to lack of available normalization factors.

[9] Ryberg, M., Vieira, M.D.M., Zgola, M., Bare, J., and Rosenbaum, R.K., 2014. Updated US and Canadian normalization factors for TRACI 2.1. Clean Techn Environ Policy, 16: 329-339.

Weighting is an additional optional step in LCA that provides a link between the quantitative results and subjective choices of decision makers. This study applies weights to the normalized results described above. The weights utilized here were developed by the National Institute of Standards and Technology (NIST) for the BEES (Building for Environmental and Economic Sustainability) software.[10] This weighting set was created specifically for the buildings sector context, which may not be completely compatible with the water treatment sector. However, due to lack of a weighting set specific to the water treatment sector, this NIST weighting set has been utilized.

3. LCA METHODOLOGY

Development of a life cycle assessment requires significant input data, an LCA modeling platform, and impact assessment methods. This section provides background on the development of the LCA model. Section 3.1 discusses the data collection method and model, Section 3.2 describes the unit processes, Section 3.3 lists the data sources, and Section 3.4 describes limitations of the LCA model.

In this study, GCWW provided much of the LCA input data for the unit processes listed in Table 1. This study also used publicly accessible and private databases to provide underlying data sets describing the supply chains of inputs to the processes modeled here. For example, in addition to the unit processes described in Section 3.2, an LCA also includes impacts from the production of any materials required in the process.

3.1 Data Collection and Model

The accuracy of the study is directly related to the quality of input data. Data were collected electronically using Excel templates designed by the project team to be completed by GCWW. Data collection was an iterative process whereby the project team asked GCWW multiple rounds of questions to ensure all necessary life cycle and cost information was being reported and properly interpreted in the assessment. The quality and objectivity of results were ensured through carefully adhering to the data collection protocols and quality procedures laid out in the Quality Assurance Project Plan prior to beginning work on the project.

Each unit process in the life cycle inventory was constructed independently of all other unit processes. This allows objective review of individual data sets before their contribution to the overall life cycle results has been determined. Also, because these data are reviewed individually, EPA reviewed assumptions based on their relevance to the process rather than their effect on the overall outcome of the study.

The model was constructed in OpenLCA, an open-source LCA software package provided by GreenDelta.

[10] Gloria, T.P., Lippiatt, B.C., and Cooper, J. 2007. Life cycle impact assessment weights to support environmentally preferable purchasing in the United States. Environ. Sci. Technol, 41, 7551-7557.

3.2 Unit Processes

EPA developed new unit processes for the specific DWT processes listed below (categorized by the overall life cycle stage). As shown in Figure 1, the DWT base case unit processes start with source water acquisition and end with drinking water use. Unit processes from background LCI database (e.g., ecoinvent v2.2 and U.S. LCI) that have not been modified are identified in Section 3.3, Table 3 (Data Sources). On-site DWT plant infrastructure is included for each unit where applicable. Section 3.4 covers the details of the infrastructure modeling.

Drinking water acquisition

1. **Source Water Acquisition.** The GCWW Miller Plant used for the base case model uses surface water from a river for the raw water source.

Drinking Water Treatment Plant, Energy Usage

2. **Drinking Water Treatment Plant, Energy Usage.** Covers all electricity required to pump in raw water, and pumping energy throughout the drinking water treatment plant.

Pre-Disinfection

3. **Flocculation.** Aggregates suspended solids by adding coagulant and coagulant aid and mixing to increase the particle size to allow settling. Alum is modeled as the coagulant.
4. **Alum Coagulant**. Production of average alum derived from industrial aluminum sulfate.
5. **Sedimentation.** Removes suspended solids from water by gravity settling. In an intermediate step "lime addition", lime is added in clarification basins prior to filtration.
6. **Disposal, Sedimentation Waste.** Disposal of settled solids to surface water.
7. **Filtration.** Removes remaining solids from water using a sand filter. Includes replacement of filter materials during normal operation life of the filter.
8. **Adsorption.** Removes organics by a granular activated carbon (GAC) system. As noted in Table 1, adsorption is not included in Base Case 2.
9. **Granular Activated Carbon Production.** Production of average U.S. granular activated carbon from bituminous coal. GAC production is not included in Base Case 2.
10. **Granular Activated Carbon Regeneration**. Regenerates activated carbon by conventional thermal regeneration method with natural gas as the required energy source. Also includes carbon loss and replacement. GAC regeneration is not included in Base Case 2.
11. **Conditioning**. Adjust pH using sodium hydroxide and addition of a polyphosphate, sodium hexametaphosphate.
12. **Pre-Disinfection.** This unit process aggregates the upstream pre-disinfection unit processes from flocculation through conditioning.

Disinfection

13. **Primary Disinfection, Gaseous Chlorine.** Representative of a conventional DWT system using gaseous chlorine for primary disinfection.

Distribution

14. **Fluoridation.** Hydrofluorosilicic acid addition prior to distribution.
15. **Transport, Treated Drinking Water, Water Supply Pipeline.** Transporting treated drinking water to end users. Accounts for pumping energy.

16. **Valves for Distribution System.** Steel required for production of valves for distribution system.
17. **Pumps for Distribution System.** Cast iron and steel for production of pumps for distribution system.
18. **Motors for Distribution System.** Steel, copper, aluminum, and cast iron for production of motors for distribution system.
19. **Water Storage Infrastructure.** Concrete and steel for construction of water storage tanks, earthworks associated with reservoir construction.
20. **Distribution Pipe Network.** Production and installation of concrete and iron pipes for distribution system.
21. **Distribution.** This unit process aggregates upstream distribution unit processes including fluoridation, pipeline transport of the treated drinking water, and infrastructure components of the distribution system. Sodium hypochlorite is also added as an input to the distribution life cycle stage as it is used in small amounts to boost the chlorine levels in certain sections of the distribution system.

Use

22. **Drinking Water Consumption.** Final delivery of water to an average consumer. This unit process aggregates the other main life cycle stages and is used to build the final product system. There are no actual impacts associated with the drinking water consumption life cycle stage itself.

3.3 Base Case Data Sources

Table 3 displays the data sources used for the DWT base case model. In general, data from GCWW were used where available. GCWW provided data for their Richard Miller Treatment Plant, which produces approximately 106 MGD of finished drinking water. The incoming and outgoing water quality metrics for the Richard Miler Treatment Plant reported for this study are shown in Table 4. For upstream processes that would not be known by GCWW such as information on chemical production, EPA used information from the National Renewable Energy Laboratory's U.S. Life Cycle Inventory Database (U.S. LCI), a publically available life cycle inventory source.[11] Where data were not available from GWCC or the U.S. LCI, EPA used ecoinvent v2.2, a private Swiss LCI database with data for many unit processes.[12] Table 5 presents the complete DWT base case LCI data used in the model on the basis of one cubic meter of drinking water delivered to the consumer.

[11] National Renewable Energy Lab. US LCI Database. See: http://www.nrel.gov/lci/database/default.asp.

[12] Ecoinvent Centre (2010), ecoinvent data v2.2. ecoinvent reports No. 1-25, Swiss Centre for Life Cycle Inventories.

Table 3. Data sources.

Process	Data Source
Source Water Acquisition	Data Collection-GCWW
Incoming Transport of Chemicals to DWTP	Data Collection-GCWW
Gaseous Chlorine Production	ecoinvent v2.2
Sodium Chloride Production	ecoinvent v2.2
Flocculation	Data Collection-GCWW
Aluminum Sulfate Production (Powder)	ecoinvent v2.2
Sulfuric Acid Production	ecoinvent v2.2
Aluminum Hydroxide Production	ecoinvent v2.2
Iron Sulfate	ecoinvent v2.2
Sedimentation (Operation)	Data Collection-GCWW
Disposal of Sedimentation Waste	Data Collection-GCWW
Filtration (Operation)	Data Collection-GCWW
Sand Production (for Use in Filter)	ecoinvent v2.2
Adsorption	Data Collection-GCWW
GAC Production	Data Collection-GCWW
GAC Regeneration	Data Collection-GCWW
Bituminous Coal Production	U.S. LCI
Conditioning	Data Collection-GCWW
Sodium Hydroxide Production	ecoinvent v2.2
Sodium Hexametaphosphate[a]	ecoinvent v2.2
Lime Production	U.S. LCI
Primary Disinfection	Data Collection-GCWW
Gaseous Chlorine Production	ecoinvent v2.2
Sodium Hypochlorite Production	ecoinvent v2.2
Fluoridation	Data Collection-GCWW
Hydrofluorosilicic Acid Production[b]	ecoinvent v2.2
Distribution (Operation)	Data Collection-GCWW
Background Fuels and Energy	U.S. LCI
Infrastructure at the DWT Plant	Data Collection-GCWW
Infrastructure in the Distribution System	Data Collection-GCWW
Background Transportation Processes	U.S. LCI

[a] Using sodium tripolyphosphate as surrogate, since no available LCI data exists for sodium hexametaphosphate.
[b] Using hydrogen fluoride (HF) as surrogate, since fluorosilicic acid is a by-product of HF production, and no available LCA data exists for hydrofluorosilicic acid production.

Table 4. Incoming and outgoing water quality metrics for GCWW Richard Miller Treatment Plant (per m^3 water).

	Incoming Water			Outgoing Water			
Water Metrics	Minimum	Maximum	Average	Minimum	Maximum	Average	Unit (per m^3 water)
Ammonia	<0.010	0.19	0.050	0	0	0	g
Arsenic	<0.001	0.0016	<0.001	<0.001	<0.001	<0.001	g
Chromium	<5.0E-04	0.0029	0.0010	<0.010	<0.010	<0.010	g
Dissolved organic carbon	2.50	3.30	2.99	0.61	1.01	0.94	g
Dissolved solids	158	299	229	132	317	228	g
Iron	0.30	0.30	0.30	<0.020	<0.020	<0.020	g
Manganese	0.053	0.053	0.053	<0.010	<0.010	<0.010	g
Nitrate	0.63	1.14	0.89	0.62	1.06	0.86	g
pH	7.50	8.40	7.80	8.20	8.80	8.80	pH
Phosphorus	0.030	0.11	0.060	0.15	0.20	0.17	g
Suspended solids	1.90	225	43.1	0	0	0	g
Temperature	5.10	33.0	18.0	4.70	29.0	17.0	ºC
Total organic carbon	2.10	4.80	3.05	0.40	1.43	0.85	g
Turbidity	2.40	307	46.0	0.050	0.13	0.070	NTU
TTHM	<5.0E-04	<5.0E-04	<5.0E-04	0.0078	0.020	0.016	g
Chlorine	0	0	0	1.13	1.66	1.37	g
Cryptosporidium	<20.0	<91.0	<51.0	<0.80	<1.10	<1.00	oocysts
Giardia	<20.0	200	20.0	<0.80	<1.10	<1.00	oocysts
E. coli	0	6,030,000	1,340,000	0	0	0	counts
Heterotrophic plate count	0	14,000,000,000	2,250,000,000	0	0	0	counts

Source: GCWW primary data collection for the year 2011.

Table 5. Base case DWT LCI model-input and output operational data (per m³ drinking water delivered to consumer).

			TOTAL	Quantity by Life Cycle Stage														
		Unit	Quantity	Source Water Acquisition	Energy for Pumping	Flocculation	Sedimentation	Disposal, Sedimentation Waste	Lime Addition	Filtration	Adsorption	GAC Reactivation	Conditioning	Primary Disinfection, Gaseous Chlorine	Fluoridation	Distribution	Transport, Treated Drinking Water, Water Supply Pipeline	Drinking Water Consumption
Inputs																		
Primary Raw Material	Raw water, river	m3	**1.19**	1.19														
Energy	Purchased electricity	kWh	**0.74**		0.32												0.62	
	Electricity from on-site hydroelectric cogeneration	kWh	**0.019**		0.019													
	Natural gas	m3	**0.0026**									0.0026						
Material and Chemical Inputs	Alum coagulant, 48% aluminum sulfate	kg	**0.019**			0.019												
	Polymer (polyDADMAC, 10%)	kg	**0.0021**			0.0021												
	Ferric sulfate	kg	**0.0014**				0.0014											
	Quicklime at plant	kg	**0.0032**						0.0032									
	Sand	kg	**0.0082**							0.0082								
	GAC from bituminous coal	kg	**0.0030**								0.0030							
	Sodium hypochlorite, 15%	kg	**5.0E-04**													5.0E-04		
	Sodium hydroxide, 50%	kg	**0.027**										0.027					
	Sodium hexametaphosphate, 30%	kg	**0.0024**										0.0024					
	Gaseous chlorine	kg	**0.0021**											0.0021				
	Hydrofluorosilicic acid, 24%	kg	**0.0051**												0.0051			
Transport	Combination truck transport, alum coagulant	tkm	**0.0012**			0.0012												
	Combination truck transport, lime	tkm	**1.2E-04**						1.2E-04									
	Combination truck transport, ferric sulfate	tkm	**8.6E-04**				8.6E-04											
	Combination truck transport, gaseous chlorine	tkm	**1.3E-04**											1.3E-04				
	Rail transport, gaseous chlorine	tkm	**7.3E-04**											7.3E-04				
	Combination truck transport, hydrofluorosilicic acid	tkm	**1.2E-04**												1.2E-04			
	Rail transport, hydrofluorosilicic acid	tkm	**0.0076**												0.0076			

		Unit	TOTAL Quantity	Quantity by Life Cycle Stage: Source Water Acquisition	Energy for Pumping	Flocculation	Sedimentation	Disposal, Sedimentation Waste	Lime Addition	Filtration	Adsorption	GAC Reactivation	Conditioning	Primary Disinfection, Gaseous Chlorine	Fluoridation	Distribution	Transport, Treated Drinking Water, Water Supply Pipeline	Drinking Water Consumption
	Combination truck transport, sodium hypochlorite	tkm	**2.7E-05**													2.7E-05		
	Combination truck transport, sodium hydroxide	tkm	**2.7E-05**										2.7E-05					
	Barge transport, sodium hydroxide	tkm	**6.0E-04**										6.0E-04					
	Combination truck transport sodium hexametaphosphate	tkm	**1.3E-04**										1.3E-04					
	Combination truck transport polymer (polyDADMAC)	tkm	**9.8E-04**			9.8E-04												
	Combination truck transport GAC	tkm	**6.5E-04**								6.5E-04							
Outputs																		
Waste & Loss	Disposal of sedimentation waste	liters	**0.048**				0.048											
	Water loss	m3	**0.19**	0.0036												0.19		
Water Emissions	Aluminum (water emissions)	kg	**0.0016**					0.0016										
	Ammonia (water emission)	kg	**3.6E-06**					3.6E-06										
	Biological oxygen demand (water emission)	kg	**3.9E-04**					3.9E-04										
	Chemical oxygen demand (water emission)	kg	**0.0081**					0.0081										
	Suspended solids (water emission)	kg	**0.016**					0.016										
Air Emissions	Carbon monoxide (air emission)	kg	**2.7E-05**									2.7E-05						
	Nitrogen oxides (air emission)	kg	**9.2E-05**									9.2E-05						
	Particulates, <10 um (air emission)	kg	**1.5E-05**									1.5E-05						
	Particulates, <2.5 um (air emission)	kg	**1.5E-05**									1.5E-05						
	Sulfur oxides (air emission)	kg	**2.9E-04**									2.9E-04						
	Volatile organic compounds (air emission)	kg	**1.3E-05**									1.3E-05						
Final Product	Drinking water delivered to consumer	m3	**1.00**															1.00

Source: GCWW primary data collection from the year 2011.

3.4 Infrastructure Modeling

Infrastructure at the drinking water treatment plant and for the distribution system was included in the model based on primary data collected from GCWW. In the Figure 2 system boundaries, infrastructure components modeled are shown in red. Each infrastructure component was normalized to a cubic meter of water delivered to a consumer. It was assumed, based on discussion with engineers at GCWW regarding replacement rates, that the lifetime of the buildings, features, and pipes is 100 years. A shorter lifetime of 25 years was estimated for the pumps and motors. Infrastructure was normalized by dividing the total infrastructure impact by the total lifetime of the component, and then by the water delivered per year. It is assumed that the water delivered per year (for every year during the infrastructure component lifetime) is 123,560,247 cubic meters, which is the volume of drinking water delivered to consumers in 2011. The infrastructure requirements for plant buildings and features (e.g., reservoirs, tanks), at plant piping, distribution system piping, water storage in distribution system, and distribution pumps and motors are shown in Table 6 through Table 9. To simplify the model for the distribution system piping, only pipe types that represent more than 0.5 percent of the total length were included. Pipe types greater than 0.5 percent of the length were then scaled up to represent 100 percent of the total distribution system pipe length. Construction burdens were determined based on the volume of earthworks required per infrastructure component.

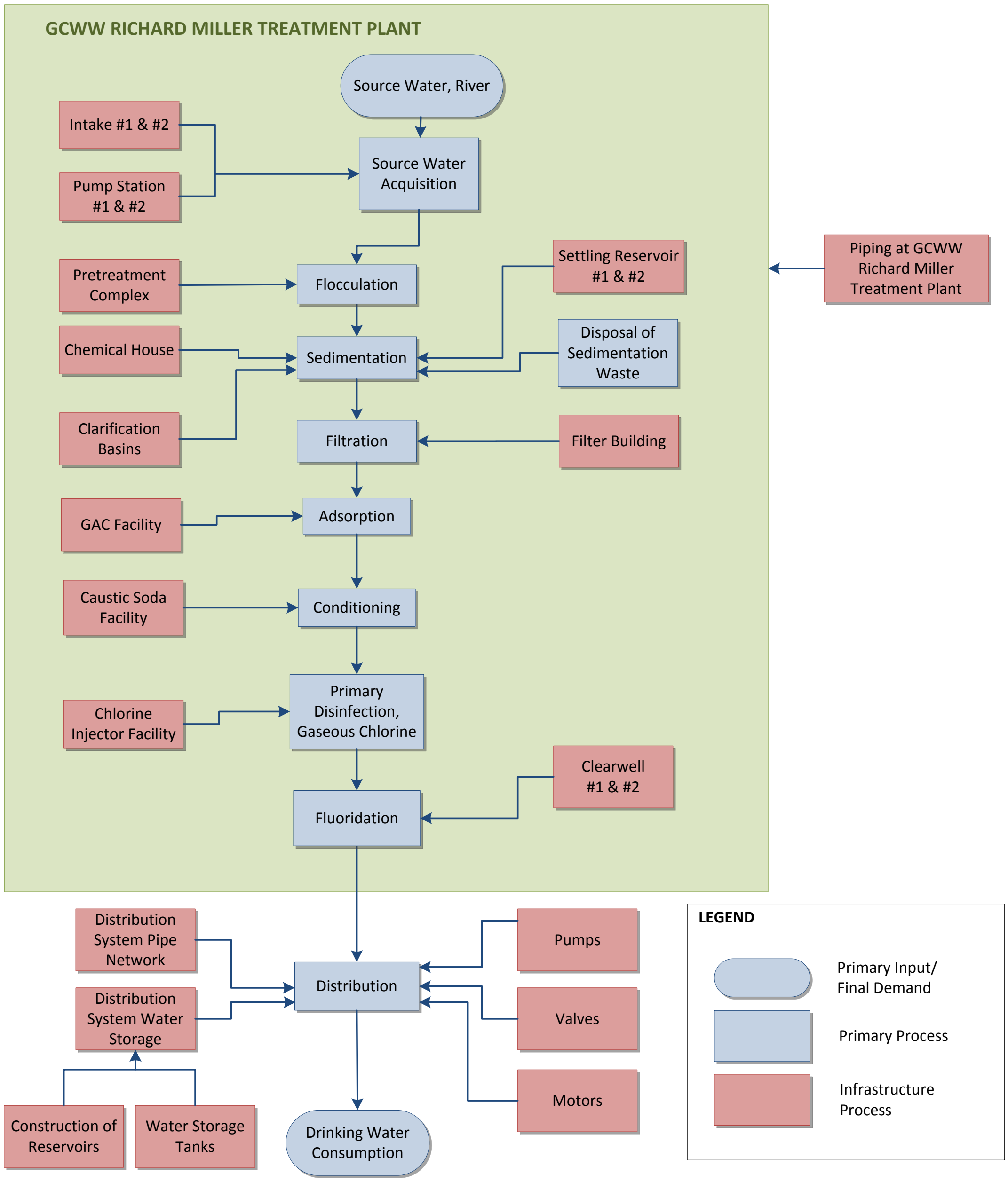


Figure 2. System boundaries of drinking water treatment base case showing infrastructure input.

Table 6. Infrastructure requirements for drinking water treatment plant buildings and features (per m^3 water delivered to consumer).

		Material Type					
Life Cycle Stage	**Infrastructure Component**	*Earthworks (m3)*	*Reinforcing Steel (kg)*	*6.5' Concrete piping (m)*	*Concrete (m3)*	*Bricks (kg)*	*Limestone (kg)*
Source Water Acquisition	Intake 1 (to Pump Station 1)	1.2E-05	0	0	0	9.4E-04	0.0012
	Intake 2 (to Pump Station 2)	1.2E-05	0	0	0	9.4E-04	0.0012
	Pump Station 1 (Near River)	8.9E-07	0	0	0	0	0.0024
	Pump Station 2 (Farther from River)	3.3E-06	5.1E-05	6.9E-08	6.0E-07	0	0
Flocculation	Pretreatment Complex	7.4E-06	1.1E-04	1.5E-07	1.3E-06	0	0
Sedimentation	Settling Reservoir #1 (Closer to Pump Station)	4.8E-05	0	0	0	1.8E-04	0
	Settling Reservoir #2 (Farther from Pump Station)	5.3E-05	0	0	0	1.9E-04	0
	Chemical House (East)	9.3E-07	1.4E-05	1.9E-08	1.7E-07	0	0
	Clarification Basins	6.4E-06	0	0	4.1E-07	0	0
Filtration	Filter Building	5.2E-06	8.0E-05	1.1E-07	9.3E-07	0	0
Adsorption	GAC Facility	1.4E-05	2.1E-04	2.9E-07	2.5E-06	0	0
Conditioning	Caustic Soda Facility	4.1E-06	6.4E-05	8.6E-08	7.4E-07	0	0
Primary Disinfection	Chlorine Injector Facility	2.6E-07	4.1E-06	5.5E-09	4.8E-08	0	0
Fluoridation	Clearwell #1	9.9E-06	0	0	4.7E-07	0	0
	Clearwell #2	2.4E-06	0	0	1.8E-07	0	0

Source: GCWW primary data collection with estimations made with facility map.

Table 7. Infrastructure requirements for drinking water treatment plant on-site piping (per m^3 water delivered to consumer).

		Pipe Type				
Life Cycle Stage	**Diameter**	*Gray Iron Pipe (m)*	*Ductile Iron Pipe (m)*	*Concrete Pipe (m)*	*Total Length (m)*	*Earthworks (m3)*
Source Water Acquisition	7'	0	0	9.8E-08	9.8E-08	1.0E-06
	36"	2.7E-09	1.6E-09	2.4E-10	4.6E-09	1.8E-08
	50"	3.8E-08	2.3E-08	3.4E-09	6.4E-08	3.5E-07
	54"	1.9E-09	1.2E-09	1.7E-10	3.3E-09	2.0E-08
	72"	1.2E-09	7.0E-10	1.0E-10	2.0E-09	1.7E-08
Flocculation	60"	6.5E-09	4.0E-09	5.9E-10	1.1E-08	7.6E-08
	72"	7.4E-08	4.5E-08	6.7E-09	1.3E-07	1.1E-06
Sedimentation	36"	2.3E-09	1.4E-09	2.1E-10	3.9E-09	1.5E-08
	54"	2.7E-09	1.6E-09	2.4E-10	4.6E-09	2.8E-08
	60"	7.3E-08	4.4E-08	6.6E-09	1.2E-07	8.4E-07
	72"	1.8E-08	1.1E-08	1.7E-09	3.1E-08	2.7E-07
	60"	3.7E-08	2.2E-08	3.3E-09	6.3E-08	4.3E-07
Filtration	36"	1.2E-08	7.4E-09	1.1E-09	2.1E-08	7.0E-08
Adsorption	36"	6.9E-09	4.2E-09	6.2E-10	1.2E-08	4.6E-08
Conditioning	36"	3.1E-09	1.9E-09	2.8E-10	5.2E-09	2.1E-08
Fluoridation	36"	1.5E-08	9.3E-09	1.4E-09	2.6E-08	1.0E-07

Source: GCWW primary data collection with estimations made with facility map.

Table 8. Infrastructure requirements for drinking water treatment distribution system piping (per m^3 water delivered to consumer).

		Pipe Type									
Life Cycle Stage	**Diameter**	*Gray Iron (m)*	*Ductile Iron (m)*	*Concrete (m)*	*Steel (m)*	*Copper (m)*	*PVC (m)*	*HDPE (m)*	*Transite (m)*	*Total Length (m)*	*Earthworks (m3)*
Distribution	0.75"	2.30E-09	1.39E-09	2.07E-10	1.81E-11	4.78E-12	1.26E-12	5.41E-12	1.27E-11	3.95E-09	4.21E-09
	1"	6.76E-09	4.10E-09	6.09E-10	5.32E-11	1.41E-11	3.70E-12	1.59E-11	3.73E-11	1.16E-08	1.25E-08
	1.5"	1.06E-08	6.41E-09	9.52E-10	8.33E-11	2.20E-11	5.78E-12	2.49E-11	5.84E-11	1.81E-08	2.01E-08
	2"	2.90E-07	1.76E-07	2.61E-08	2.28E-09	6.03E-10	1.59E-10	6.82E-10	1.60E-09	4.97E-07	5.67E-07
	2.5"	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	3"	1.88E-08	1.14E-08	1.69E-09	1.48E-10	3.90E-11	1.03E-11	4.41E-11	1.04E-10	3.22E-08	3.87E-08
	4"	1.52E-06	9.19E-07	1.37E-07	1.19E-08	3.15E-09	8.30E-10	3.57E-09	8.38E-09	2.60E-06	3.29E-06
	6"	7.52E-05	4.55E-05	6.77E-06	5.92E-07	1.56E-07	4.11E-08	1.77E-07	4.15E-07	1.29E-04	1.80E-04
	8"	9.28E-05	5.62E-05	8.36E-06	7.31E-07	1.93E-07	5.07E-08	2.18E-07	5.12E-07	1.59E-04	2.43E-04
	10"	4.05E-06	2.45E-06	3.65E-07	3.19E-08	8.41E-09	2.21E-09	9.52E-09	2.24E-08	6.94E-06	1.16E-05
	12"	3.21E-05	1.94E-05	2.89E-06	2.53E-07	6.67E-08	1.76E-08	7.55E-08	1.77E-07	5.50E-05	9.97E-05
	16"	3.85E-06	2.33E-06	3.47E-07	3.03E-08	8.00E-09	2.11E-09	9.06E-09	2.13E-08	6.60E-06	1.40E-05
	20"	8.10E-06	4.91E-06	7.29E-07	6.38E-08	1.68E-08	4.43E-09	1.90E-08	4.47E-08	1.39E-05	3.39E-05
	24"	4.71E-06	2.85E-06	4.24E-07	3.71E-08	9.78E-09	2.57E-09	1.11E-08	2.60E-08	8.07E-06	2.25E-05
	30"	9.96E-07	6.03E-07	8.97E-08	7.84E-09	2.07E-09	5.45E-10	2.34E-09	5.50E-09	1.71E-06	5.71E-06
	35"	3.98E-06	2.41E-06	3.58E-07	3.13E-08	8.26E-09	2.17E-09	9.35E-09	2.20E-08	6.82E-06	2.62E-05
	36"	4.55E-06	2.76E-06	4.10E-07	3.58E-08	9.45E-09	2.49E-09	1.07E-08	2.51E-08	7.80E-06	3.08E-05
	42"	9.26E-07	5.61E-07	8.34E-08	7.29E-09	1.92E-09	5.06E-10	2.18E-09	5.11E-09	1.59E-06	7.30E-06
	44"	2.95E-06	1.79E-06	2.66E-07	2.32E-08	6.13E-09	1.61E-09	6.94E-09	1.63E-08	5.06E-06	2.44E-05
	46"	3.57E-07	2.16E-07	3.22E-08	2.81E-09	7.42E-10	1.95E-10	8.40E-10	1.97E-09	6.13E-07	3.10E-06
	48"	1.29E-06	7.82E-07	1.16E-07	1.02E-08	2.68E-09	7.06E-10	3.04E-09	7.13E-09	2.21E-06	1.17E-05
	54"	2.73E-07	1.66E-07	2.46E-08	2.15E-09	5.68E-10	1.49E-10	6.42E-10	1.51E-09	4.68E-07	2.83E-06
	60"	3.06E-07	1.85E-07	2.76E-08	2.41E-09	6.36E-10	1.67E-10	7.19E-10	1.69E-09	5.25E-07	3.58E-06

Source: GCWW Primary data collection from 2011 water main inventory.

Table 9. Infrastructure requirements for drinking water treatment distribution system water storage, motors, pumps, and valves (per m^3 water delivered to consumer).

		Material Type							
Life Cycle Stage	**Infrastructure**	*Concrete (m3)*	*Steel (kg)*	*Earthworks (m3)*	*Electrical steel (kg)*	*Stainless 18/8 coil (kg)*	*Cast Iron (kg)*	*Aluminum (kg)*	*Copper (kg)*
Distribution	Water Storage Tanks	3.2E-08	6.4E-05	0	0	0	0	0	0
	Reservoirs	0	0	2.9E-05	0	0	0	0	0
	Motors	0	8.8E-06	0	4.1E-05	0	3.9E-05	2.4E-06	7.1E-06
	Pumps	0	0	0	0	4.5E-06	6.0E-05	0	0
	Valves	0	0.0021	0	0	0	0	0	0

Source: GCWW primary data collection.

3.5 LCA Limitations

While limitations of this study are discussed throughout this paper, some of the main limitations that readers should understand when interpreting the data and findings are as follows:

- **Water Quality Metrics.** A unique aspect to this study is that detailed water metrics were collected for source water quality, disinfection by-products, and pathogens. The majority of metrics under these categories are not included in standard LCIA methods; therefore, these metrics are excluded from the OpenLCA model and are not linked to changes in the model. However, TTHM and cryptosporidium exposure are reported as results categories under the distribution life cycle stage. They are reported under the distribution life cycle stage as this is where human exposure to these pathogens and DBPs occurs.
- **Infrastructure and Capital Equipment.** While primary data were collected for infrastructure at the drinking water plant, only material and installation burdens are included. Assembly of the actual components (e.g., pumps, motors, tanks) and end-of-life of the infrastructure are excluded due to lack of available data. Exclusion of assembly is not the case for the piping (at plant and in distribution system), which does includes impacts from assembly. Additionally, the infrastructure burdens are normalized over each component's total lifetime assuming that the water delivered every year is 123,560,247 cubic meters, which was the volume of delivered to consumers in 2011. In actuality, there would be differences in water delivered per year over time. The lifetimes assumed for each component are estimates based on historical information of the GCWW facility; however, the study does include a sensitivity analysis to look at a wider range of potential lifetimes of infrastructure components.
- **DWT Plant Electricity Consumption.** Electricity consumption at the drinking water treatment plant could not be split out by life cycle stages within the plant. Therefore, this electricity consumption is reported as a separate life cycle stage in the results ("Pumping Energy, at Drinking Water Treatment Plant"), when in reality it should be allocated among DWT unit processes.
- **Support Personnel Requirements.** Support personnel requirements are included in the cost analysis, but excluded from the LCA model. The energy and wastes associated with research and development, sales, and administrative personnel or related activities are not included.
- **Transferability of Results.** While this study is intended to inform decision-making for a wide range of stakeholders, the data presented here relate to one representative facility. Further work is recommended to understand the variability of key parameters across specific situations.
- **Representativeness of Background Data.** Background processes are representative of either U.S. average data (in the case of data from U.S. LCI) or European average (in the case of ecoinvent) data. In some cases European ecoinvent processes were used to represent U.S. inputs to the model (e.g., for chemical inputs) due to lack of available representative U.S. processes for these inputs. The background data, however, met the criteria listed in the project QAPP for completeness, representativeness, accuracy, and reliability.

- **Representativeness of supply chains for sodium hexametaphosphate and sodium fluorosilicate.** LCI data for sodium hexametaphosphate or sodium fluorosilicate were not available for use in this study. Therefore, surrogate processes of sodium tripolyphosphate and hydrogen fluoride were used to model sodium hexametaphosphate and sodium fluorosilicate respectively. These surrogates were chosen as the production processes for these chemicals were closest to the actual chemicals used.
- **Data Accuracy and Uncertainty.** In a complex study with literally thousands of numeric entries, the accuracy of the data and how it affects conclusions is truly a difficult subject, and one that does not lend itself to standard error analysis techniques. The reader should keep in mind the uncertainty associated with LCA models when interpreting the results. Comparative conclusions should not be drawn based on small differences in impact results.

4. BASE CASE COST ANALYSIS

The focus of the cost analysis is to understand the contribution of life cycle stages to the overall cost of water delivered and, moving forward, to determine how different disinfection alternatives impact the final cost of water to the consumer. The remainder of this section provides additional details on the cost analysis data, methodology, and assumptions.[13]

4.1 Base Case Data Sources

The costs analysis used actual cost data provided by GCWW. GCWW provided annual operating costs for the Richard Miller Treatment Plant from 2011 and capital improvement project costs from 2000 to 2011. GCWW provided the treatment plant operating costs detailed by treatment unit process.

4.1.1 *Annual Operating Costs*

Table 10 shows the costs included in each DWT stage. GCWW does not track maintenance for the acquisition system separately. Therefore, costs were not allocated to the drinking water acquisition process. In addition, many costs, such as operating and maintenance labor, are incurred on a plant-wide basis. Therefore, a separate line item for overhead is included in the costs. Table 10 also shows the total plant costs for both Base 1 and Base Case 2.

In addition to the cost data elements listed in Table 10, GCWW also provided information on revenues and the price of drinking water to the consumer. EPA used these data elements to evaluate how changes to the disinfection technology may change revenues and consumer prices. These data were not used in the base case model.

[13] All supporting data used in the cost analysis are included in a separate Excel file.

Table 10. Annual Costs collected from GCWW.

Stage	Unit Processes Included in Base Cases 1 and 2	Cost Elements	Cost ($/year)
Drinking Water Acquisition	Acquisition	None	Included in overhead
Drinking Water Treatment Plant, Energy and Infrastructure		• Electricity for pumping[a]	$1,283,000
Pre-Disinfection	Flocculation	• Chemicals (alum, polymer)	$983,000
	Sedimentation	• Lime • Sludge removal	$69,000
	Filtration (sand)	• Sand replacement • Sand disposal	$30,000
	GAC adsorption	• GAC replacement • GAC regeneration (natural gas, permit costs)[b]	$1,515,000
	Conditioning	• Chemicals (caustic soda, sodium hexametaphosphate)	$898,000
Primary Disinfection	Gaseous chlorine	• Chemicals (gaseous chlorine) • Maintenance[c]	$128,000
Distribution	Fluoridation	• Chemicals (hydrofluorosilicic acid)	$365,000
	Distribution	• Chemicals (sodium hypochlorite) • Electricity[d]	$2,508,000
Overhead	Plant overhead for all processes other than primary disinfection	• Labor • Maintenance	$2,212,000
Total Base Case 1			**$9,992,000**
Total Base Case 2 (no GAC)			**$8,477,000**

[a] GCWW provided an annual amount of purchased electricity at the plant of 39,125,286 kWh and a unit cost of electricity of $0.0328/kWh. EPA calculated the annual cost of electricity.
[b] GCWW estimated that 42,000 ccf of natural gas are required per regeneration of GAC and 18 regenerations occur per year. GCWW provided a unit cost of natural gas of $0.0057/scf (1 ccf = 100 scf). EPA calculated the annual cost of natural gas.
[c] Maintenance costs for the disinfection unit process are broken out separately from the overall maintenance costs to evaluate potential changes for the alternative disinfection technology.
[d] GCWW provided an annual amount of electricity for distribution of 76,137,689 kWh and a unit cost of electricity of $0.0328/kWh. EPA calculated the annual cost of electricity.

4.1.2 *Capital Costs*

GCWW provided data on capital improvement project (CIP) expenditures from 2000 to 2011 for all of their operations (not limited to the Richard Miller Treatment Plant). GCWW provided the capital spending data in two categories:

- Facilities, including water treatment plants, distribution pump stations, backup generators, reservoirs, and storage tanks; and
- Water mains, including replacements and expansions.

Table 11 summarizes the CIP spending from 2000 to 2011. As can be seen, yearly capital spending can vary significantly depending on the extent and nature of capital improvement projects. For example, the $14,855,000 CIP spending on facilities in 2011 covered 29 projects, including: beginning construction of the UV treatment facility and replacing a portion of the filter house roof at the Richard Miller Treatment Plant; repairing secondary clarifiers and building a new sewer line at the Bolton Treatment Plant; and construction of a pump station, backup generator, reservoir, and elevated storage tank along the distribution system.

From 2000 to 2011, the average annual facility CIP spending is $9,076,083 with a standard deviation of $4,023,380, or about 44% of the average. This standard deviation reflects the large variation from year to year.

GCWW has a goal of replacing 1% of water mains each year. In 2011, the 34.4 miles of water main work encompassed 4.8 miles of new main extensions and 29.6 miles (or about 0.94%) of water main replacement. The running average of water main replacement from 2000 to 2011 is 0.98% per year. From 2000 to 2011, the average annual water main CIP spending is $32,511,458 with an average of 44 miles of water main work per year. The standard deviation of spending is $6,545,454, or about 20% of the average. The average spending per mile of water main work is approximately $739,180 per mile.

Table 11. GCWW Capital Improvement Projects Spending for Facilities and Water Mains from 2000 to 2011

Year	Facilities Capital Improvement Projects	Water Main Installations Capital Improvement Projects	
	CIP Spending	Miles Completed	Water Main Design Estimated Value
2011	$ 14,855,000	34.4	$ 33,207,825
2010	$ 12,157,000	36.2	$ 40,169,576
2009	$ 5,889,000	32.3	$ 40,997,569
2008	$ 4,833,000	46.3	$ 27,779,798
2007	$ 3,985,000	35.1	$ 35,469,183
2006	$ 8,061,000	44.9	$ 32,067,642
2005	$ 7,936,000	52.3	$ 22,707,669
2004	$ 9,773,000	61.1	$ 28,039,881
2003	$ 13,197,000	61.0	$ 35,999,391
2002	$ 14,693,000	48.4	$ 42,008,784
2001	$ 9,856,000	30.3	$ 26,693,046
2000	$ 3,678,000	45.5	$ 24,997,132

Source: GCWW Engineering Division Report to the Director.

4.2 <u>Base Case Cost Method</u>

EPA calculated the Base Case 1 and 2 costs directly from input provided by GCWW using the steps below.

1. Match provided costs to the unit processes shown in Table 1. Note that GCWW did not provide costs for ferric sulfate, which was only used 100 days in 2011. Costs for this chemical are not included.

2. Calculate the unit costs for items using the total annual costs and the quantities provided (e.g., compute costs in $/pound chemical). Where GCWW provided average, minimum, and maximum quantities, EPA calculated the unit cost using the average value. These unit costs were not needed to compute total costs because GCWW provided the total annual costs. However, EPA used unit costs in the sensitivity analyses and in the evaluation of alternative disinfection technologies.

3. Calculate Base Case 1 and 2 totals using the costs provided. Base Case 2 does not include GAC; therefore, EPA did not include the GAC replacement or regeneration costs in Base Case 2.

4. Normalize the total costs to a cubic meter of drinking water delivered.

4.3 Cost Data Quality, Assumptions, and Limitations

As stated previously, all data used in the cost analysis were provided by GCWW and are for calendar year 2011. The plant size and characteristics should be considered when translating these costs to other DWT plants.

Because GCWW was not able to provide a breakout of labor by unit process, EPA used the total labor costs for workers involved in all plant operations. These labor costs exclude personnel involved in administration. However, administration costs and similar overhead that are not tied directly to operations (e.g., administration personnel and expenses, office building utility bills, insurance) are less likely to change in response to implementing new technologies in the DWT plant. Therefore, all of the alternate technologies studied here are assumed to have similar administration and overhead costs as the base case.

An important note is that plant labor is a significant component of the total plant costs and may have the most variability between drinking water plants due to size and age differences.

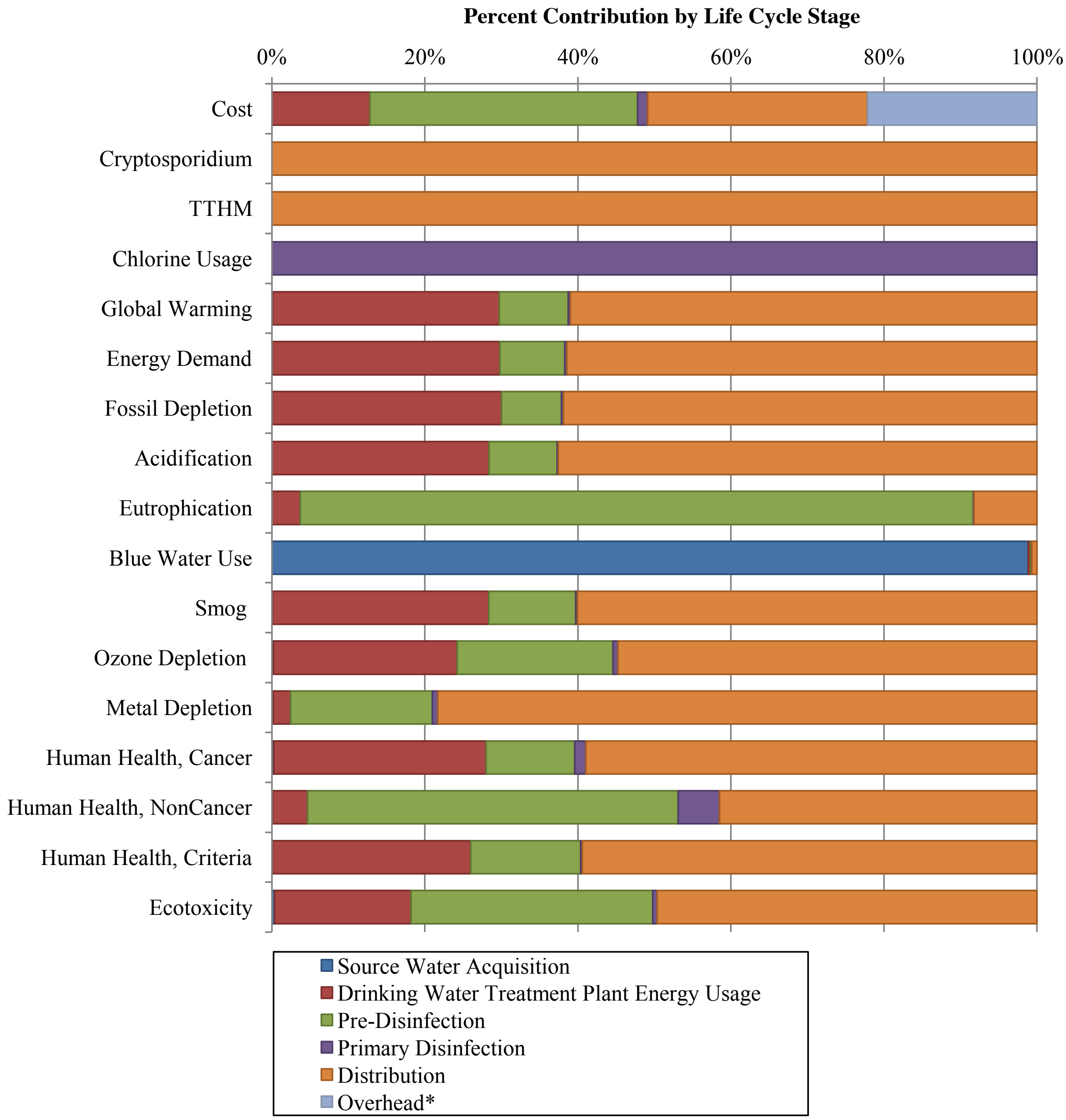
5. Base Case Results

Figure 3 displays the Base Case 1 contribution analysis results, Figure 4 displays more detailed Base Case 1 results on the unit process level, Figure 5 presents comparative summary results by life cycle stage for Base Case 1 versus Base Case 2, Figure 6 presents the percent change across the impact results when adsorption is excluded, and Table 12 provides Base Case 1 and Base Case 2 results per functional unit.[14] This study was not able to collect data to determine whether the use of GAC influences the effluent quality such as cryptosporidium and TTHM; therefore, these categories are excluded from the Base Case 2 results' figures and tables.

Base case findings of note include:

[14] The results for the life cycle assessment and cost analysis are presented in a separate Excel file.

- Base Case 1 shows slightly increased environmental impacts compared to Base Case 2 due to the addition of adsorption. Smog and human health criteria impacts are the most sensitive to the difference.
- Labor and energy costs are the largest contributions to DWT plant costs (18% and 38%, respectively, for Base Case 1; and 21% and 45%, respectively, for Base Case 2; including both plant and distribution costs).
- Eliminating adsorption (including GAC production and regeneration) reduces total costs by approximately 15 percent.
- Disposal of sedimentation waste is the largest contributor to eutrophication potential impacts (Figure 4). This is a result of the waterborne emissions of BOD, COD, and ammonia leaching from the sedimentation waste (Table 4).
- 1.2 m^3 of blue water are required to deliver 1 m^3 of treated drinking water to the consumer. A majority of the water loss occurs during the distribution stage. Based on data collected from GCWW, 0.19 m^3 of water is lost per m^3 of drinking water delivered during the distribution stage.
- Global warming, energy demand, fossil depletion, acidification, human health cancer, human health criteria and ecotoxicity impacts are largely driven by electricity consumption at the drinking water treatment plant and during distribution to the consumer.
- Distribution is the largest contributor to metal depletion, accounting for 78 percent of impacts. The distribution metal depletion is due primarily to the metal used in the iron pipes throughout the distribution network infrastructure. Infrastructure at the DWT plant and pre-disinfection account for 19 percent of metal depletion impacts, which is largely attributable steel used for construction of the DWT plant and upstream infrastructure required for production of the chemicals used during pre-disinfection processes (e.g., alum coagulant, sodium hexametaphosphate, sodium hydroxide, iron sulfate).
- Overall, the primary disinfection with gaseous chlorine life cycle stage only contributes zero to five percent to the total life cycle impacts of DWT for the results categories examined.



Overhead is only considered as stage for cost results category.

Figure 3. Base Case 1 contribution analysis results.

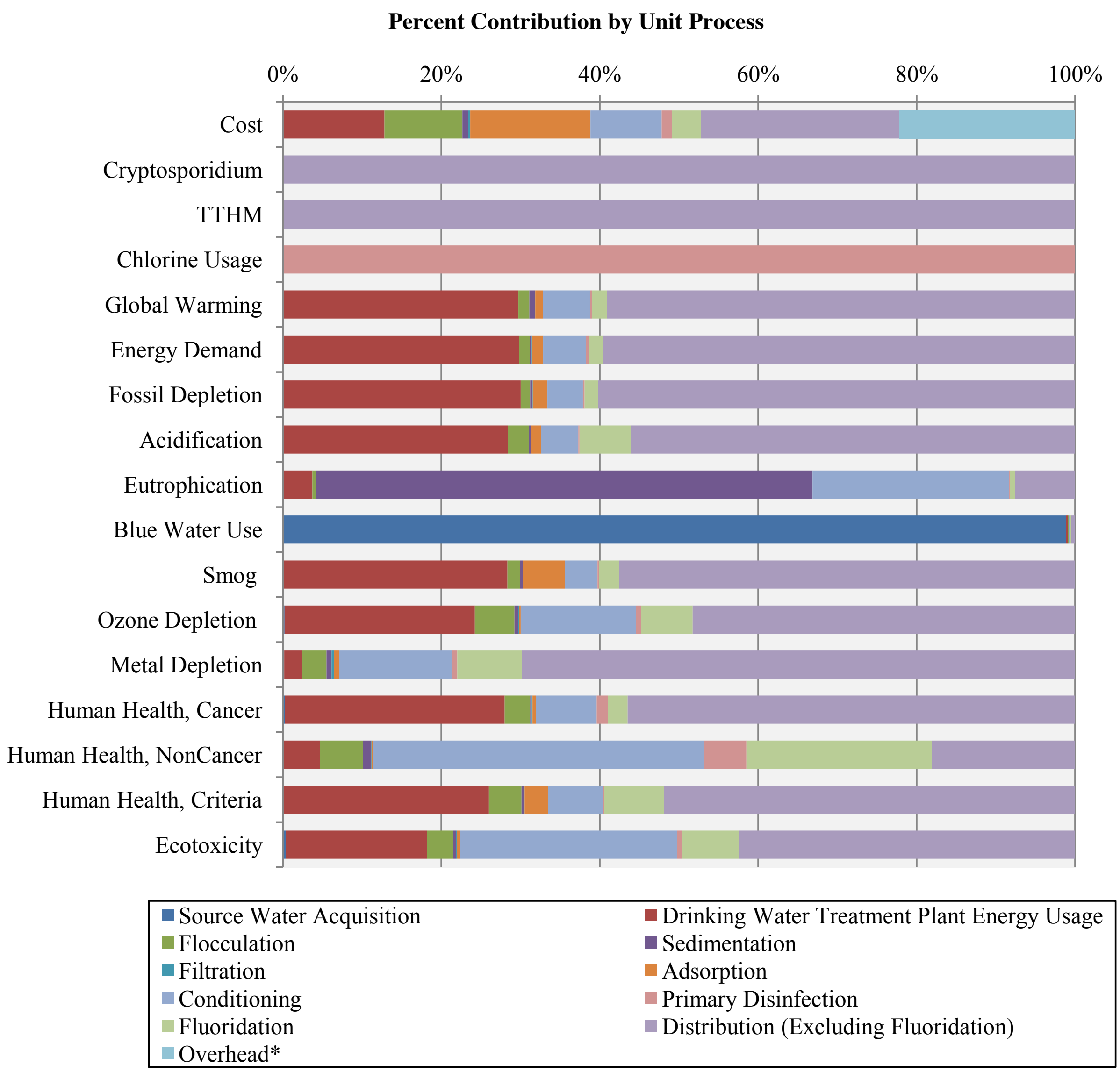


Figure 4. Base Case 1 contribution analysis results with unit process detail.

**Overhead is only considered as stage for cost results category.*

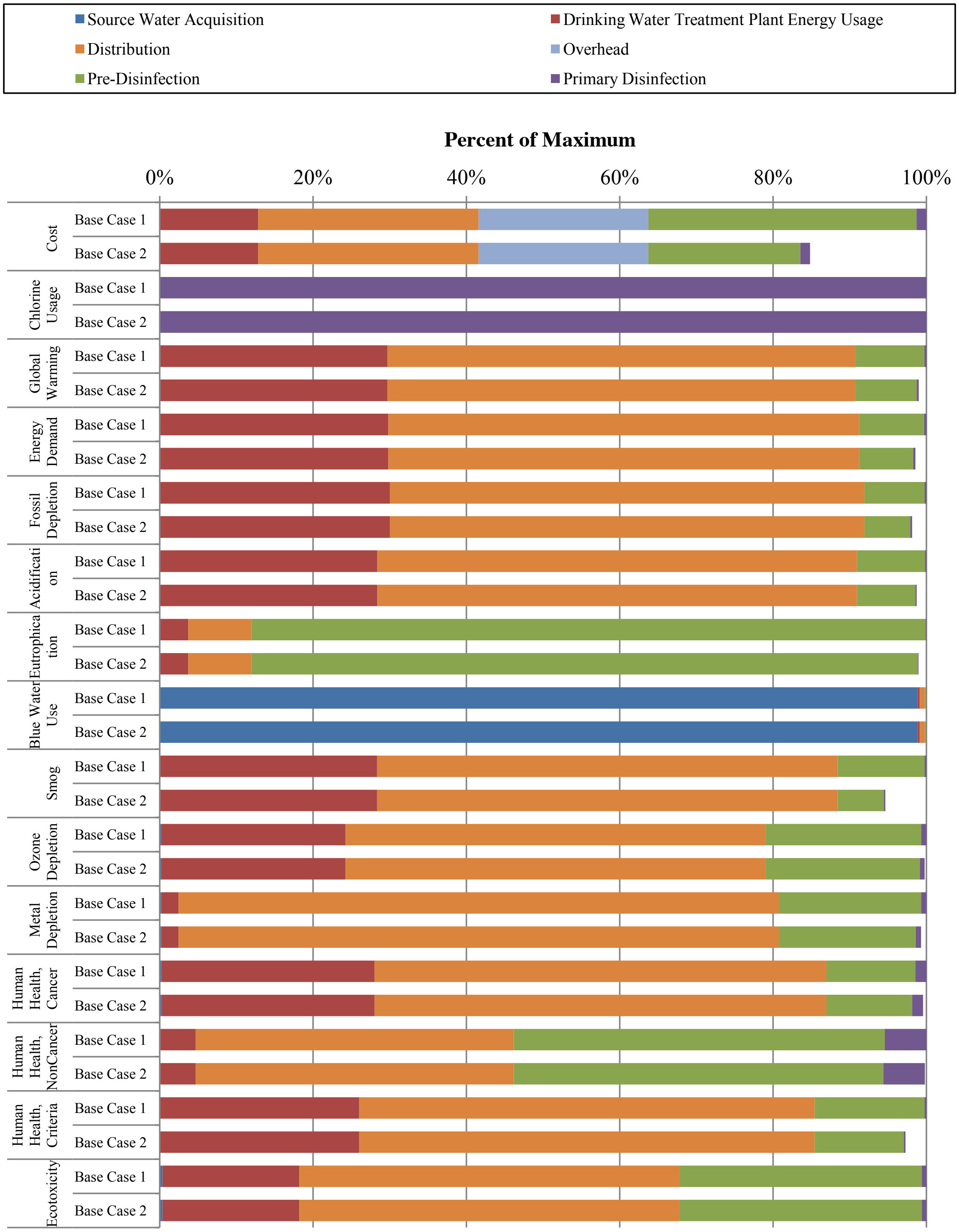


Figure 5. Base Case 1 and Base Case 2 comparative summary results.

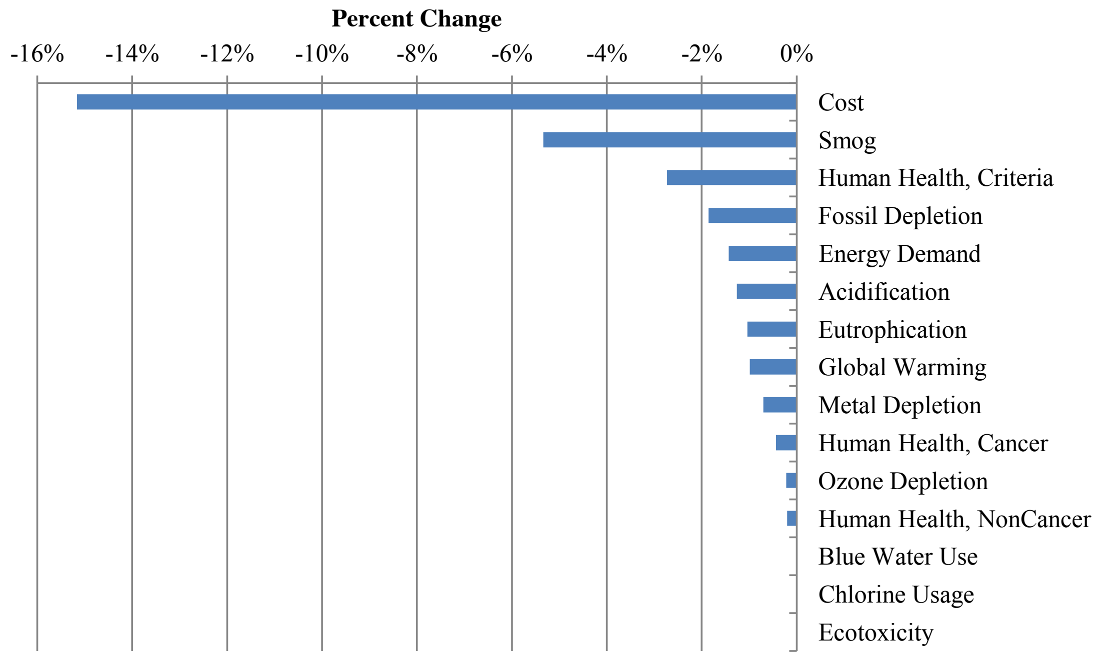


Figure 6. Percent change in impacts if adsorption is excluded.

Table 12. Base Case 1 and Base Case 2 results per m^3 drinking water delivered to the consumer.

Results Category	Unit	Base Case 1	Base Case 2
Cost	*$*	0.081	0.069
Cryptosporidium	*oocyst*	1.00	
TTHM	*kg TTHM*	1.6E-05	
Chlorine Usage	*kg Cl_2*	0.0018	0.0018
Global Warming	*kg CO_2 eq*	1.04	1.03
Energy Demand	*MJ*	19.8	19.5
Fossil Depletion	*kg oil eq*	0.36	0.35
Acidification	*kg H+ mole eq*	0.48	0.47
Eutrophication	*kg N eq*	9.7E-04	9.6E-04
Blue Water Use	*m^3*	1.20	1.20
Smog	*kg O_3 eq*	0.067	0.063
Ozone Depletion	*kg CFC-11 eq*	2.8E-08	2.8E-08
Metal Depletion	*kg Fe eq*	0.036	0.035
Human Health, Cancer, Total	*CTU*	2.9E-11	2.9E-11
Human Health, NonCancer, Total	*CTU*	3.2E-11	3.2E-11
Human Health, Criteria	*kg PM10 eq*	0.0015	0.0014
Ecotoxicity, Total	*CTU*	4.4E-04	4.4E-04

5.1 Base Case Normalized Results

Figure 7 displays the Base Case 1 normalized results. Larger sections of the chart indicate those impacts where DWT makes relatively larger contributions to national per capita impacts. Impacts related to fossil fuel combustion from electricity such as acidification potential, smog formation potential, global warming potential, and human health criteria are relatively high. Eutrophication impacts are also relatively high, primarily due to the disposal of the sedimentation waste. Other metrics such as ozone depletion potential, ecotoxicity, human health cancer and noncancer are relatively low.

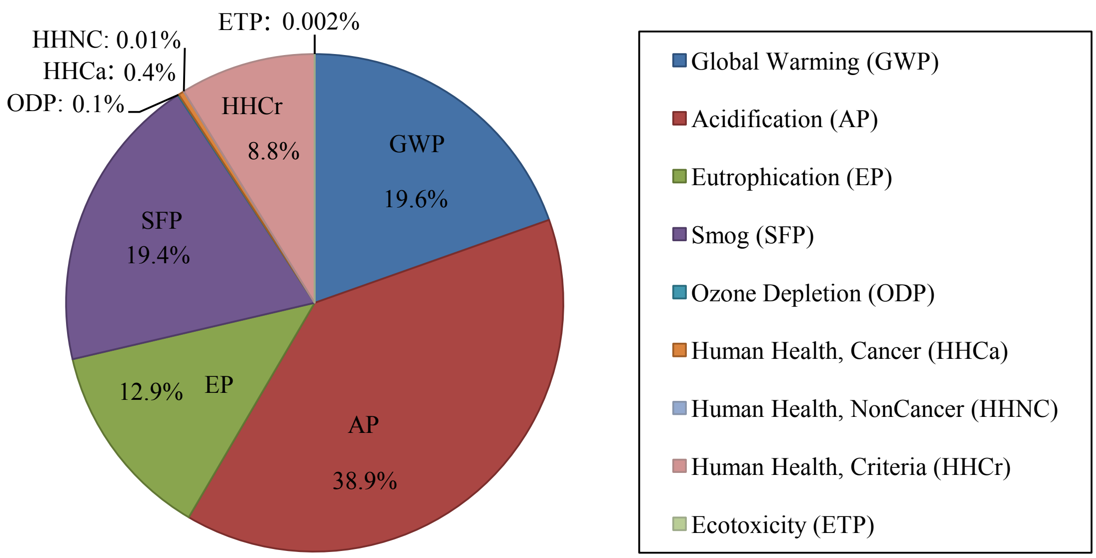


Figure 7. Base case normalized results.

5.2 Infrastructure Contribution to Base Case Results

Table 13 and Figure 8 display the contribution of infrastructure at the drinking water treatment plant and in the distribution system to the Base Case 1 results. For the majority of impact categories, the distribution pipe network is the infrastructure component with the highest impacts. For the majority of impact categories, excluding metal depletion and ecotoxicity, infrastructure contributes 5% or less to the total impacts. Metal depletion, however, is largely driven by infrastructure, with infrastructure from the drinking water treatment plant and distribution system accounting for approximately 68% of all metal depletion impacts. The remaining metal depletion impacts are also primarily due to upstream infrastructure impacts, for instance from the construction of plants which produce chemicals used for water treatment.

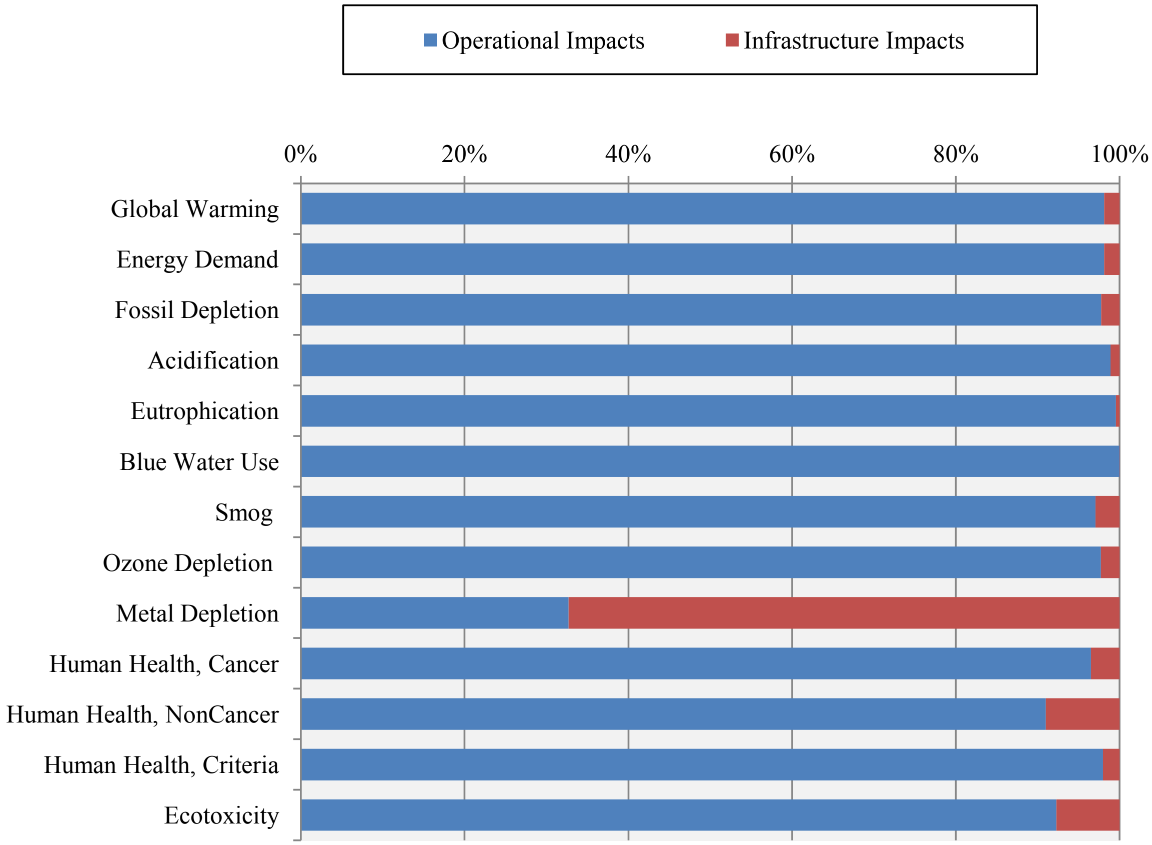


Figure 8. Infrastructure contribution analysis.

Table 13. Contribution of infrastructure to Base Case 1 results per m^3 drinking water delivered to the consumer.

		Impact Category												
		Global Warming	Energy Demand	Fossil Depletion	Acidification	Eutrophication	Blue Water Use	Smog	Ozone Depletion	Metal Depletion	Human Health, Cancer, Total	Human Health, NonCancer, Total	Human Health, Criteria	Ecotoxicity, total
Life Cycle Stage	**Subprocess**	*kg CO_2 eq*	*MJ*	*kg oil eq*	*kg H+ mole eq*	*kg N eq*	m3	*kg O_3 eq*	*kg CFC11 eq*	*kg Fe eq*	*CTU*	*CTU*	*kg PM10 eq*	*CTU*
Source Water Acquisition	Source water acquisition infrastructure	8.4E-04	0.010	2.0E-04	1.4E-04	1.5E-07	4.8E-06	5.1E-05	6.5E-11	7.2E-05	7.6E-14	3.0E-14	7.0E-07	1.7E-06
Pre-Disinfection	Conditioning infrastructure	3.6E-04	0.0033	6.4E-05	5.2E-05	5.2E-08	4.6E-06	1.9E-05	1.6E-11	7.3E-05	2.4E-14	1.4E-14	4.4E-07	3.3E-07
	Adsorption infrastructure	0.0012	0.011	2.2E-04	1.7E-04	1.7E-07	1.6E-05	6.3E-05	5.5E-11	2.5E-04	8.1E-14	4.8E-14	1.5E-06	1.1E-06
	Filtration infrastructure	4.5E-04	0.0041	8.1E-05	6.5E-05	6.5E-08	5.8E-06	2.4E-05	2.0E-11	9.1E-05	3.0E-14	1.8E-14	5.5E-07	4.1E-07
	Lime addition infrastructure	2.3E-04	0.0019	3.7E-05	3.2E-05	3.4E-08	2.9E-06	1.3E-05	1.0E-11	1.9E-05	1.0E-14	9.0E-15	1.7E-07	1.6E-07
	Sedimentation infrastructure	2.0E-04	0.0033	7.1E-05	6.2E-05	8.3E-08	4.3E-07	2.8E-05	2.0E-11	5.5E-06	1.3E-14	4.4E-15	2.4E-07	4.3E-07
	Flocculation infrastructure	6.9E-04	0.0069	1.4E-04	1.1E-04	1.0E-07	8.4E-06	3.9E-05	3.0E-11	1.3E-04	4.4E-14	2.6E-14	8.2E-07	6.6E-07
Primary Disinfection	Primary disinfection infrastructure	2.3E-05	2.1E-04	4.1E-06	3.3E-06	3.3E-09	2.9E-07	1.2E-06	1.0E-12	4.7E-06	1.5E-15	9.0E-16	2.8E-08	2.1E-08
Distribution	Pipe Network	0.011	0.26	0.0057	0.0036	2.9E-06	3.2E-05	0.0015	1.7E-10	0.015	1.1E-13	3.3E-14	7.8E-06	1.7E-05
	Water Storage	1.6E-04	0.0025	5.0E-05	3.9E-05	4.1E-08	1.6E-06	1.3E-05	1.0E-11	2.3E-04	1.8E-14	3.3E-14	5.4E-07	3.0E-07
	Valves	0.0043	0.069	0.0014	9.1E-04	7.4E-07	4.6E-05	2.3E-04	2.2E-10	0.0076	5.6E-13	1.1E-12	1.6E-05	8.8E-06
	Pumps	1.3E-04	0.0022	4.4E-05	2.9E-05	2.3E-08	9.7E-07	7.4E-06	6.1E-12	1.4E-04	2.4E-14	4.9E-15	5.0E-07	3.9E-07
	Motors	1.5E-04	0.0026	4.8E-05	8.3E-05	4.6E-08	1.4E-06	1.2E-05	9.6E-12	3.5E-04	3.0E-14	1.6E-12	7.7E-07	2.5E-06
Total	**All**	**0.020**	**0.37**	**0.0081**	**0.0053**	**4.4E-06**	**1.2E-04**	**0.0020**	**6.3E-10**	**0.024**	**1.0E-12**	**2.9E-12**	**3.0E-05**	**3.4E-05**
	% of total impact	**1.9%**	**1.9%**	**2.3%**	**1.1%**	**0.5%**	**0.0%**	**3.0%**	**2.3%**	**67.3%**	**3.5%**	**9.0%**	**2.0%**	**7.7%**

6. BASELINE SENSITIVITY ANALYSES

To see the influence of the assumptions made in an LCA model, it is important to conduct sensitivity analyses. To carry out such an analysis, the assumption of interest is changed and the entire LCA is recalculated. In this study, EPA conducted sensitivity analyses for key base case assumptions. Table 14 shows the sensitivity analyses for the base case, the values used, and whether LCA or cost results were generated for the sensitivity. Costs results were generated if changes to the LCA parameter could impact the costs. For example, changing the quantity of chlorine used at the plant would change the costs. On the other hand, varying the quantity of cryptosporidium in the final drinking water would not result in cost changes if no changes to the plant were made. Table 15 provides the electricity grid fuel mix used in both the baseline and the sensitivity analysis.

Table 14. Sensitivity analyses for base case model runs.

Parameter	Values	LCA Results	Cost Results
Chlorine usage	Minimum, maximum, and average values obtained from GCWW	Yes	Yes
Lime consumption	Minimum, maximum, and average values obtained from GCWW	Yes	Yes
Alum coagulant usage	Minimum, maximum, and average values obtained from GCWW	Yes	Yes
Sodium hypochlorite usage during distribution	Minimum, maximum, and average values obtained from GCWW	Yes	Yes
Natural gas for GAC reactivation	Minimum, maximum, and average values obtained from GCWW	Yes	Yes
DBP exposure	Minimum, maximum, and average values obtained from GCWW	Yes	No
Cryptosporidium exposure	Minimum, maximum, and average values obtained from GCWW	Yes	No
Electricity usage at plant [a]	±10% of value obtained from GCWW	Yes	Yes
Electricity usage during distribution [a]	±10% of value obtained from GCWW	Yes	Yes
Electricity unit cost (plant and distribution)	±20% of value obtained from GCWW	No	Yes
Electricity grid	Average U.S. grid, RFCW NERC regional grid	Yes	No
Lifetime of DWTP infrastructure components	±25 years for buildings, pipes, and other features (baseline = 100 years)	Yes	No
Lifetime of DWT distribution system infrastructure components	±25 years for buildings, pipes, and other features (baseline = 100 years); ±10 years for pumps and motors (baseline = 25 years)	Yes	No

[a] Varying the electricity usage by ±10% also provides an indication of the effects of varying the total cost of electricity by ±10%. EPA also varied total electricity costs by ±20% (plant and distribution) as shown on the cost results worksheet.

Table 15. U.S. electrical grid fuel profiles[15]

Electricity source	U.S. Average	RFCW NERC Region
Bituminous coal	46.24%	77.06%
Lignite coal	1.96%	0%
Natural gas	21.43%	2.41%
Distillate oil	0.18%	0.14%
Residual oil	0.57%	0.0024%
Biomass	1.33%	0.48%
Nuclear	19.57%	18.24%
Hydro	6.03%	0.62%
Wind	1.34%	0.20%
Solar	0.021%	0%
Geothermal	0.36%	0%
MSW, non-biogenic	0.15%	0.028%
Petroleum coke	0.35%	0.20%
Petroleum waste oil	0.022%	0.0014%
Tire derived fuel	0.030%	0.0083%
Other fuels	0.072%	0.060%
Other gases	0.28%	0.54%

Sensitivity analyses findings of note include:

- As displayed in Figure 9, the use of the U.S. average grid electricity mix resulted in considerably lower global warming, smog, and acidification impacts compared to use of the ReliabilityFirst Corporation West (RFCW) grid, which is the North American Electrical Reliability Corporation (NERC) region the GCWW Richard Miller Treatment Plant is located. This is largely due to the higher use of coal in the RFCW grid compared to the U.S. average grid. However, use of the RFCW grid electricity mix significantly reduced Human health cancer and ecotoxicity impacts, which is due to the lower natural gas usage in the RFCW grid mix compared to the U.S. average grid mix.
- Figure 10 shows the results of eight cost sensitivity analyses in terms of percent change from the baseline. Labor and energy are the highest contributors to the overall plant costs, so changes in chemical quantities and costs generally do not have a significant impact on the overall costs. Cost results are, however, sensitive to the electricity unit cost.
- Increases/decreases in plant electricity usage had the most effect on impacts associated with fossil fuel production and combustion such as global warming potential, human health criteria, smog, acidification, fossil depletion, human health cancer and energy demand (Figure 11).
- Impact results vary +/- zero to six percent when varying the distribution electricity usage +/- 10 percent (Figure 12). Impacts related to fossil fuel combustion (e.g., global warming, energy demand, fossil depletion, acidification) are most affected. These results clearly show the DWT model is sensitive to the electricity usage during distribution, and

[15] eGRID 2008 (Emissions and Generation Resource Integrated Database). U.S. EPA. (www.epa.gov/cleanenergy/egrid).

that electricity usage during distribution is an impactful process in the overall DWT life cycle. The model is more sensitive to varying electricity usage during distribution compared to varying electricity usage at the DWTP since distribution requires almost twice as much electricity compared to treatment at the plant.

- Crypto sensitivity results show that exposure results vary on average approximately -15 percent/+10% from Base Case 1.
- TTHM sensitivity results indicate that exposure results vary on average approximately -50 percent/+32 percent from Base Case 1.
- Chlorine usage results vary on average approximately -27 percent/+46 percent from Base Case 1 (Figure 13). No other impact categories are sensitive to the chlorine usage range.
- Results of the infrastructure sensitivity analysis are displayed in Figure 14 (infrastructure at DWTP) and Figure 15 (infrastructure for distribution system). The lifetimes assumed for each infrastructure component are estimates based on historical information of the GCWW facility (100 years for buildings, pipes, other features, and 25 years for pumps and motors); however, the study does include a sensitivity analysis to look at a wider range of potential lifetimes of infrastructure components. For building, pipes and other features (e.g., tanks and reservoirs) the lifetime is varied +/- 25 years, while for the pumps and motors, the lifetime is varied +/- 10 years. Overall life cycle impacts increase with a decrease in the infrastructure lifetime, since the infrastructure burdens are normalized over less total water delivered. The infrastructure lifetime is only sensitive to the metal depletion category, since this is the only impact category in which infrastructure is a significant component. All other impact categories vary less than 5 percent from the base case for this sensitivity analysis. The distribution system infrastructure has the greatest impact on metal depletion results as approximately 95 percent of the 3,135 miles of distribution system piping is iron.
- Figure 16, Figure 17, Figure 18, and Figure 19 show the sensitivity analysis results for alum coagulant usage during flocculation, lime usage during sedimentation, sodium hypochlorite usage during distribution, and natural gas consumption for GAC reactivation respectively. The LCA model is not sensitive to these parameters within the potential operational range supplied by GCWW. Cost results vary the most for the input quantity of alum coagulant.

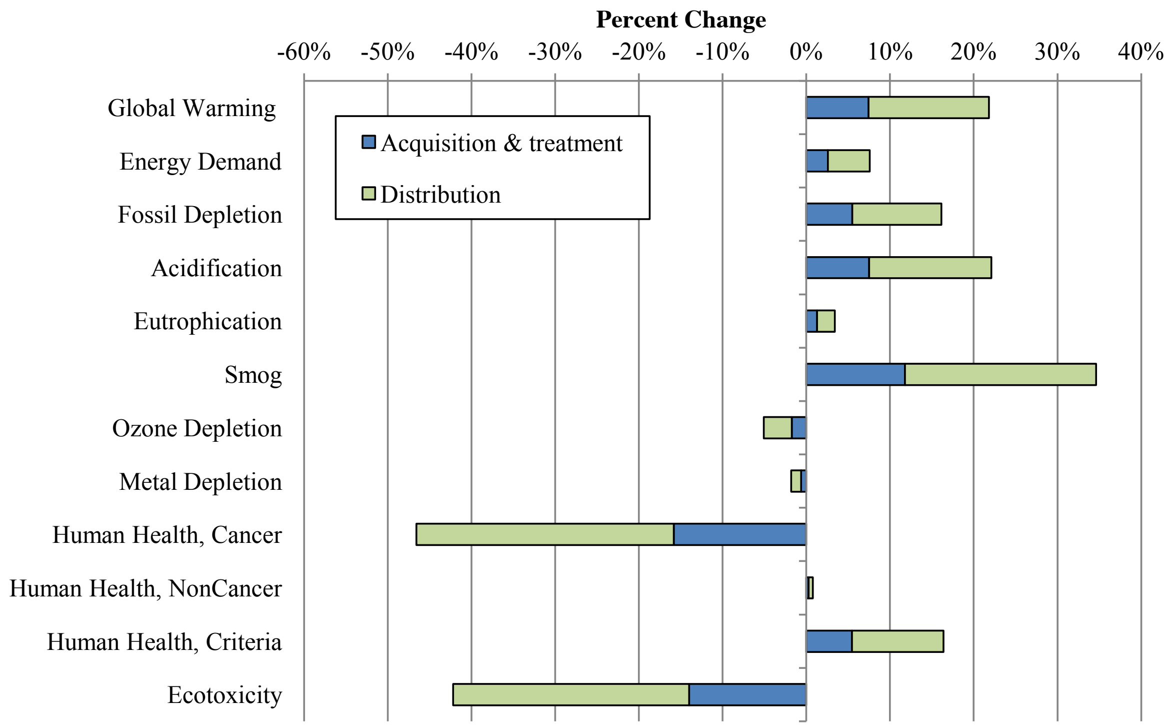


Figure 9. Significance of electricity mix: RFC West versus U.S. average baseline.

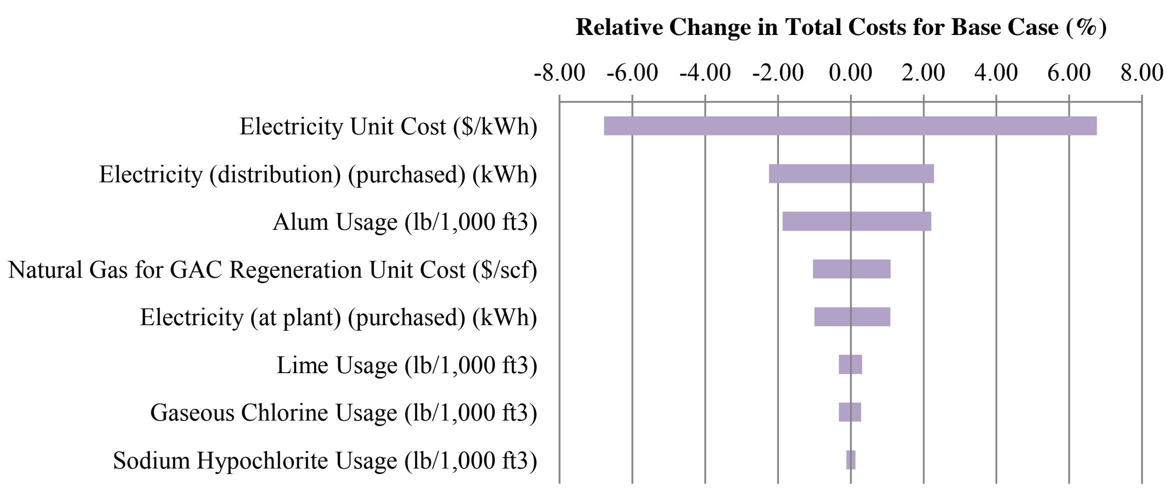


Figure 10. Tornado chart of the sensitivity analysis results for the relative changes in total costs for Base Case 1.

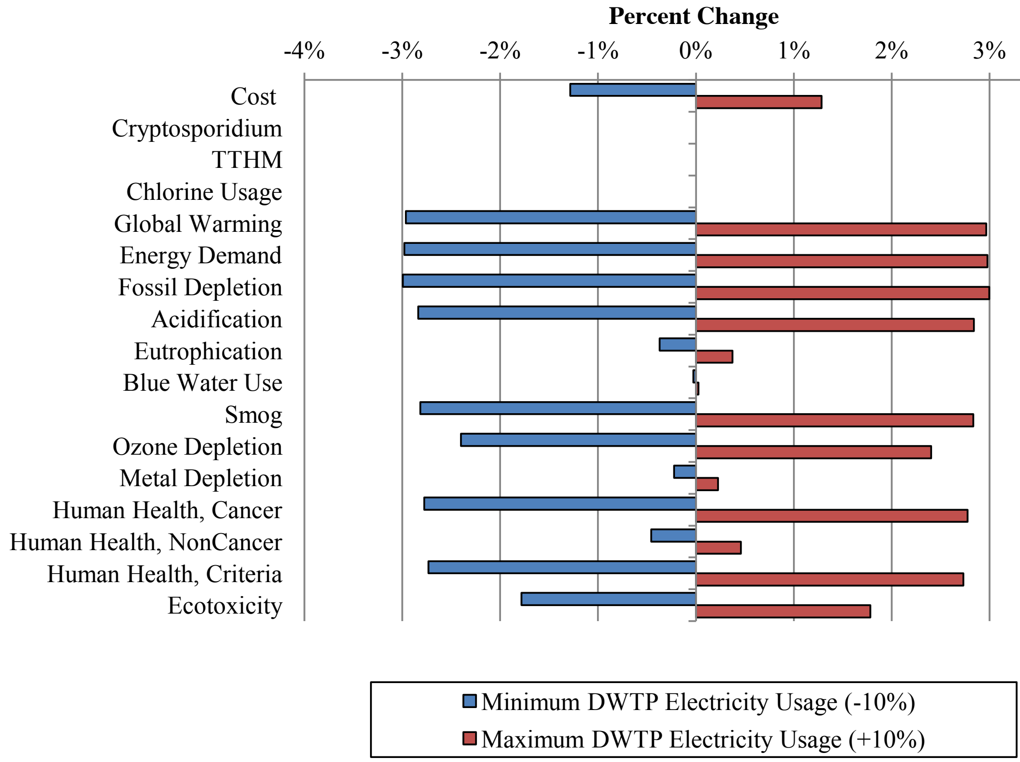


Figure 11. Base Case 1 DWTP electricity usage sensitivity analysis.

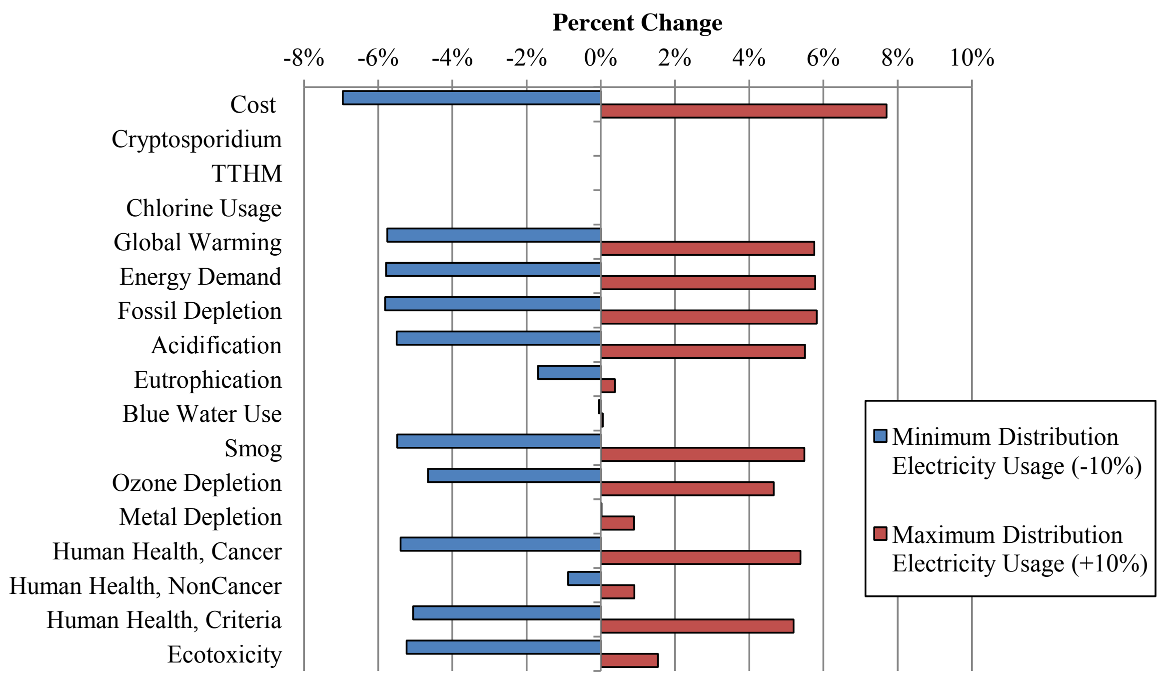


Figure 12. Base case 1 distribution system electricity usage sensitivity analysis.

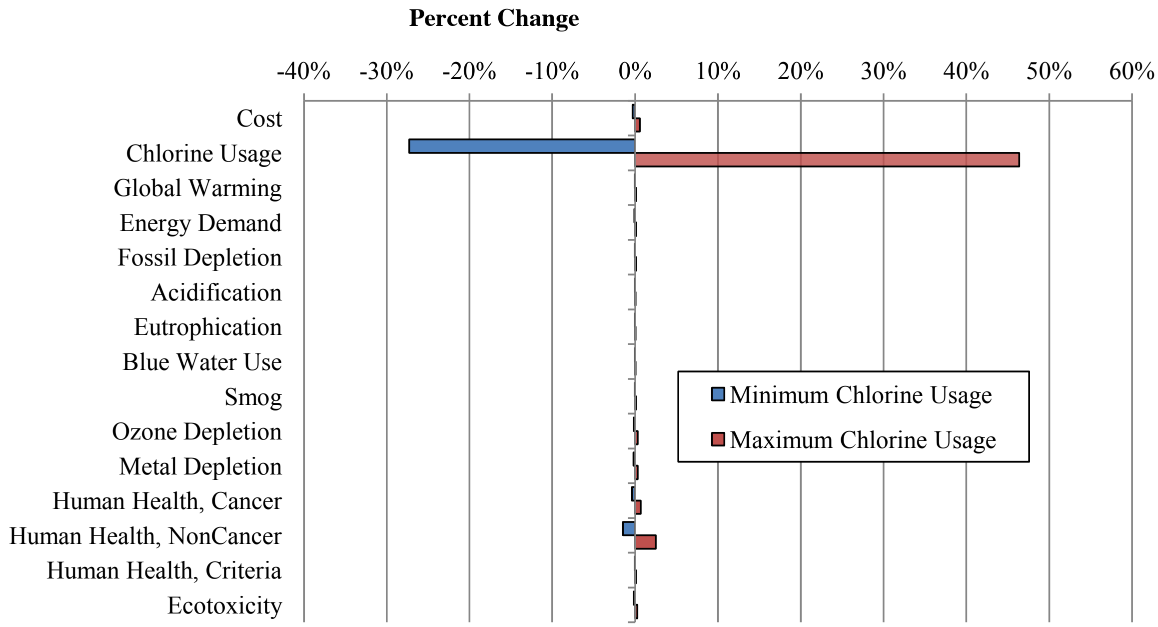


Figure 13. Base Case 1 chlorine usage sensitivity analysis.

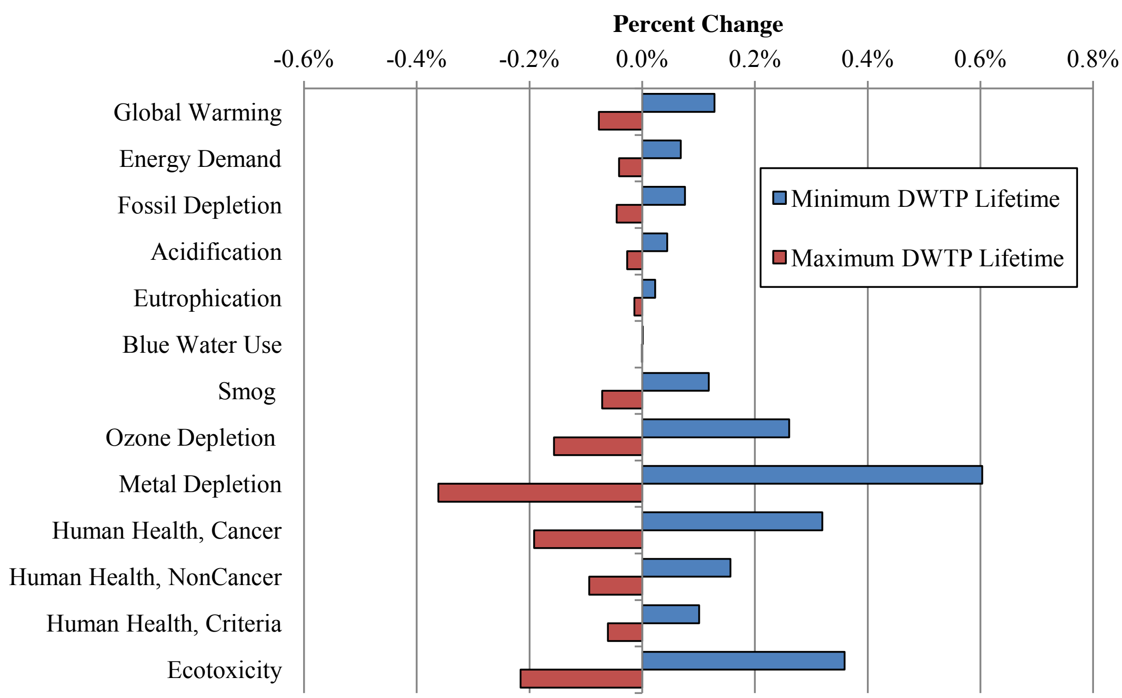


Figure 14. Base Case 1 DWTP infrastructure lifetime sensitivity analysis.

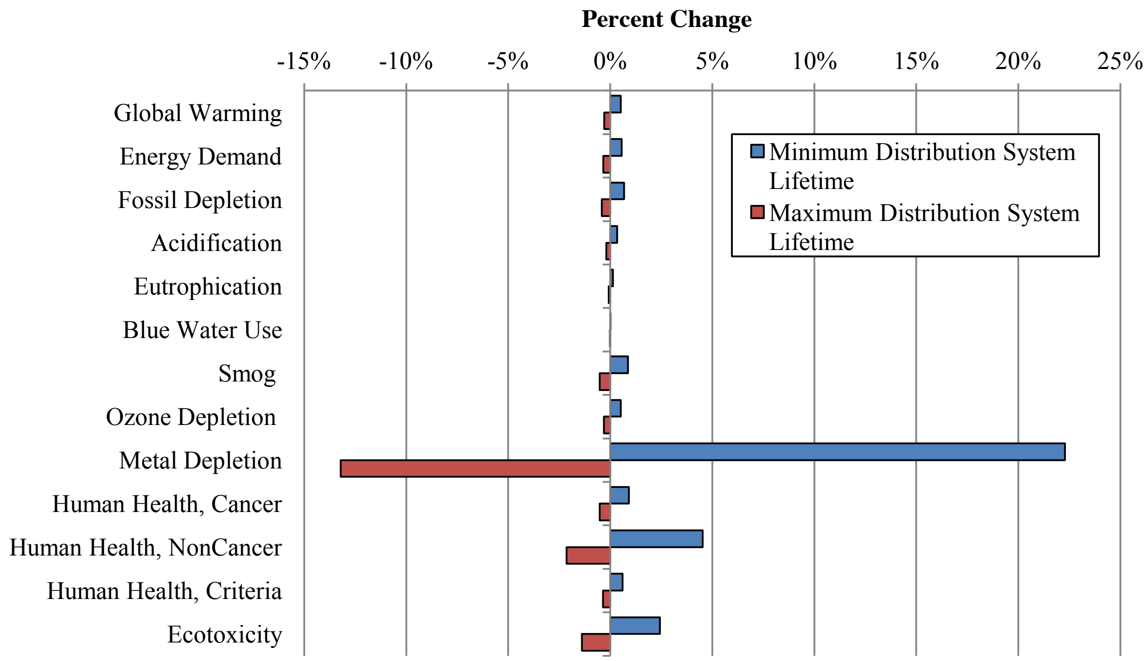


Figure 15. Base Case 1 distribution system infrastructure lifetime sensitivity analysis.

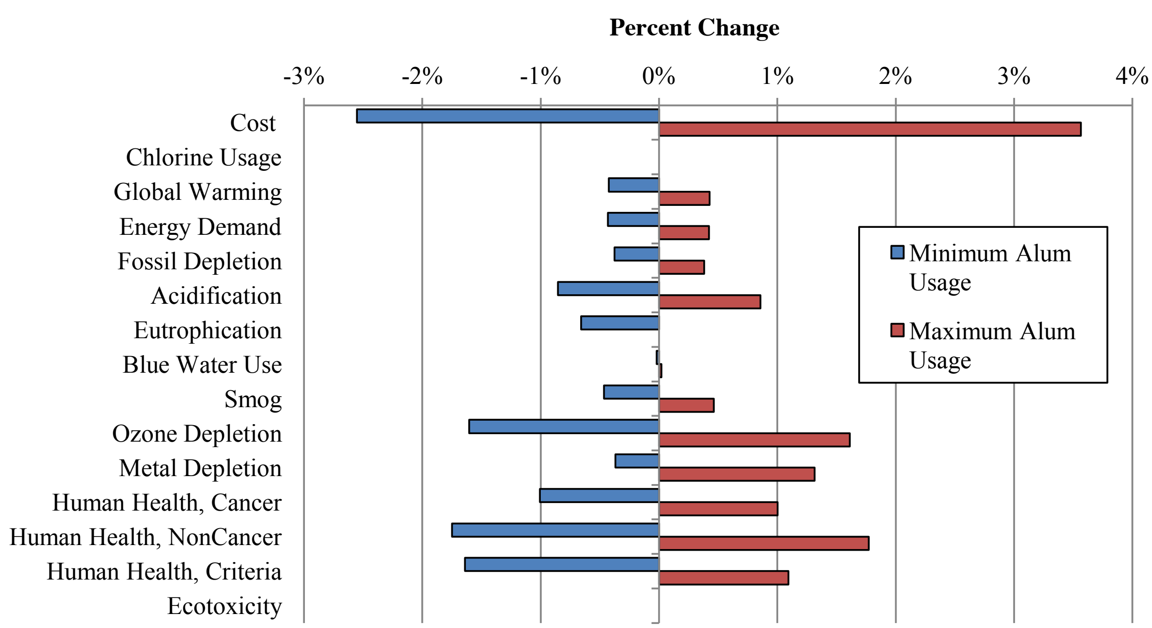


Figure 16. Base Case 1 alum coagulant usage sensitivity analysis.

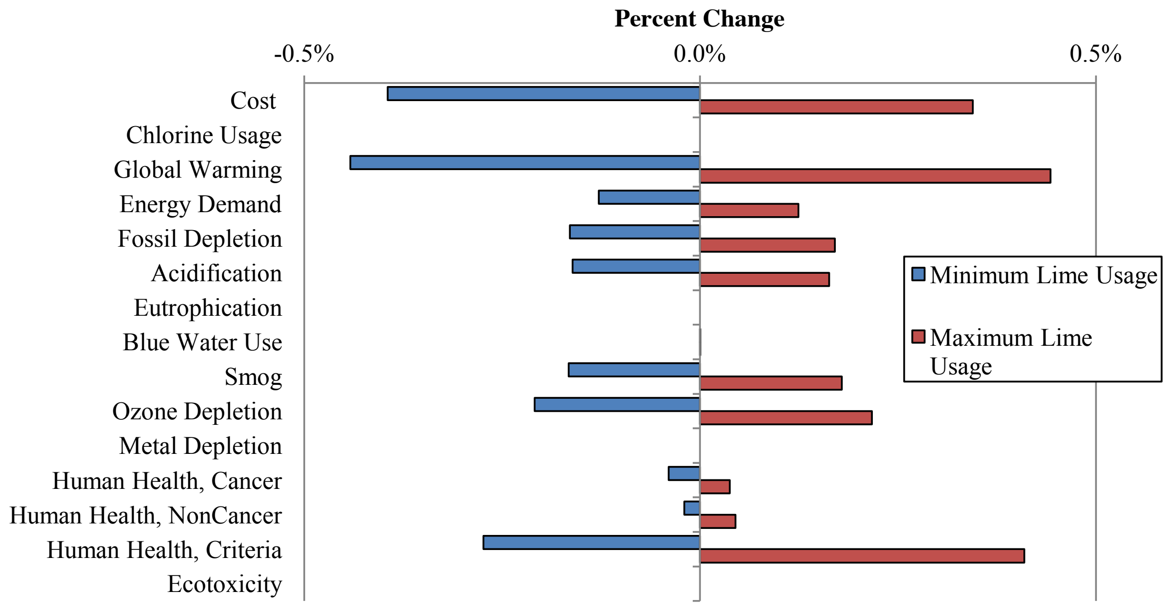


Figure 17. Base Case 1 lime usage sensitivity analysis.

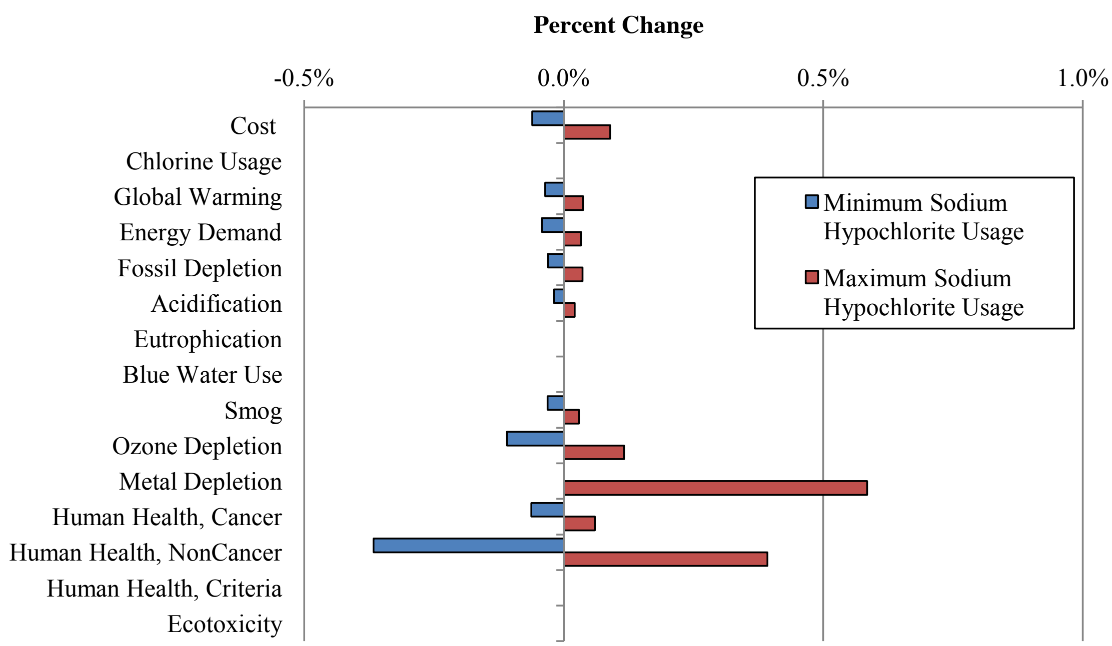


Figure 18. Base Case 1 distribution sodium hypochlorite usage sensitivity analysis.

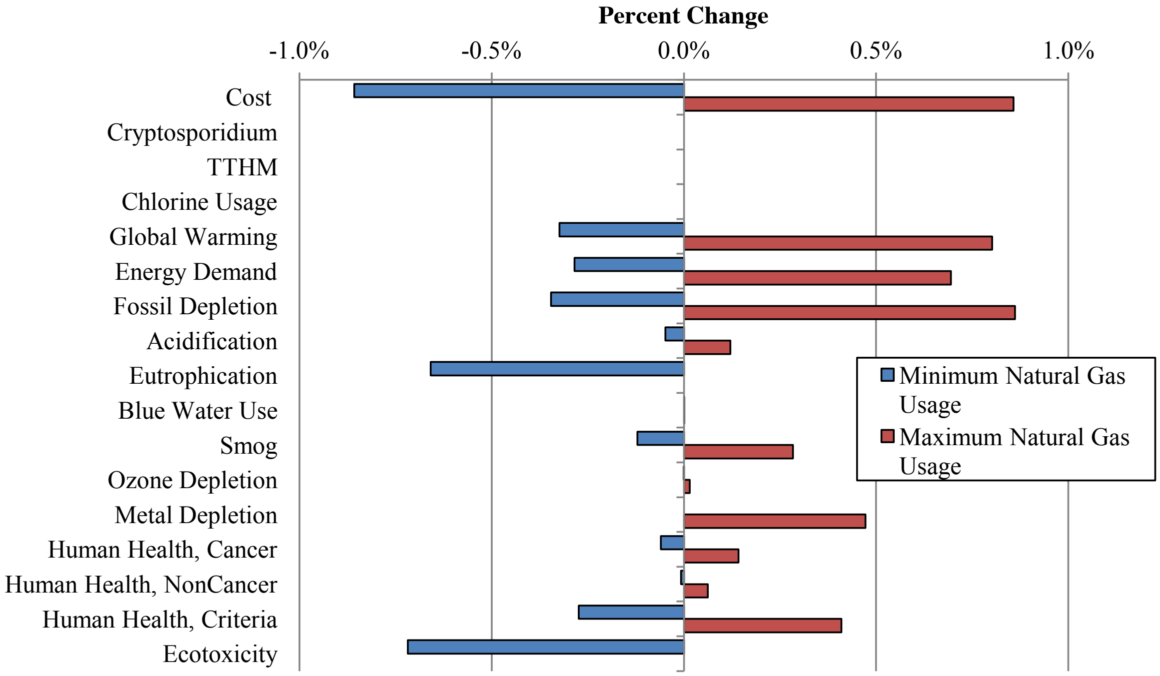


Figure 19. Base Case 1 natural gas for GAC reactivation sensitivity analysis.

7. In-Plant Alternative Disinfection Technologies

EPA investigated the use of the following in-plant disinfection alternatives by collecting data from the EPA partners noted.

- Conventional mercury-vapor ultraviolet (UV) disinfection (Aquionics)
- LED UV disinfection (Aquionics)
- Ferrate disinfection (Ferrate Treatment Technologies, LLC (FTT))

EPA had intended to include plasma-bead UV disinfection from Imaging Systems Technology (IST) in this study. While EPA investigated plasma-bead UV technologies and collected information from IST, it was determined that this technology is still too early in development to model quantitatively.

Table 16 shows where each technology is implemented in the drinking water model plant. The following subsections describe each technology, EPA's data collection for the technology, the methodology used to compare impacts and costs for the alternative technology, and the final results.

Table 16. Unit process matrix for alternative disinfection technologies.

Life Cycle Stage Reported	Unit Processes Covered	Base Case 1	Base Case 2	Conventional mercury-vapor UV	LED UV	Ferrate
Source Water Acquisition	Source Water Acquisition	X	X	X	X	X
Drinking Water Treatment Plant, Energy and Infrastructure	Drinking Water Treatment Plant, Energy and Infrastructure	X	X	X	X	X
Pre-Disinfection	Flocculation	X	X	X	X	
	Alum Coagulant	X	X	X	X	
	Sedimentation	X	X	X	X	
	Ferrate oxidation					X
	Disposal, Sedimentation Waste	X	X	X	X	X
	Filtration	X	X	X	X	X
	Adsorption	X		X	X	
	GAC Production	X		X	X	
	GAC Regeneration	X		X	X	
Primary Disinfection	Primary Disinfection, Gaseous Chlorine	X	X	X	X	X
	Alternate UV Disinfection (conventional, LED)			X	X	
	Ferrate disinfection					X
Distribution	Fluoridation	X	X	X	X	X
	Transport, Treated Drinking Water, Water Supply Pipeline	X	X	X	X	X
	Distribution Infrastructure, Drinking Water	X	X	X	X	X
Use	Drinking Water Consumption	X	X	X	X	X

7.1 System Boundaries

Figure 20 illustrates the system boundaries for the DWT base case and in-plant disinfection alternatives. The system boundaries are the same as the base case model, starting at acquisition of source water from a river and ending at delivery of the treated drinking water to the consumer. A majority of the in-plant disinfection technologies (i.e., conventional UV and LED UV) only affect the primary disinfection life cycle stage. However, as discussed in Section 7.4, use of ferrate for drinking water treatment can also impact upstream pre-disinfection unit processes.

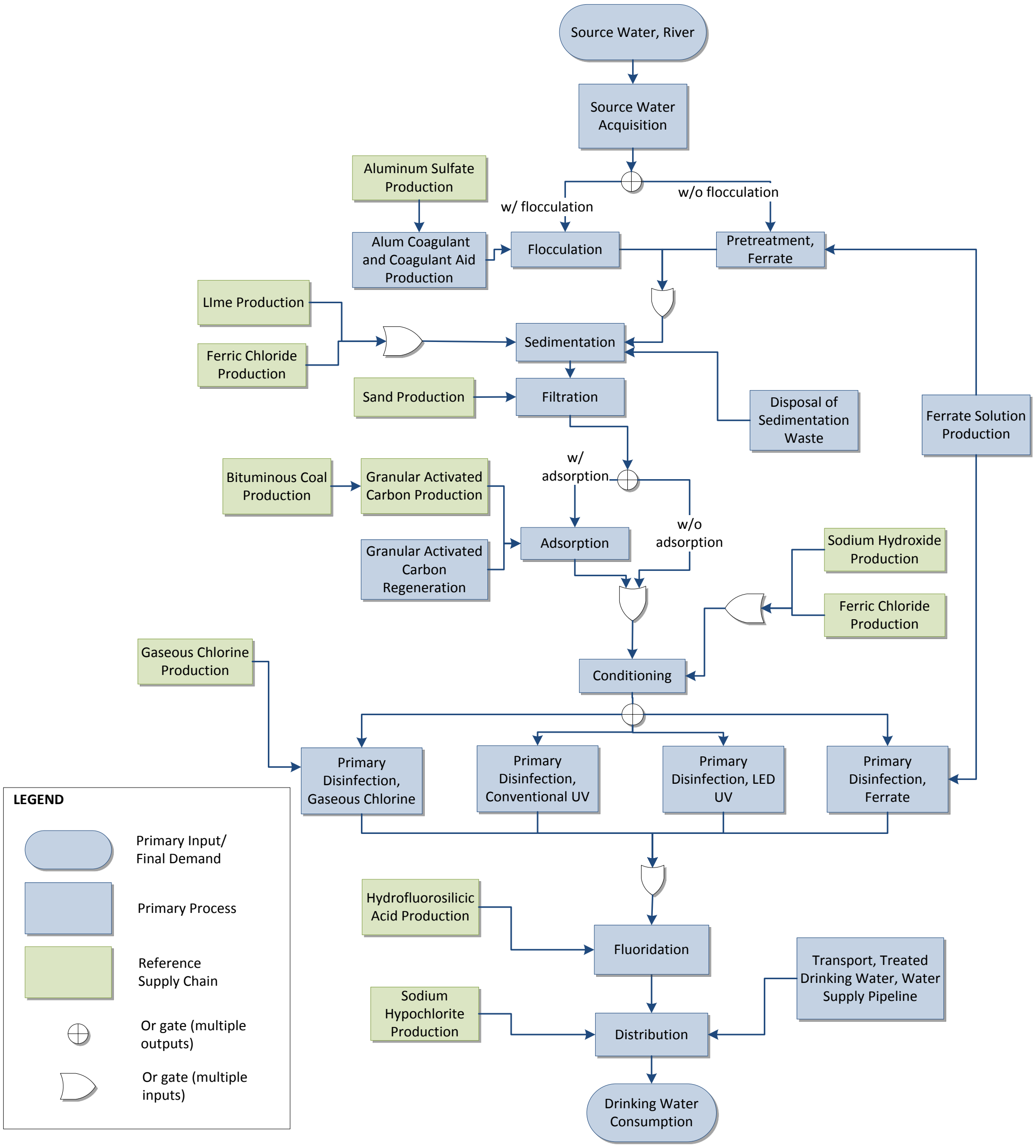


Figure 20. System boundaries of drinking water treatment base case and in-plant disinfection alternatives.

7.2 Aquionics Conventional UV Disinfection System

Aquionics provides UV disinfection equipment for drinking water and municipal treatment plants. EPA has partnered with Aquionics to provide data on conventional and LED UV for this study. Conventional UV uses mercury-vapor lamps to provide the UV light which de-activates microorganisms. UV can also breakdown unwanted chemicals such as organic compounds. According to Aquionics product information, Aquionics UV systems use low wavelength UV light, which can breakdown total organic carbon (TOC) molecules into smaller compounds that can then be removed by other unit processes.[16] Potential benefits of UV include:

- Removes chlorine-resistant pathogens;
- Reduces chlorine quantities required on site; and
- Reduces generation of DBPs.

EPA collected data on conventional UV directly from Aquionics.

7.2.1 *LCA Model*

For the conventional UV LCA model, only the primary disinfection stage is changed from the base case DWT model. Aquionics provided electricity and infrastructure data to assist in developing the LCA model. EPA made the following assumptions for the conventional UV model based on the data provided by Aquionics:

- For primary disinfection, a 3.6 MGD UV unit was modeled. Therefore, 30 active units and one backup unit would be required for disinfection at the 106 MGD GCWW base case facility.
- Conventional mercury-vapor UV disinfection requires 0.042 kWh electricity per cubic meter of water treated. This value was calculated using Aquionics' estimate that 210,240 kWh/yr of electricity are required to treat 3.6 MGD of water at a dose of 40 mJ/cm^2.
- Each 3.6 million gallon per day (568 m^3 per hour) UV disinfection unit consists of six mercury-vapor bulbs. The lamp lifetime is approximately 8,000 hours.
- The weight of each disinfection unit is 288 lb. The unit consists of a stainless steel vessel, quartz sleeves for the lamps, electronics for control units, synthetic rubber for wiper rings, and the mercury vapor lamps. Aquionics estimated a lifetime for each part (see Table 18). With the exception of the lamps, EPA used the average lifetime of the disinfection components of five years for the LCA model for simplicity. The conventional UV unit infrastructure has a negligible impact on the LCA results; therefore, the results are not sensitive to this assumption.
- Disinfection with conventional UV does not result in any formation of DBPs.
- Disinfection with conventional UV can lead to the same levels of cryptosporidium reduction as disinfection with gaseous chlorine.

EPA made some additional assumptions to complete the conventional UV LCA model:

- No chlorine is required for primary disinfection, but some gaseous chlorine is still required to maintain a chlorine residual in the distribution system. This is based on information from FTT (see Section 7.4). The sodium hypochlorite added during distribution is still added in the same amount as this is required to boost chlorine residual in certain parts of the distribution system. This sodium hypochlorite boost may not be applicable for other drinking water systems.

[16] Aquionics website (www.aquionics.com)

- EPA assumed there was 400 mg mercury per lamp.[17]
- Other components of the UV lamp were modeled based on an amalgam lamp: 7.5 mm^3 argon/lamp, 200 mg indium/lamp, 200 mg molybdenum/lamp, 4 g soldering materials/lamp, 20 g ceramics/lamp, and 300 g glass (assumed to be quartz sleeve)/lamp.[18] The total weight of one lamp was therefore assumed to be 321.1305 grams.
- Besides the weight of the lamp, no data were available on the weight breakdown of components of the 288 lb UV unit; therefore, the following assumptions were made: the stainless steel vessel accounts for 85% of the unit weight, the electronics account for 13% of the weight, the synthetic rubber wiper rings account for 0.5% of the total unit weight, and the remainder of the unit weight (1.47%) is from the lamps.

Because the conventional UV lamps include mercury, which is considered a hazardous material, the "chlorine usage" category from the base case analysis is expanded here to "hazardous materials" to account for this mercury. This unique flow, which is not a typical category in LCA studies, is only tracked based on data reported by data providers for specific life cycle stages, and does not cover all potential upstream hazardous materials. However, this category aids in understanding the hazardous materials at the drinking water treatment plant that workers may be exposed to.

7.2.1.1 Unit Processes

The specific unit processes added for the conventional UV LCA model are identified below.

<u>Disinfection</u>

1. **Primary Disinfection, Conventional UV**. Primary disinfection with conventional (mercury-vapor) UV. The inputs to this unit process include operation and infrastructure requirements for the UV units.
2. **Conventional UV Drinking Water Treatment, Operation**. This process covers electricity usage associated with operation of the UV units.
3. **Conventional UV Drinking Water Treatment, Infrastructure**. Infrastructure inputs for the UV units are aggregated in this unit process.
4. **Conventional UV Lamp**. Represents infrastructure requirements for the mercury-UV lamp and quartz sleeve encompassing the lamp.
5. **Stainless Steel UV Vessel**. Production of the stainless steel UV vessel.
6. **Wiper Ring**. Covers infrastructure requirements for synthetic rubber wiper rings.
7. **Conventional UV Electronic Control Unit**. Production requirements for an electronics control unit.

[17] Malley, J.P., Jr. 2006. Development of Standard Operating Plans for Mercury Release from UV Technologies. Used in Drinking Water Treatment Plants. Course Lecture Materials University of New Hampshire, Durham, NH

[18] Ekwall, Cecilia. 2004. LCA of tap water disinfection - a comparison of chlorine and UV-light. Department of Biometry and Engineering, Swedish University of Agricultural Sciences. http://ex-epsilon.slu.se/archive/00000280/01/cecilia_ekwall_0402.pdf

Use

8. **Drinking Water Consumption, Conventional UV**. Final delivery of water, which is disinfected with conventional UV, to an average consumer. This unit process aggregates the other main life cycle stages and is used to build the final product system. There are no actual impacts associated with the drinking water consumption life cycle stage itself.

Table 17 displays the data sources used for the conventional UV model in addition to the data sources used in the base case model (See Table 3). In general, data from Aquionics were used where available. For upstream processes that would not be known by Aquionics, such as information on production of UV lamp materials (e.g., mercury, molybdenum, glass), EPA used information from ecoinvent v2.2. Data sets from ecoinvent v2.2 have not been adapted for this project.

Table 17. Conventional UV data sources.

Process	Data Source
Conventional UV disinfection operation	Data Collection-Aquionics
Infrastructure for UV unit	Data Collection-Aquionics, and assumptions from secondary sources[17, 18]
Stainless steel for UV vessel	ecoinvent v2.2
Mercury for UV lamp	ecoinvent v2.2
Molybdenum for UV lamp	ecoinvent v2.2
Ceramics for UV lamp	ecoinvent v2.2
Glass (i.e., quartz sleeve) for UV lamp	ecoinvent v2.2
Argon for UV lamp	ecoinvent v2.2
Indium for UV lamp	ecoinvent v2.2
Electronics module	ecoinvent v2.2
Synthetic rubber for wiper rings	ecoinvent v2.2

7.2.2 *Cost Analysis*

Table 18 lists information Aquionics provided for use in the cost analysis.[19] After adding in the conventional UV system (including electricity usage, parts replacement, and amortized capital investment) and reducing the gaseous chlorine usage, the total annual cost is $10,666,000, an increase of $674,000 from Base Case 1.

[19] Input data, calculations, and results for the UV cost analysis are included in the supporting Excel file.

Table 18. Cost data provided by Aquionics.[a]

Cost Element	Lifetime (years)	Cost
UV unit[b]	20	$45,050/unit
PLC and Control Cabinet	20	$90,100/unit
Online UVT Monitor	20	$7,500/unit
Lamps[c]	0.9	$450/lamp
Quartz Sleeves	5	$70/sleeve
Wiper Rings	2	$18/ring
UV Sensors	8	$500/sensor

[a] See Excel worksheets for detailed cost calculations.
[b] Costs are for one unit, which can treat 3.6 MGD. EPA scaled the 3.6 MGD system to the base case plant size and included one back-up unit.
[c] 8,000 hours equals approximately 0.9 years.

In addition, EPA included the following information and assumptions based on information provided by Aquionics:

1. The Aquionics system is for a 3.6 MGD small-scale system. As described Section 7.2.1, the Aquionics system was scaled up to 30 active units plus one backup unit for disinfection at the 106 MGD GCWW base case facility. This scale-up factor of 31 was applied to the capital costs of the UV unit and the PLC and control cabinet. Only one UVT monitor is required. The resulting total capital equipment cost is $4,200,000.

2. Costs include replacement parts (lamps, quartz sleeves, wiper rings, and UV sensors). Aquionics provided the cost and lifetime of each part and noted each UV unit uses six lamps. EPA assumed each lamp requires one quartz sleeve, one wiper ring, and one UV sensor.

3. Cost multipliers are often applied to equipment costs to account for other direct costs such as installation, site work, and ancillary equipment and indirect costs such as permitting, monitoring, and training. This study assumes Aquionics would provide piping and electrical equipment required for the UV system. A contingency of 25% of total capital equipment costs was included. The resulting total capital investment is $5,250,000.

4. EPA amortized the total capital costs over the 20-year expected lifetime of a UV system using a bond rate of 6 percent. The resulting annual, amortized cost is $457,000.

5. EPA did not include cost credits for any equipment that is no longer required with use of the UV system. Plants may be able to reduce equipment required for chlorine addition because less chlorine is required.

7.2.3 *Results*

Table 19 displays results of the conventional UV analysis on the basis of 1 m^3 water delivered to the consumer. Figure 21 presents comparative summary results by life cycle stage for Base Case

1 versus conventional UV disinfection. Figure 22 presents the percent change across the impact results when using conventional UV disinfection rather than gaseous chlorine disinfection. Section 7.6 presents results comparisons between the three alternative disinfection technologies and the base case. Some findings to note for the conventional UV results as compared to the base case:

- Application of conventional UV technology increases impacts during disinfection through increased electricity consumption and through new capital investment, but eliminates the formation of disinfection by-products and greatly reduces hazardous chlorine usage.
- With the exception of hazardous materials and DBP formation (i.e., TTHM results category), the choice of disinfection technology does not significantly impact overall life cycle results, since most impacts are driven by energy consumption for pumping at the DWT plant and during distribution. This pumping energy consumption is not affected by choice of disinfection technology.
- For the hazardous materials category, the quantity of mercury from the bulbs is negligible compared to the quantity of chlorine used to maintain a residual in the distribution network. This study does not distinguish between different hazard levels of chlorine versus mercury in the “hazardous materials” results category.

Table 19. Conventional UV results per m^3 drinking water delivered to the consumer.

Results Category	Unit	Conventional UV
Cost	*$*	*$0.086*
Cryptosporidium	*oocyst*	*1.00*
TTHM	*kg TTHM*	*0*
Hazardous Materials	*kg Cl_2 & Hg*	*4.4E-04*
Global Warming	*kg CO_2 eq*	*1.07*
Energy Demand	*MJ*	*20.4*
Fossil Depletion	*kg oil eq*	*0.37*
Acidification	*kg H+ mole eq*	*0.49*
Eutrophication	*kg N eq*	*9.7E-04*
Blue Water Use	*m^3*	*1.20*
Smog	*kg O_3 eq*	*0.069*
Ozone Depletion	*kg CFC-11 eq*	*2.8E-08*
Metal Depletion	*kg Fe eq*	*0.036*
Human Health, Cancer, Total	*CTU*	*3.0E-11*
Human Health, NonCancer, Total	*CTU*	*3.1E-11*
Human Health, Criteria	*kg PM10 eq*	*0.0015*
Ecotoxicity, Total	*CTU*	*4.5E-04*

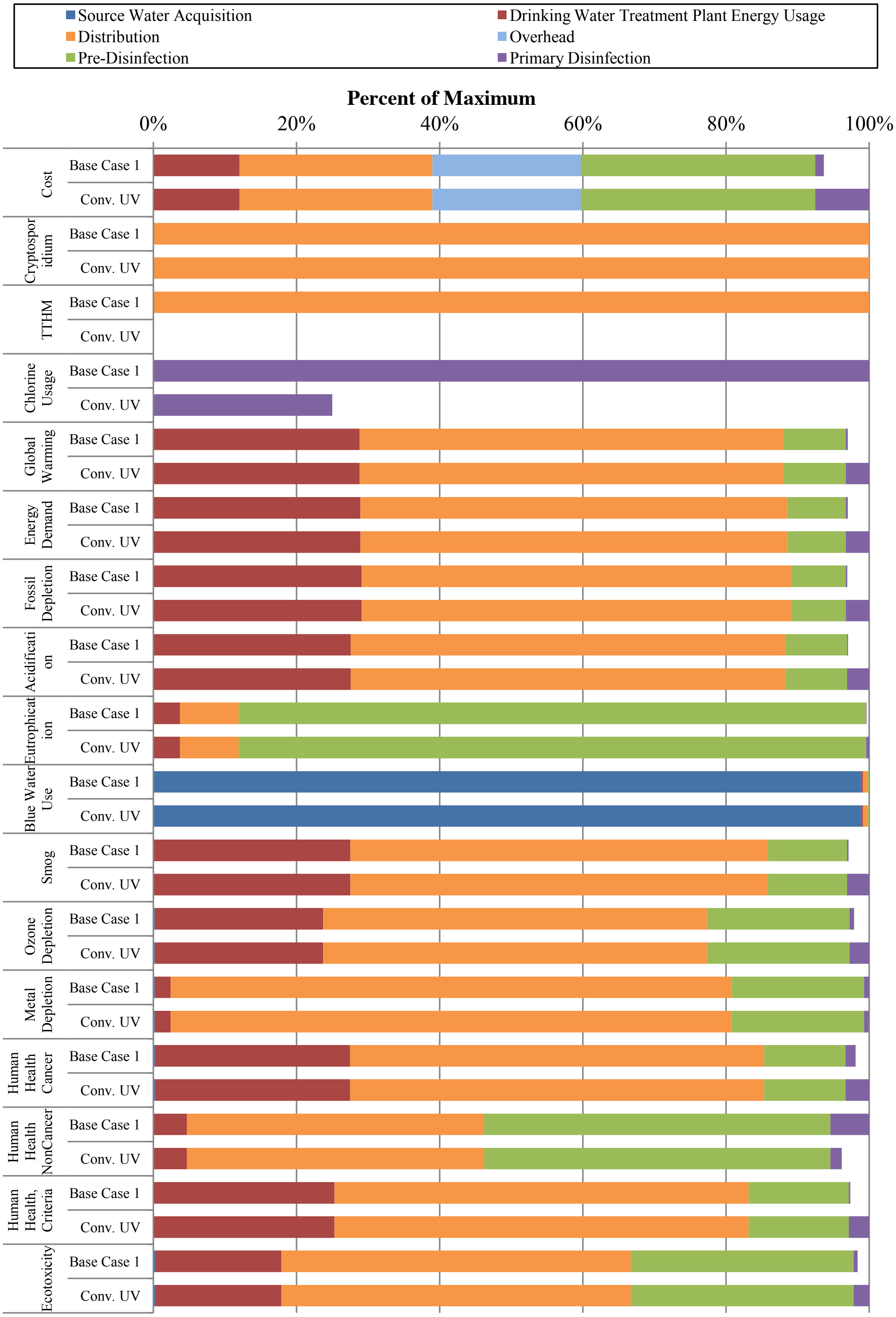


Figure 21. Base Case 1 and conventional UV comparative summary results.

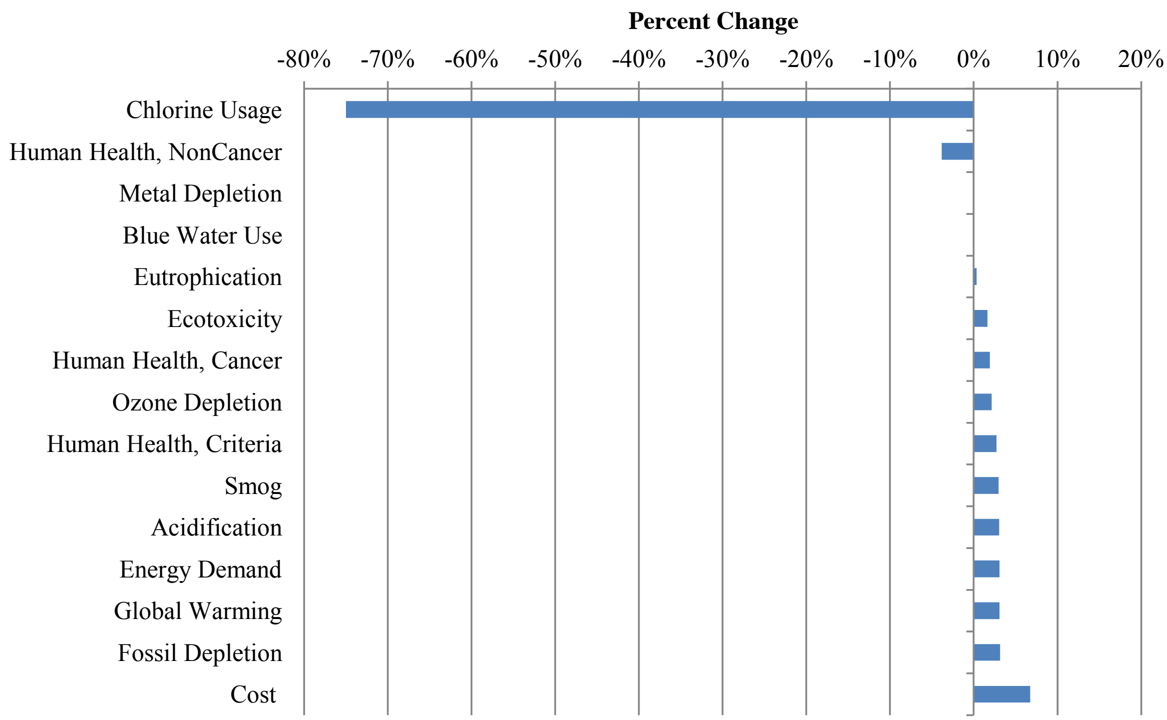


Figure 22. Percent change in impacts if using conventional UV rather than gaseous chlorine for disinfection.

For most impacts examined, the increase seen for utilization of conventional UV versus gaseous chlorine for primary disinfection is due to increased electricity usage. Therefore, a sensitivity analysis is run here varying the electricity usage for conventional UV disinfection +/- 25 percent. Figure 23 presents the results of this analysis. Overall, the total life cycle impacts for DWT disinfection with conventional UV do not vary more than +/- 0.9% when varying the electricity usage for conventional UV operation +/- 25 percent. This is primarily a result of the overall small impact of the primary disinfection life cycle stage as compared to other life cycle stages that are larger consumers of energy (e.g., pumping at the DWT plant, distribution of the treated water to the consumer).

Figure 24 presents a tornado chart that displays the results of the total cost sensitivity analysis. The cost sensitivity analysis performed a Monte Carlo simulation, varying the following:

- Amount of electricity required by the conventional UV system by ±25% (same as was performed for the LCA sensitivity analysis).
- Cost of a conventional UV unit by ±10% ($45,050/unit).
- Bond rate from four to eight percent (a ±33% change from the baseline value of six percent).

The sensitivity results show that the total costs are most sensitive to the bond rate and closely followed by the amount of electricity required by the conventional UV system. However, the total cost changes are within approximately ±0.6%. Therefore, although the total costs are more sensitive to the bond rate and electricity required by the UV unit than they are to the capital equipment cost, the total costs are negligibly changed by the parameter values studied. This result is expected as the disinfection costs are less than 8% of the total costs. Therefore, changes to disinfection costs have a smaller impact on the total costs compared to the larger costs: pre-disinfection (33%); distribution (27%); overhead (21%); and plant energy (12%).

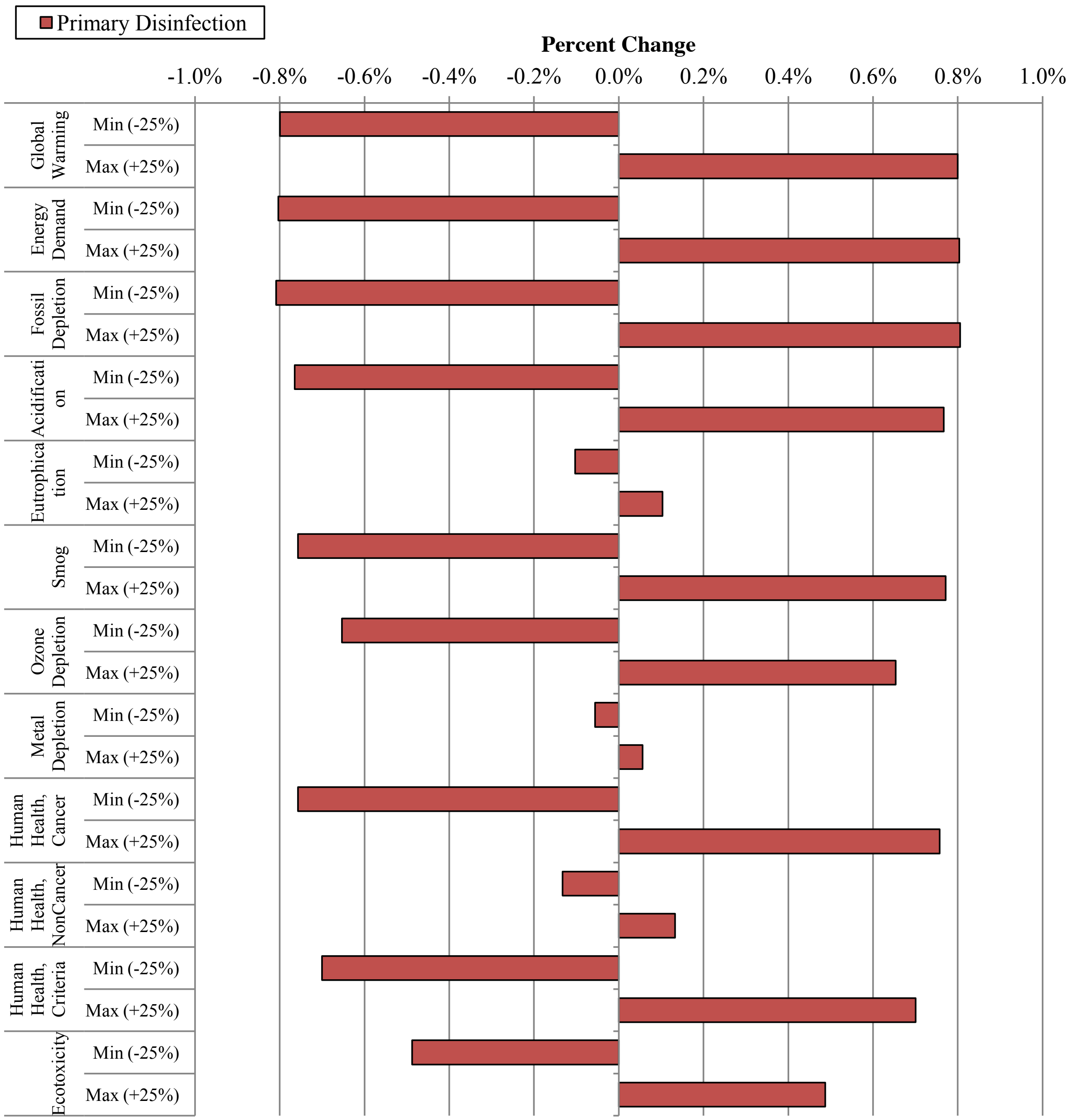


Figure 23. Conventional UV electricity usage sensitivity analysis.

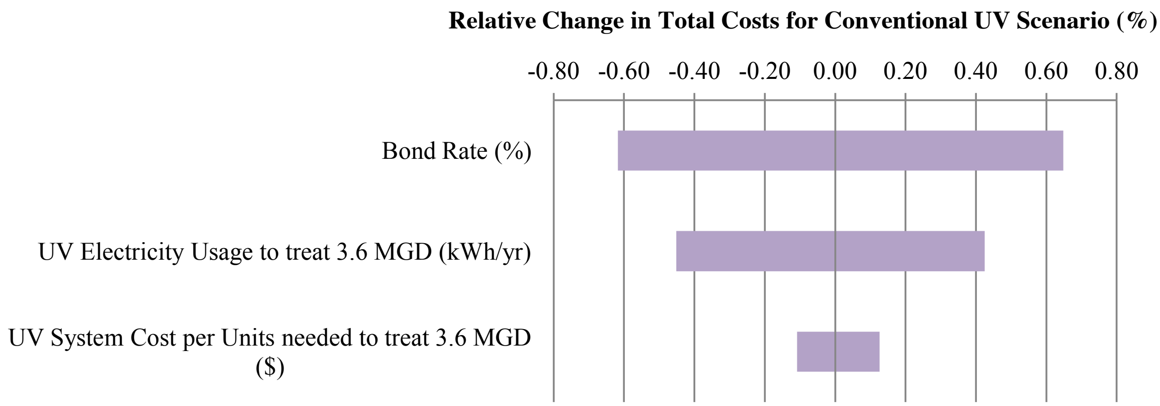


Figure 24. Tornado chart of the sensitivity results for the relative changes in total costs for the conventional UV scenario.

7.3 Aquionics LED UV Disinfection System

Aquionics offers a line of UV-LED disinfection equipment, which provides the same benefits of conventional UV but uses an LED light source rather than a mercury lamp. The LED UV system Aquionics has developed is for point-of-use applications (e.g., for laboratory equipment, health care equipment, stand-alone point-of-use). EPA made some assumptions to scale this technology to the 106 MGD system from the base case, but it is important to note that such large-scale LED UV disinfection technology does not currently exist. Utilization of LED for small-scale point-of-use applications is examined in Section 8. Cost data were not available for LED UV disinfection and are not included in this analysis.

7.3.1 *LCA Model*

EPA made the following assumptions for the in-plant LED UV analysis:

- For the LED UV LCA model, only the primary disinfection stage is changed from the base case DWT model.
- Water treated per disinfection unit is assumed equivalent to that treated under the conventional UV scenario (since no large-scale LED UV system exists, primary data on water treated for large-scale LED UV systems was not available).
- It is also assumed that the LED UV lamps are housed in the same stainless steel vessel with electronic controls as the conventional UV, and that the lifetime of these components is five years.
- Based on equipment specifications from Aquionics, 0.0039 kWh of electricity are required per m^3 water treated via LED UV.
- LED lamp infrastructure requirements were modeled based on a U.S. Department of Energy (DOE) LCA on energy and environmental impacts of LED lighting

products.[20] This study identified the background ecoinvent data sets and associated quantities utilized in the life cycle inventory model, and EPA replicated this LCI model (See Table 5-3, 5-6, and 5-8 of DOE study). The DOE study (and therefore this study) assumes the LEDs are produced in China.
- Disinfection with LED UV does not result in any formation of DBPs.
- Disinfection with LED UV can lead to the same levels of cryptosporidium reduction as disinfection with gaseous chlorine.
- No chlorine is required for primary disinfection, but some gaseous chlorine is still required to maintain a chlorine residual in the distribution system. This is based on information from FTT (see Section 7.4). The sodium hypochlorite added during distribution is still added in the same amount as this is required to boost chlorine residual in certain parts of the distribution system. This sodium hypochlorite boost may not be applicable for other drinking water systems.

7.3.2 *Unit Processes*

The specific unit processes added for the LED UV LCA model are identified below.

<u>Disinfection</u>

1. **Primary Disinfection, LED UV**. Primary disinfection with LED UV. The inputs to this unit process include operation and infrastructure requirements for the UV units.
2. **LED UV Drinking Water Treatment, Operation**. This process covers electricity usage associated with operation of the UV units.
3. **LED UV Drinking Water Treatment, Infrastructure**. Infrastructure inputs for the UV units are aggregated in this unit process. Infrastructure processes included are the LED die fabrication, LED packaging assembly, three-inch sapphire wafer manufacture, production of the stainless steel UV vessel, and production of the LED UV electronics control unit.
4. **Three-Inch Sapphire Wafer Manufacture.** Preparation of sapphire wafers to use for LED die fabrication.
5. **LED Die Fabrication.** LED semiconductor device fabrication.
6. **LED Packaging Assembly.** Packaging and assembly of the LED devices.
7. **Stainless Steel UV Vessel.** Production of the stainless steel UV vessel.
8. **LED UV Electronics Control Unit.** Production requirements for an electronics control unit.

<u>Use</u>

9. **Drinking Water Consumption, LED UV**. Final delivery of water, which is disinfected with LED UV, to an average consumer. This unit process aggregates the other main life cycle stages and is used to build the final product system. There are no actual impacts associated with the drinking water consumption life cycle stage itself.

[20] U.S. Department of Energy: Buildings Technology Program. June 2012. Life Cycle Assessment of Energy and Environmental Impacts of LED Lighting Impacts. Accessed at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_led_lca-pt2.pdf

Table 20 displays the data sources used for the LED UV model in addition to the data sources used in the base case model (See Table 3). Aquionics' equipment specifications were used to determine operational energy requirements. Upstream infrastructure was modeled based on a DOE LCA of LEDs.[20] This study identified the background ecoinvent data sets and associated quantities utilized in the LCI and EPA replicated this LCI model.

Table 20. LED UV data sources.

Process	Data Source
LED UV disinfection operation	Aquionics' equipment specifications
Infrastructure for UV lamp	DOE LED LCA[20]
Infrastructure for UV vessel and electronics	Equivalent to conventional UV analysis
Three-Inch Sapphire Wafer Manufacture	DOE LED LCA[20]
LED Die Fabrication	DOE LED LCA[20]
LED Packaging Assembly	DOE LED LCA[20]
Materials for LED production	ecoinvent v2.2
Energy for LED production	ecoinvent v2.2

7.3.3 *Results*

Table 21 provides results of the LED UV analysis on the basis of 1 m^3 water delivered to the consumer. Figure 25 presents comparative summary results by life cycle stage for Base Case 1 versus LED UV disinfection. As previously mentioned, no cost data was available for LED UV disinfection, so this is excluded from the figure. Figure 26 presents the percent change across the impact results when using LED UV disinfection rather than gaseous chlorine disinfection. Section 7.6 presents results comparisons between the three alternative disinfection technologies and the base case. Overall LED UV results are similar to conventional UV results, but LED UV is more energy efficient compared to conventional UV. With the exception of the decrease in hazardous material usage, decrease in human health noncancer impacts, and the elimination of the formation of DBPs under the LED UV scenario, the LCA results for the gaseous chlorine base case and primary disinfection with LED UV are essentially equivalent. Human health noncancer results decrease because of the elimination of gaseous chlorine with the LED UV disinfection system. The primary emission leading to human health noncancer impacts during the production of gaseous chlorine is CFC-10.

Table 21. LED UV results per m^3 drinking water delivered to the consumer.

Results Category	Unit	LED UV
Cryptosporidium	*oocyst*	*1.00*
TTHM	*kg TTHM*	*0*
Hazardous Materials	*kg Cl_2*	*4.4E-04*
Global Warming	*kg CO_2 eq*	*1.04*
Energy Demand	*MJ*	*19.8*
Fossil Depletion	*kg oil eq*	*.36*
Acidification	*kg H+ mole eq*	*0.48*
Eutrophication	*kg N eq*	*9.7E-04*
Blue Water Use	*m^3*	*1.20*
Smog	*kg O_3 eq*	*0.067*
Ozone Depletion	*kg CFC-11 eq*	*2.8E-08*
Metal Depletion	*kg Fe eq*	*0.036*
Human Health, Cancer, Total	*CTU*	*2.9E-11*
Human Health, NonCancer, Total	*CTU*	*3.0E-11*
Human Health, Criteria	*kg PM10 eq*	*0.0015*
Ecotoxicity, Total	*CTU*	*4.5E-04*

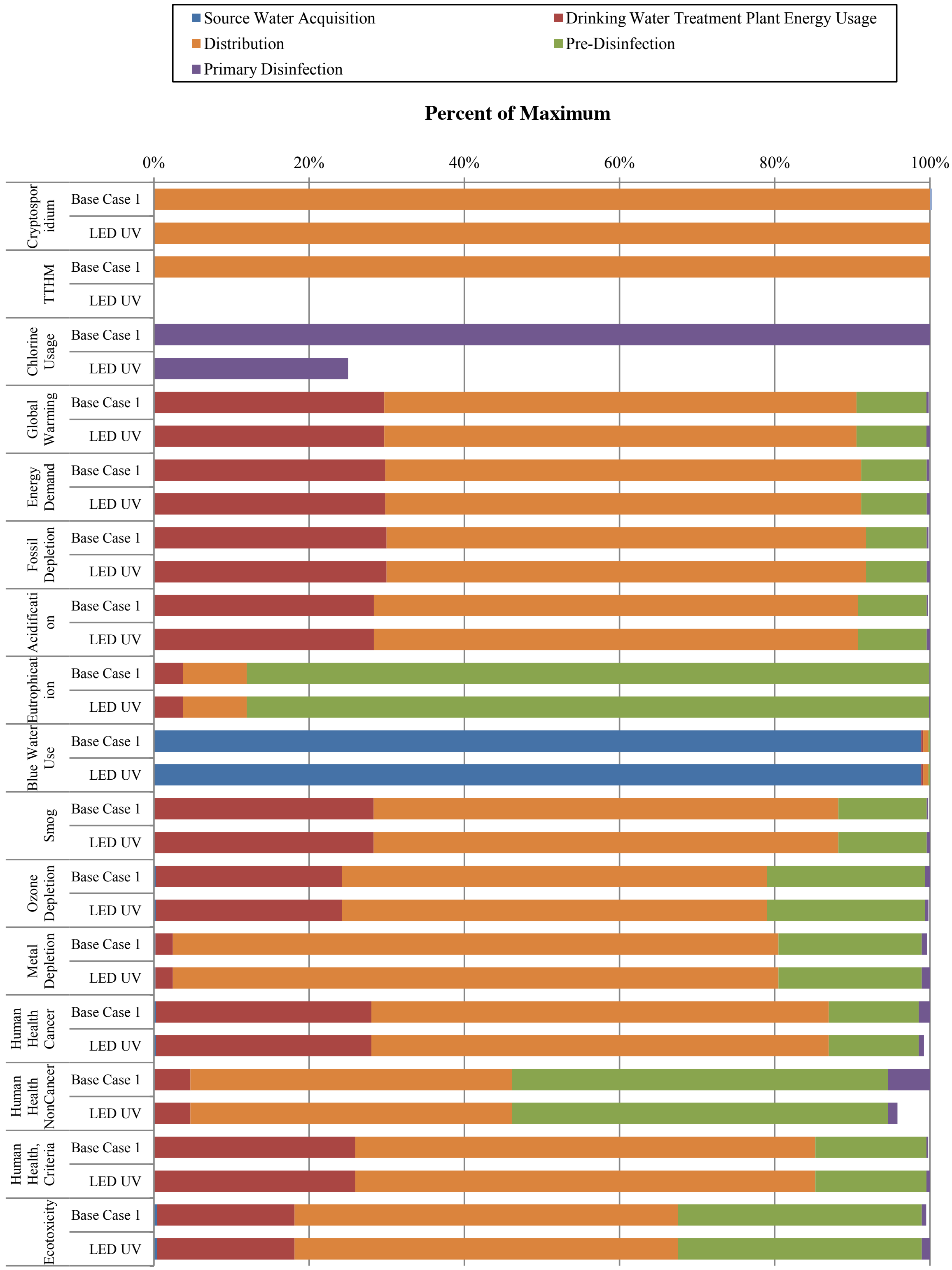


Figure 25. Base Case 1 and LED UV comparative summary results.

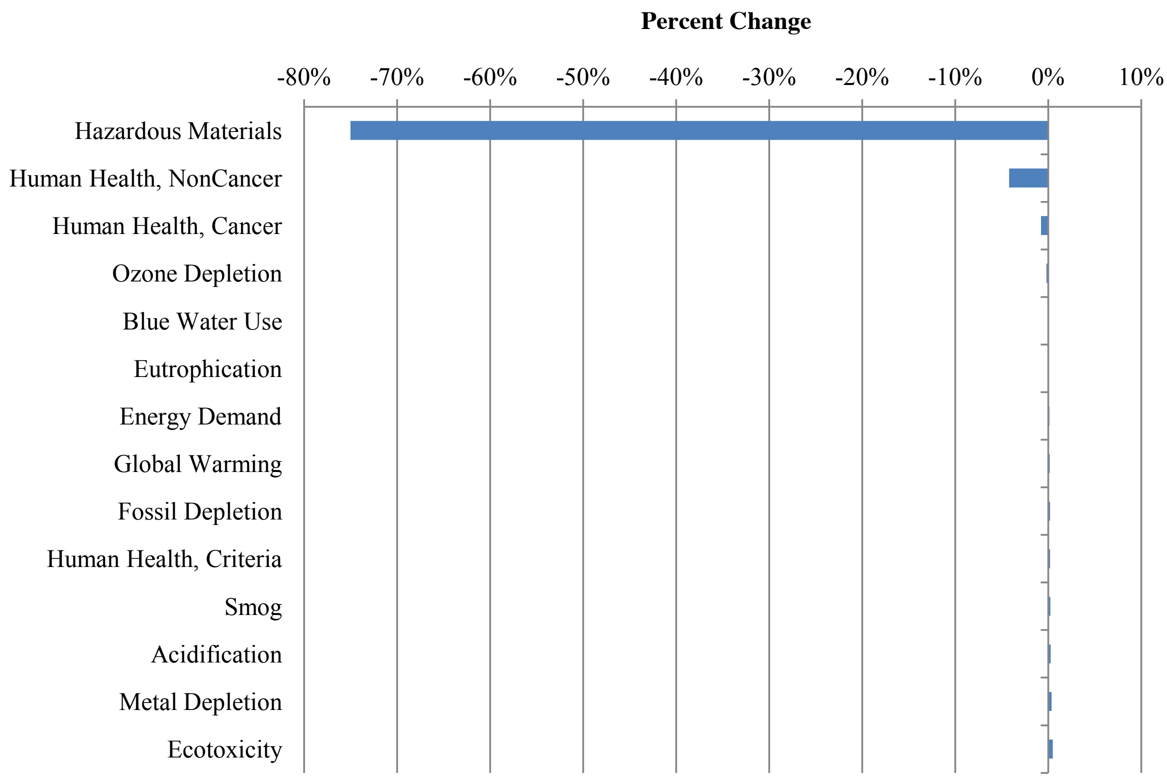


Figure 26. Percent change in impacts if using LED UV rather than gaseous chlorine for disinfection.

Similar to the conventional UV analysis, for most impacts examined (excluding the formation of DBPs), the change seen for utilization of LED UV versus gaseous chlorine for primary disinfection is due to increased electricity usage with LED UV. Therefore, a sensitivity analysis is run here varying the electricity usage for LED UV disinfection +/- 25 percent. Figure 27 presents the results of this analysis. Overall, the total life cycle impacts for DWT disinfection with LED UV do not vary more than +/- 0.1% when varying the electricity usage for LED UV operation +/- 25 percent. This is primarily a result of the overall small impact of the primary disinfection life cycle stage as compared to other life cycle stages that are larger consumers of energy (e.g., pumping at the DWT plant, distribution of the treated water to the consumer). The change for the +/- 25 percent electricity usage for LED UV operation is less than that seen in the same sensitivity analysis conducted for the conventional UV technology, as LED UV requires less electricity overall for disinfection compared to the conventional mercury-vapor UV.

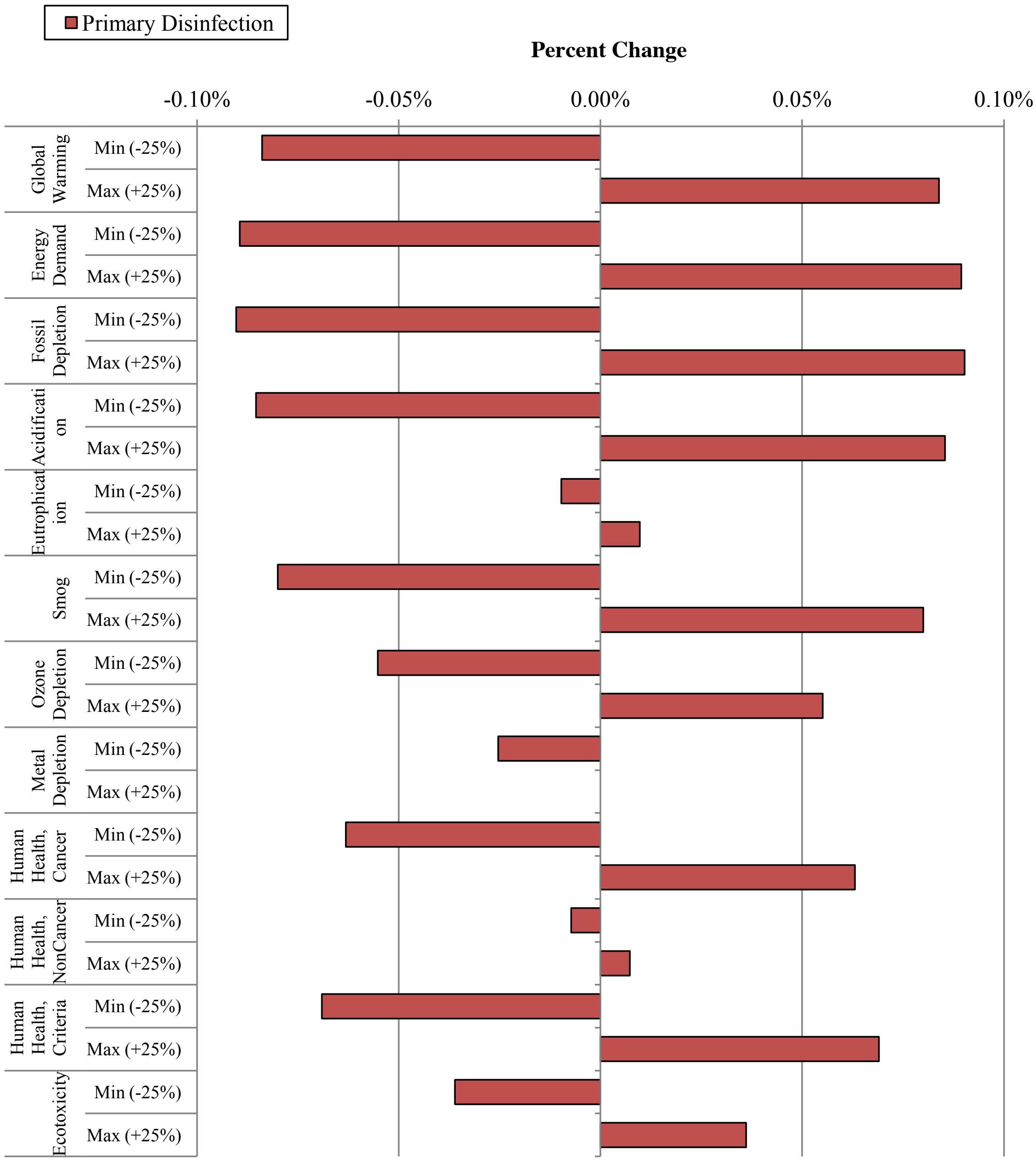


Figure 27. LED UV electricity usage sensitivity analysis.

7.4 Ferrate Technology

FTT patented an on-site reactor for municipal and industrial water treatment applications (the Ferrator®). The Ferrator® generates ferrate ions (FeO_4^{2-}) on-site from caustic, sodium hypochlorite, and ferric chloride and delivers it continuously to the process. Ferrate can be used as an oxidant, coagulant, and disinfectant. When used at the beginning of a treatment train, ferrate will oxidize organics and sulfides, eliminate taste and odor issues, and eliminate the need for GAC to remove disinfection byproducts. According to FTT, ferrate has the following benefits over chlorine disinfection:

- Reduces the chlorine dose required to maintain an adequate residual;
- Eliminates the need for alum coagulation;
- Reduces the amount of sludge generated; and
- Eliminates the generation of DBPs.

According to FTT, one of the key benefits is the reduction of DBPs. In conventional drinking water plants, DBPs form when chlorine reacts with the organics present in the raw water. Using ferrate at the pre-disinfection stage can remove solids and organics. The Ferrator® reactor controls the generation of ferrate ions such that the chlorine in the chemical feedstocks is consumed in the reaction to form sodium chloride, which will not combine with organics to form DBPs. Ferrate also provides disinfection by inactivating microorganisms. Chlorine will still need to be added to maintain a chlorine residual in the distribution system; however, the quantity of chlorine required for the residual is reduced and the chlorine is added after all organics have been removed, eliminating the formation of DBPs.

7.4.1 *Data Collection and System Boundaries*

EPA obtained information on the Ferrator® technology directly from FTT. Based on discussions with FTT, EPA made the following changes to the base case model to represent use of the Ferrator® technology:

- Added 3 ppm ferrate at the pre-disinfection stage as an oxidant/coagulant and eliminated the addition of alum and polymer as coagulants.

- Added ferric chloride for pH adjustment after addition of ferrate because ferrate will increase the pH (0.075 ppm of 40% concentration ferric chloride used at the sedimentation stage and 0.05 ppm of 40% concentration ferric chloride used at the conditioning stage). Eliminated the addition of lime and sodium hydroxide for pH control.

- Removed GAC. EPA assumed that ferrate would oxidize any organics present in the raw water and eliminate any taste and odor concerns; therefore, GAC is not required.

- Reduced volume of sludge generated (see details below).

- Added 2 ppm ferrate for primary disinfection.

- Reduced amount of chlorine required by 75 percent. This chlorine dose is required to maintain a chlorine residual in the distribution system.

- Increased electricity consumption to power the Ferrators®.

- Added infrastructure requirements for production of the Ferrator® (amortized over the useful life of the system).

EPA compared data provided by FTT to the base case model assumptions and made some adjustments to the data inputs as described below:

1. **Ferrator chemical feedstocks** – The chemical composition of Ferrate is confidential. For purposes of this analysis, EPA assumed ferrate is produced on-site at the DWT plant in a Ferrator® using sodium hydroxide (50% concentration), sodium hypochlorite (15% concentration, estimated based on available data), and ferric chloride (40% concentration) at a mass ratio of 3:1:0.5.

2. **Sludge generation** – GCWW does not dewater sludge from the sedimentation basin and returns a watery sludge stream to the river. EPA computed an estimated mass of sludge generated given the TSS concentration of raw river water and GCWW's dosage of alum, polymer, and lime, which all contribute to the sludge generated. EPA calculated approximately 3.6 lb dry sludge is generated per 1,000 ft^3 of water produced in the base case given a raw water TSS concentration of 43 mg/L.[21] EPA performed similar calculations to determine the amount of sludge generated from ferrate (3.0 lb dry sludge/ 1,000 ft^3 of water).

Additional assumptions specific to the LCA model and cost analysis are described in the subsections below. Because use of ferrate impacts or eliminates the need for many unit processes in the base case, the system boundaries for the ferrate drinking water treatment model are provided in Figure 28.

[21] Calculations based on equations from Appendix E Sludge Production from Coagulants and Other Treatment Chemicals, AWWA Research Foundation, "Trace Contaminants in Drinking Water Chemicals", 2002.

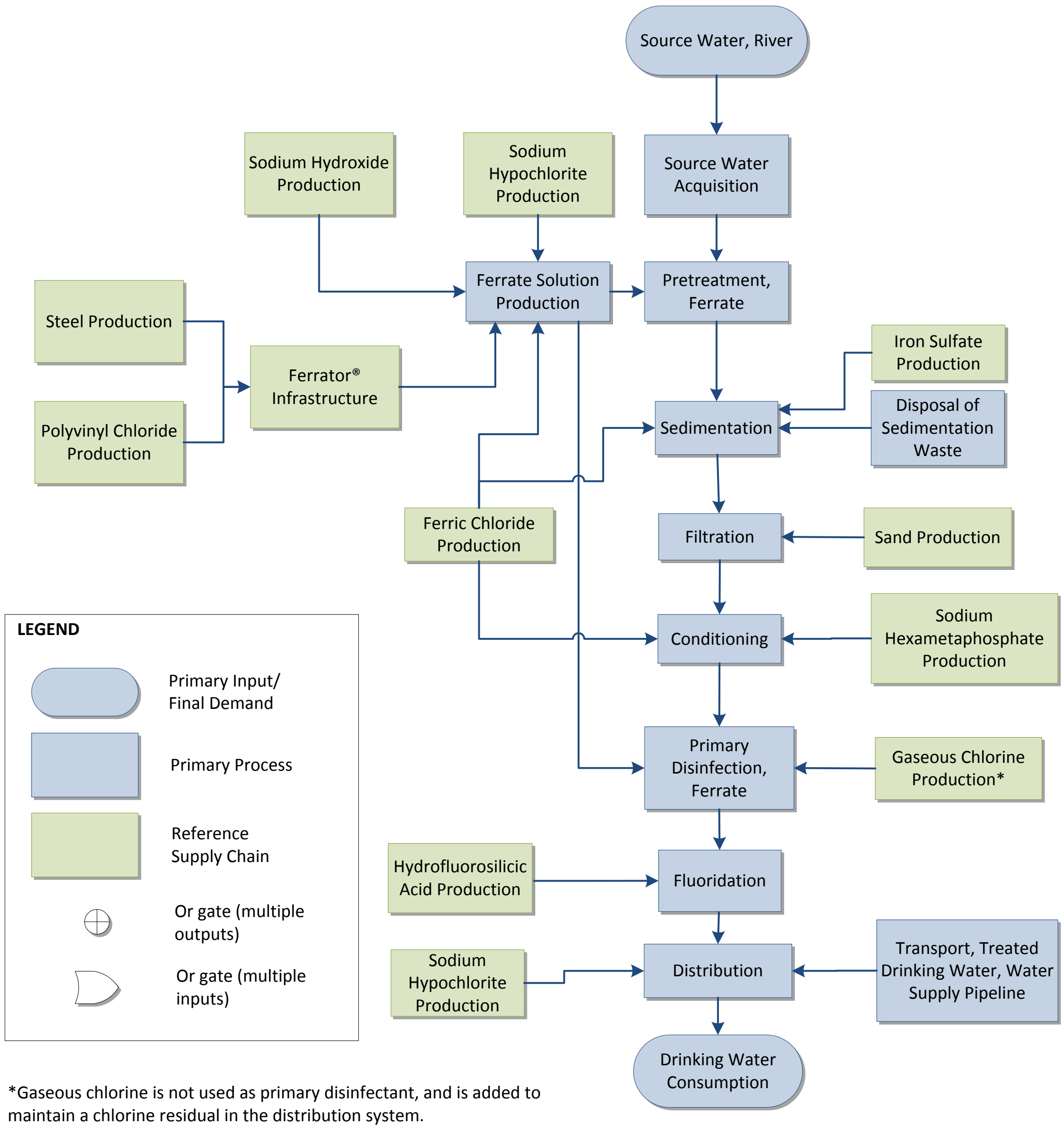


Figure 28. System boundaries of ferrate drinking water treatment.

7.4.2 *LCA Model*

This section provides information on the unit processes developed and data sources used for the ferrate DWT LCA model.

7.4.2.1 Unit Processes

EPA developed new unit processes for the specific ferrate DWT processes listed below (categorized by the overall life cycle stage or material). As shown in Figure 28, the ferrate DWT unit processes start with source water acquisition and end with drinking water use. Unaffected unit processes from the base case are not listed here. Additional ferrate unit processes from background LCI database (e.g., ecoinvent v2.2 and U.S. LCI) that have not been modified are identified in Section 7.4.2.2, Table 22 (Ferrate Data Sources).

Ferrate Solution

1. **Ferrate Solution.** Ferrate solution is produced on-site at the DWT plant in a Ferrator® using sodium hydroxide (50%), sodium hypochlorite (15%, estimated based on available data), and ferric chloride (40%) at a mass ratio of 3:1:0.5. Some electricity is required for operating the Ferrator® to produce the ferrate solution at the DWT plant. The Ferrator® infrastructure, amortized over lifetime production of ferrate, is an input to the ferrate solution unit process.
2. **Ferrator® (Fe300) Production.** This unit process includes production of one Fe300 Ferrator®. The Ferrator® has a lifetime of 15 years, weighs 14,000 lbs, and is composed primarily of steel (for the frame and skid) and PVC (for piping valves and fittings). EPA assumed the Ferrator® is, by weight, 90% steel and 10% PVC. This unit process only includes material production for the Ferrator®, no assembly information was available, and is therefore excluded.

Pre-Disinfection

3. **Pre-Treatment, Ferrate.** Ferrate solution is used at 3 ppm during pre-treatment to act as an oxidant/coagulant.
4. **Sedimentation, Ferrate.** Ferric chloride is added during sedimentation to adjust pH (as opposed to lime addition in the base case). The sedimentation unit process has been otherwise unchanged from the base case.
5. **Disposal, Sedimentation Waste, Ferrate.** Use of ferrate decreases the suspended solids and total sludge amount since alum is no longer used as a coagulant. Waterborne emissions of aluminum from the base case are also removed with the elimination of flocculation in the ferrate model. The overall waterborne emissions of ammonia, BOD, and COD remain unchanged from the base case, since it is assumed ferrate removes these emissions at the same rate as the base case model.
6. **Conditioning, Ferrate.** Ferric chloride is used for pH adjustment, and the use of sodium hydroxide is eliminated.
7. **Pre-Disinfection, Ferrate.** This unit process aggregates the upstream ferrate pre-disinfection unit processes from ferrate pre-treatment through conditioning.

Disinfection

8. **Primary Disinfection, Ferrate.** Representative of a DWT system using ferrate solution for primary disinfection. Ferrate is used at a 2 ppm dosage for primary disinfection. Some gaseous chlorine (reduced 75% from base case) is still included to have a chlorine residual in the distribution system.

Use

9. **Drinking Water Consumption, Ferrate.** Final delivery of water to an average consumer. This unit process aggregates the other main ferrate life cycle stages and is used to build the final product system. There are no actual impacts associated with the drinking water consumption life cycle stage itself.

7.4.2.2 Data Sources

Table 22 displays the data sources used for the ferrate model in addition to the data sources used in the base case model (See Table 3). In general, data from FTT were used where available. For upstream processes that would not be known by FTT such as information on chemical feedstock production (e.g., ferric chloride, sodium hydroxide, and sodium hypochlorite), EPA used information from either the U.S. LCI Database or ecoinvent v2.2. Data sets from U.S. LCI Database and ecoinvent v2.2 have not been adapted for this project.

Table 22. Ferrate data sources.

Process	Data Source
Ferrate Solution	Data Collection-FTT
Sodium Hypochlorite	ecoinvent v2.2
Ferric Chloride	ecoinvent v2.2
Sodium Hydroxide	ecoinvent v2.2
Ferrator® Infrastructure	Data Collection-FTT
Polyvinyl Chloride Resin	U.S. LCI
Steel, Low-Alloyed	ecoinvent v2.2
Pre-Treatment, Ferrate	Data Collection-FTT
Primary Disinfection, Ferrate	Data Collection-FTT

7.4.3 *Cost Analysis*

Table 23 lists information FTT provided for use in the cost analysis.[22] After adding in the Ferrator® system (including electricity usage, chemical inputs, incidental repairs, and amortized capital investment); reducing the gaseous chlorine usage; eliminating GAC, alum, polymer, lime, and caustic soda; and reducing the sludge produced, the total annual cost is $8,333,000, a decrease of $1,659,000 from Base Case 1.

Table 23. Cost data provided by FTT.

Cost Element	Value	Unit
Ferrator®	$810,000[a]	$/unit
Ferrator® monitor	$20,000	$/unit
Ferrator® lifetime	15	years
Electricity requirement	15,208[b]	kWh/unit
Incidental repairs	2%[c]	% of capital cost of Ferrator® units

[a]FTT noted that quantity discounts Ferrator® costs.
[b]FTT estimated 91,250 kWh of electricity would be required to operate six Ferrators®, which is approximately 15,208 kWh per Ferrator®.
[c] FTT estimated that incidental repairs would cost approximately 2% of the total cost of Ferrator® units installed, which is approximately $97,200 for six Ferrators®.

[22] Input data, calculations, and results for the FTT cost analysis are included in the supporting Excel file.

In addition, EPA included the following information and assumptions based on discussions with FTT:

1. The number of Ferrators® required depends on the ferrate dose needed to achieve the treatment objectives. EPA assumed ferrate would be added at the pre-disinfection stage as an oxidant/coagulant at a dose of 3 ppm and as the primary disinfectant at a dose of 2 ppm. FTT estimated that this dose would require 5 Ferrators® for pre-treatment and 4 for disinfection based on a DWT plant capacity of 100 MGD. FTT also recommended including an additional Ferrator® and an additional Ferrator® monitor as back-ups. EPA scaled-up the estimates provided by FTT to match the actual volume of water treated by GCWW used in the base case model. EPA estimated that 10 active Ferrators® and one active monitor would be required with an additional Ferrator® and monitor as back-ups. The resulting total capital equipment cost is $8,950,000.

2. Costs include two Ferrate monitors (primary and backup). The required dose of Ferrate is generated on site. The monitors adjust the ferrate dose to match demand automatically. The monitor continuously measures and records the concentration of ferrate in the stream being treated after the ferrate is mixed.

3. Cost multipliers are often applied to equipment costs to account for other direct costs such as installation, site work, and ancillary equipment and indirect costs such as permitting, monitoring, and training. Ferrators® are a pre-assembled skid-mounted system that can be set up on a pad. FTT noted that values less than standard costs multipliers would be appropriate for estimates of other direct costs and indirect costs. A 2008 AWWA drinking water report used the following multipliers to develop costs for drinking water residuals processes:

   - Piping and fittings – 10% of equipment
   - Electrical – 15% of equipment, piping
   - Instrumentation – 15% of equipment, piping, electrical
   - Contingency, bonding, and mobilization – 25% of total equipment, piping, electrical, and instrumentation.[23]

   FTT noted there is little ancillary equipment required other than feedstock storage tanks and transfer pumps. Ferrators® are also self-contained on their own skid and only require connections to utilities and feedstock tanks. FTT usually connects piping as part of their contract, so only power connections are required. Because FTT provides the required instrumentation and controls, EPA only added a 25% cost factor to the capital costs of the Ferrators® to account for any contingencies. The resulting total capital investment is $11,177,500.

4. EPA amortized the total capital costs over the 15-year expected lifetime of a Ferrator® using a bond rate of 6 percent. The resulting annual, amortized cost is $1,151,000.

[23] AWWA, 2008. Costing Analysis to Support National Drinking Water Treatment Plant Residuals Management Regulatory Options. Submitted by Environmental Engineering & Technology, Inc. Newport News, VA.

5. EPA did not include cost credits for any equipment that is no longer required with use of the Ferrators®. Plants would no longer need GAC equipment and may be able to reduce equipment required for chlorine addition because less chlorine is required. EPA did include the annual operating cost reduction from the reduced chlorine use and elimination of GAC.

7.4.4 ***Results***

Table 24 provides results of the ferrate analysis on the basis of 1 m^3 water delivered to the consumer. Figure 29 displays the ferrate results compared to Base Case 1 and Base Case 2 results by life cycle stage. As can be seen in the figure, only the impacts associated with pre-disinfection and primary disinfection (green and purple bars) change when switching from Base Case 1 to the ferrate DWT system. Figure 30 shows the percent change by impact when using ferrate for pre-treatment and primary disinfection instead of the Base Case 1 scenario. Results are sorted in this figure to visually display which impact categories are most affected by use of ferrate.

Ferrate findings of note include:

- Cost results decrease 18 percent when switching from Base Case 1 to the ferrate DWT system. While primary disinfection costs increase due to the ferrate infrastructure, these costs are offset and savings are realized by cost reductions in the pre-disinfection stage. Ferrate cost savings are dominated by: 1) elimination of GAC replacement, 2) elimination of alum coagulant for flocculation, 3) elimination of sodium hydroxide for pH adjustment, and 4) elimination of natural gas combustion for regeneration of the GAC.

- Usage of gaseous chlorine for primary disinfection decreases 75 percent when using ferrate to maintain a chlorine residual in the distribution system. The sodium hypochlorite added during distribution is still added in the same amount as this is required to boost chlorine residual in certain parts of the distribution system. This sodium hypochlorite boost may not be applicable for other drinking water systems. As discussed previously, using ferrate at the pre-disinfection stage can remove solids and organics. Since chlorine is only added after the organics have been removed, DBPs are not expected to form from using ferrate as applied in this model.

- There is no expected change in human exposure to cryptosporidium when switching to a ferrate treatment system.

- Global warming potential decreases seven percent when using ferrate compared to the base case. This reduction is largely attributable to the removal of sodium hydroxide and lime for pH adjustment in the sedimentation and conditioning processes (ferric chloride is used for pH adjustment in ferrate model) and the elimination of the GAC adsorption step. Overall, electricity consumption at the plant and during distribution is the largest contributor to the GWP. Use of ferrate does not significantly impact electricity usage, with exception of a small amount of electricity required to operate the Ferrators®. The additional electricity required to operate the Ferrators® has a negligible effect on all impact results.

- Overall, the additional infrastructure required to produce the Ferrator® units has a negligible effect on all impact results with the exception of cost.

- Blue water use does not change between Base Case 1 and the ferrate DWT system. Blue water use is dominated by the actual source water acquired to produce the drinking water and the water losses during distribution, with neither of these factors being influenced by the type of disinfection technology.

- Smog formation decreases 10 percent when switching from Base Case 1 to the ferrate DWT system. This is primarily due to the elimination of the GAC adsorption step, which includes production of GAC from coal and regeneration of GAC with natural gas, as well as the elimination of the need for alum coagulant for flocculation since ferrate acts as a flocculant. Exclusion of the sodium hydroxide and lime for pH adjustment also contribute to the lower smog results for ferrate. However, a significant decrease in smog formation is not seen because most of the smog impacts are due to electricity consumption at the plant and during distribution, which are unaffected by switching to ferrate.

- Similarly, energy demand decreases eight percent and fossil depletion decreases four percent when switching from Base Case 1 to the ferrate DWT system due to the elimination of sodium hydroxide, lime, alum coagulant, and GAC adsorption.

- Eutrophication, which is dominated by disposal of the sedimentation sludge, only decreases one percent under the ferrate DWT system. While elimination of alum decreases the overall sludge at the DWT plant, it is expected that the same amount of BOD, COD and ammonia (primary emissions leading to eutrophication) will be removed from the raw water under the ferrate system; therefore, the final flows of these waterborne emissions from sedimentation sludge do not vary from the base case.

- Acidification results decrease five percent when switching from Base Case 1 to the ferrate DWT system due to the elimination of sodium hydroxide (for pH adjustment), lime, alum coagulant, and GAC adsorption. Acidification impacts in the DWT model are dominated by sulfur dioxide and nitrogen oxide emissions from fossil fuel combustion for electricity generation. Again, because ferrate does not influence electricity consumption significantly at the plant or during distribution, a large overall decrease in acidification impacts is not realized with the use of ferrate.

- Human health criteria impacts decreases nine percent under the ferrate DWT system. This is largely due to the reduction in sulfur dioxide emissions with the elimination of GAC production and regeneration as well as the elimination of the alum coagulant and sodium hydroxide for pH adjustment.

- Ozone depletion, metal depletion, human health cancer and human health noncancer results have a higher uncertainty associated with them in the comparative results due to data alignment issues between the unmodified European ecoinvent datasets and the U.S. datasets (U.S. LCI Database and EPA processes developed for this work). While reductions in impacts are expected in these categories when switching to ferrate, it is emphasized that these reductions are likely overstated in the results figures presented.

- Ozone depletion impacts decrease 15 percent under the ferrate DWT system in this model. This is primarily due to the elimination of sodium hydroxide for pH adjustment and alum coagulant for flocculation. These materials are modeled using European ecoinvent datasets. The background European electricity data for production of these materials uses an electricity grid with higher ozone depletion than the U.S. average electricity grid modeled for plant operations and drinking water distribution. The average European electricity grid ozone depletion impacts are primarily influenced by Halon 1301 emissions from crude oil production and Halon 1211 emissions from natural gas production. These emissions are not incorporated into the U.S. electricity grid fuel profiles. Therefore, it is expected that the actual reduction in ozone depletion under the ferrate system is lower than stated here, and the notable reduction is primarily influenced by data alignment issues. The uncertainty associated with the ozone depletion results is, therefore, considered high.

- Metal depletion results also decrease 15 percent when switching from Base Case 1 to the ferrate DWT system. Ecoinvent processes, specifically sodium hydroxide, that are eliminated with use of ferrate do include background infrastructure for capital equipment. This metal infrastructure leads to depletion of metals such as nickel, copper and chromium. So, some reduction in metal depletion is expected when using ferrate; however, it is likely that the metal depletion reduction value is overstated here. The ecoinvent data sets and the ferrate production do include background infrastructure, but background infrastructure is not included for any of the primary DWT processes, U.S. electricity generation, or background U.S. LCI processes. The uncertainty associated with metal depletion results is considered high due to these infrastructure data alignment concerns.

- Human health noncancer results decrease 36 percent under the ferrate DWT system. This decrease is due to elimination of the sodium hydroxide for pH adjustment, relating to the background carbon disulfide emissions from ecoinvent European electricity.

- Human health cancer decrease 11 percent when switching from Base Case 1 to the ferrate DWT system, largely from the elimination of sodium hydroxide for pH adjustment and alum coagulant for flocculation. This is primarily due to fewer dioxin and formaldehyde emissions in the background European ecoinvent electricity required to produce these material.

- Ecotoxicity results decrease 12 percent when switching from Base Case 1 to the ferrate DWT system. This reduction is due to the elimination of sodium hydroxide for pH adjustment and alum coagulant for flocculation. The main emissions associated with the supply chain of these materials that lead to ecotoxicity are cyanide, carbofuran, and phenol.

Table 24. Ferrate results per m[3] drinking water delivered to the consumer.

Results Category	**Unit**	**Ferrate**
Cost	*$*	*$0.067*
Cryptosporidium	*oocyst*	*1.00*
TTHM	*kg TTHM*	*0*
Hazardous Materials	*kg* Cl_2	*4.4E-04*
Global Warming	*kg* CO_2 *eq*	*0.97*
Energy Demand	*MJ*	*18.3*
Fossil Depletion	*kg oil eq*	*0.33*
Acidification	*kg H+ mole eq*	*0.45*
Eutrophication	*kg N eq*	*9.4E-04*
Blue Water Use	m^3	*1.20*
Smog	*kg* O_3 *eq*	*0.060*
Ozone Depletion	*kg CFC-11 eq*	*2.3E-08*
Metal Depletion	*kg Fe eq*	*0.031*
Human Health, Cancer, Total	*CTU*	*2.6E-11*
Human Health, NonCancer, Total	*CTU*	*2.0E-11*
Human Health, Criteria	*kg PM10 eq*	*0.0013*
Ecotoxicity, Total	*CTU*	*3.9E-04*

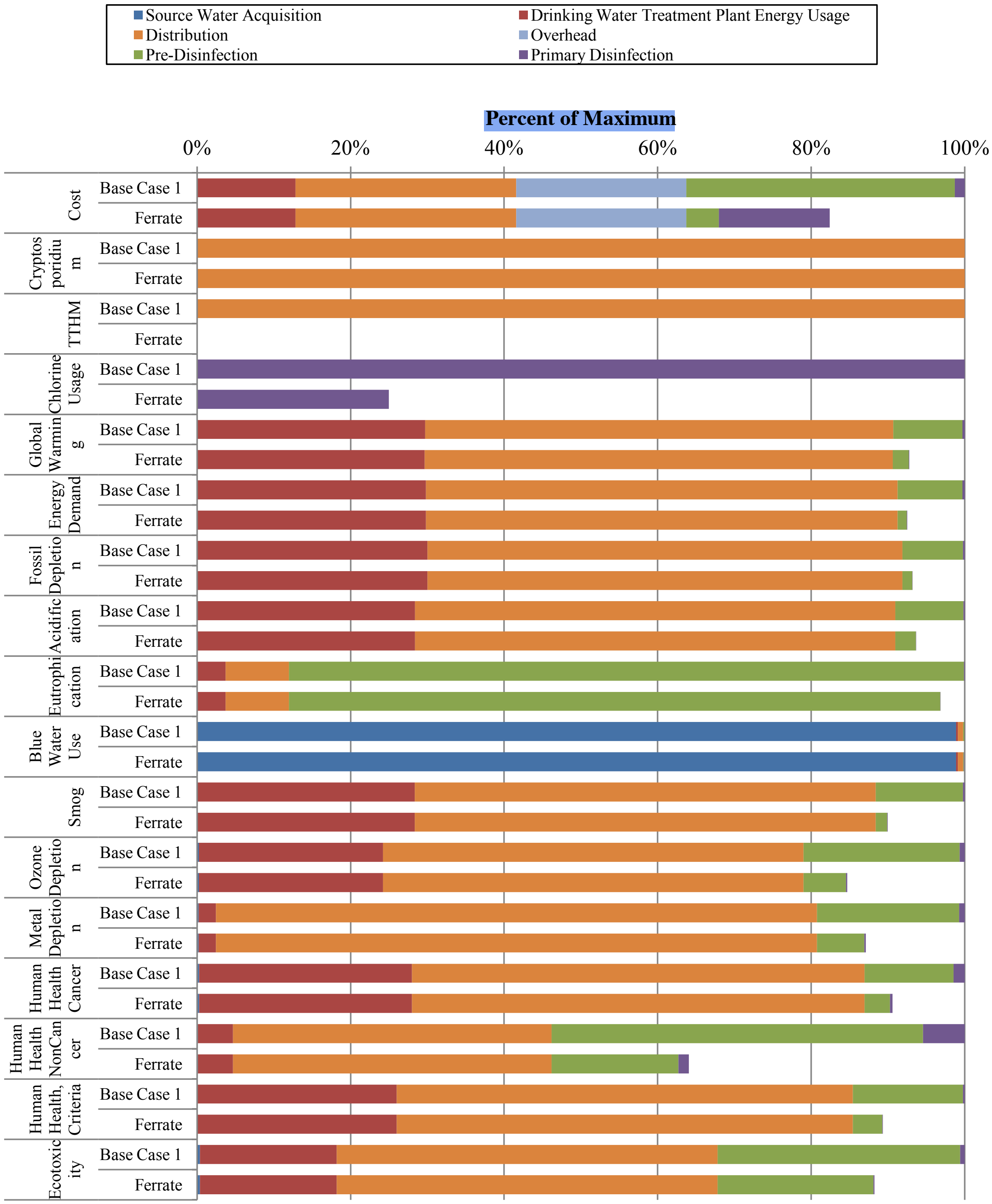


Figure 29. Base Case 1, Base Case 2, and ferrate comparative results by life cycle stage.

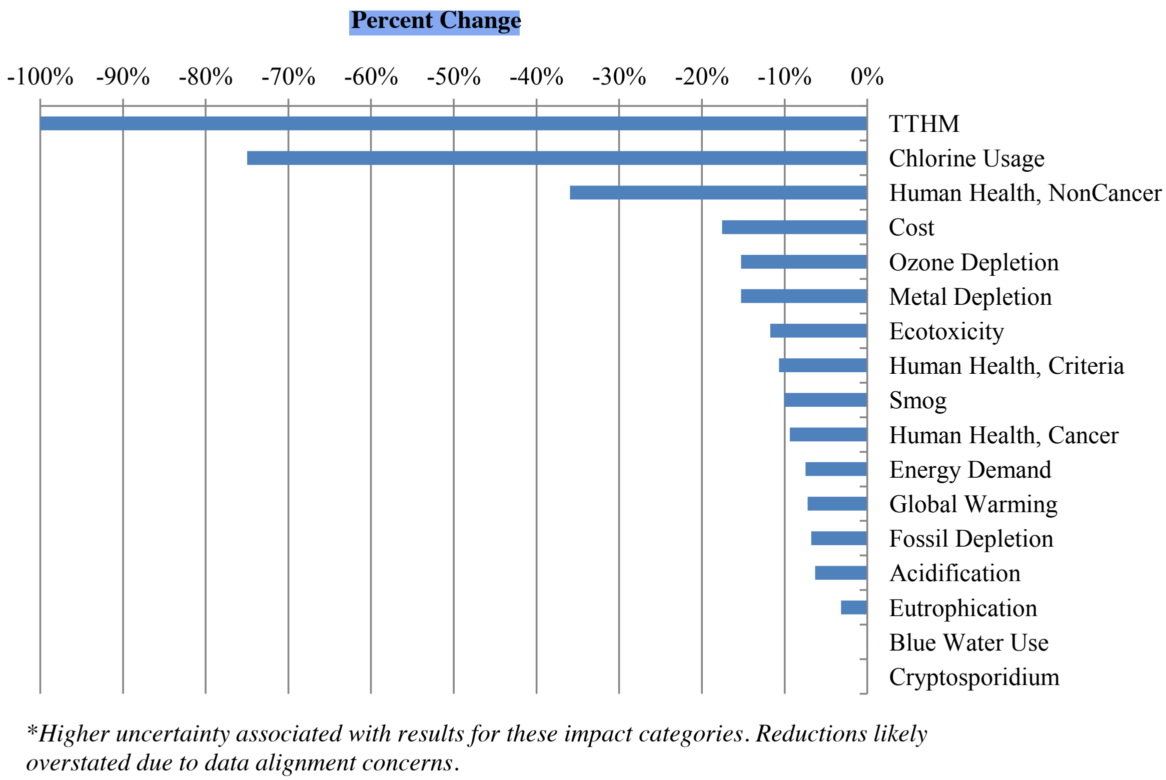


Figure 30. Percent reduction when switching from Base Case 1 to ferrate DWT system.

The ferrate base case assumes that 3 ppm of ferrate is added at the pre-disinfection life cycle stage and 2 ppm of ferrate is added during the primary disinfection life cycle stage. The actual ferrate dosage may vary depending on the specific plant conditions and the quality of the incoming water. A sensitivity analysis is conducted here varying the ferrate dosage during the pre-disinfection and primary disinfection stages. A minimum dosage of 1 ppm during pre-disinfection and 1 ppm during primary disinfection and a maximum dosage of 5 ppm during pre-disinfection and 3 ppm during primary disinfection are investigated.

Figure 31 presents the results of this sensitivity analysis. Impact assessment results do not vary more than +/- 0.80 percent in this sensitivity analysis; therefore, the ferrate LCA model is not sensitive to the ferrate dosage requirements.

Figure 32 presents a tornado chart that displays the results of the total cost sensitivity analysis. The cost sensitivity analysis performed a Monte Carlo simulation, varying the following:

- Pre-disinfection ferrate dose from 1 ppm to 5 ppm (same as was performed for the LCA sensitivity analysis).
- Disinfection ferrate dose from 1 ppm to 3 ppm (same as was performed for the LCA sensitivity analysis).
- Cost of a Ferrator® unit by ±10% (baseline value of $810,000/unit).

- Bond rate from four to eight percent (a ±33% change from the baseline value of six percent).

The sensitivity results show that the total costs are most sensitive to the bond rate and followed by the Ferrator® cost per unit, pre-disinfection ferrate dose, and the disinfection ferrate dose. However, the total cost changes are within approximately ±1.70%. Therefore, although the total costs are more sensitive to the bond rate than they are to the capital equipment cost and the ferrate doses, the total cost sensitivities are mitigated over the parameter values studied. This result is expected as the Ferrator® system only impacts the pre-disinfection and disinfection stages, which constitute 5% and 18% of the total costs, respectively (the use of ferrate increases the disinfection costs but decreases the pre-disinfection costs for an overall cost savings). The total costs are dominated by the distribution costs (35%) and overhead costs (27%). The plant energy costs constitute the remaining 15% of the total costs.

It is important to note that FTT has reported to be continuing the optimization of its ferrate manufacturing equipment, thus reducing the associated equipment costs. Compared with the estimated costs in this study, a significantly lower cost may occur in the present and future, especially for large water treatment plants.

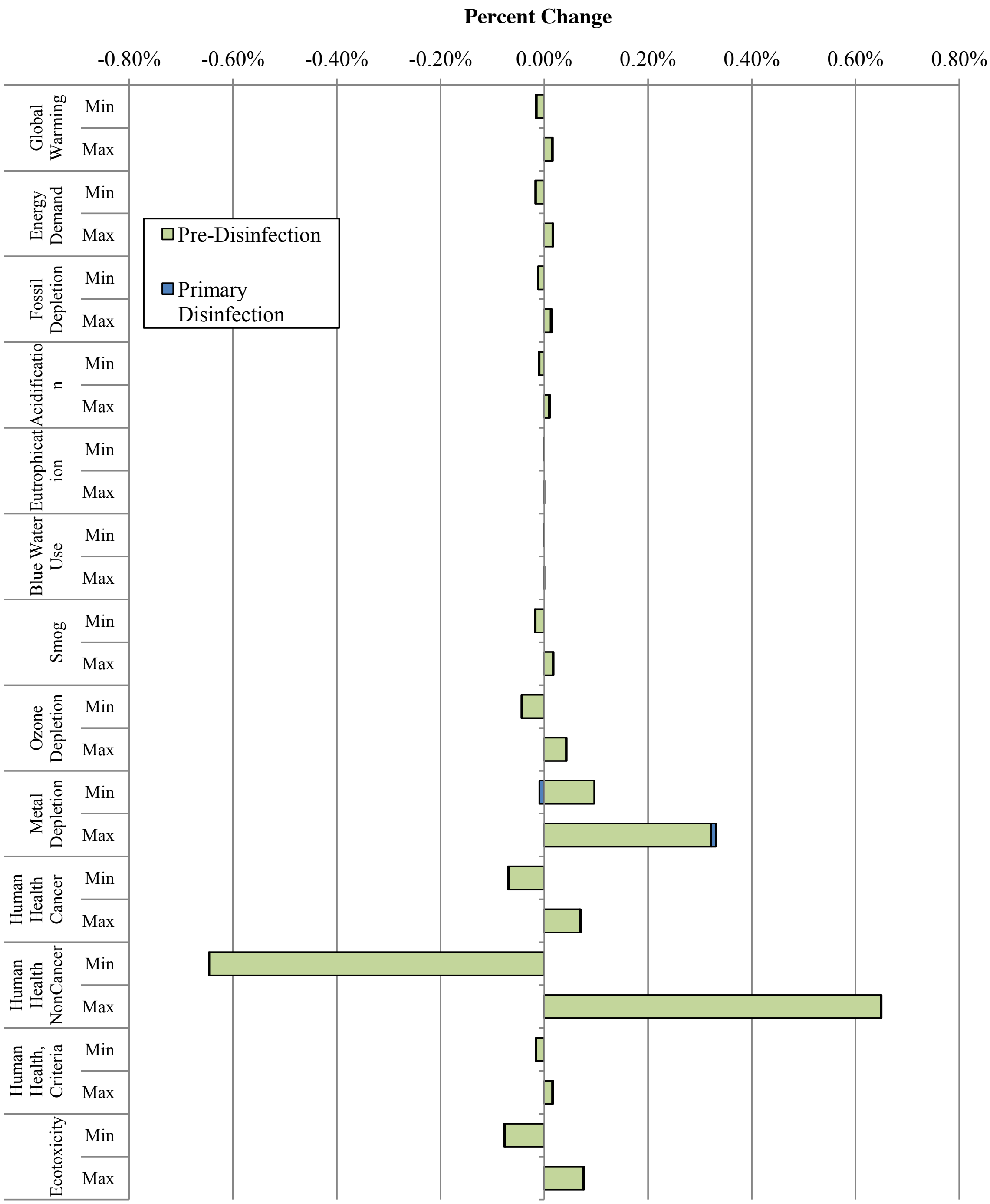


Figure 31. Ferrate dosage sensitivity analysis.

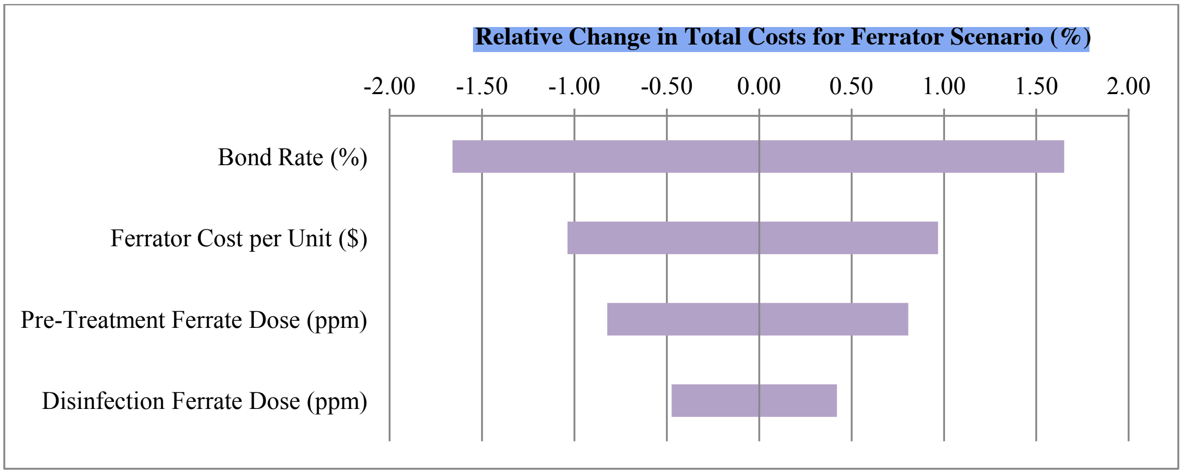


Figure 32. Tornado chart of the sensitivity results for the relative changes in total costs for the ferrate scenario.

7.5 Imaging Systems Technology

IST is an electronics and materials firm that manufactures a hollow gas encapsulating shell called a plasma-bead. When a voltage is applied across the shell, the gas ionizes into plasma to generate UV light which can be used for disinfection. Multiple plasma-beads can be configured in an array to disinfect different quantities of drinking water. IST is at the design phase of implementing their plasma-bead technology for drinking water disinfection and is looking to partner with UV vendors such as Aquionics to develop pilot- and full-scale plasma-bead disinfection technologies. As such, IST is not able to provide detailed unit process and cost data to use to develop a model to compare to the base case. EPA is working with IST to develop general assumptions regarding the manufacturing and composition of their plasma-bead technology to use in the analysis. According to IST, potential benefits of the technology include:

- Low manufacturing cost;
- Low operating cost;
- UV light source is in direct contact with water and the light output is very bright;
- Technology can scale to large sizes; and
- Plasma-bead are composed primarily of alumina oxide gas and do not contain environmentally hazardous materials such as mercury.

7.6 Comparative Results

Figure 33 presents the summary comparative results of the base case DWT model versus the alternative disinfection technology models (ferrate, conventional UV, and LED UV). Utilization of ferrate results in environmental, human health, and cost benefits for combined use in the pre-disinfection and primary disinfection stages, since ferrate acts as both a coagulant and disinfectant and only small dosages are required for treatment. Application of UV technology increases impacts during disinfection through increased electricity consumption and through new capital investment, but eliminates the formation of disinfection by-products and greatly reduces hazardous chlorine usage. LED UV is more energy efficient compared to conventional mercury-vapor UV; however, it is currently developed only for point-of-use applications, and not large-scale treatment facilities.

Figure 34 presents the comparative normalized results for the different disinfection technology life cycles. The following results are shown on this figure:

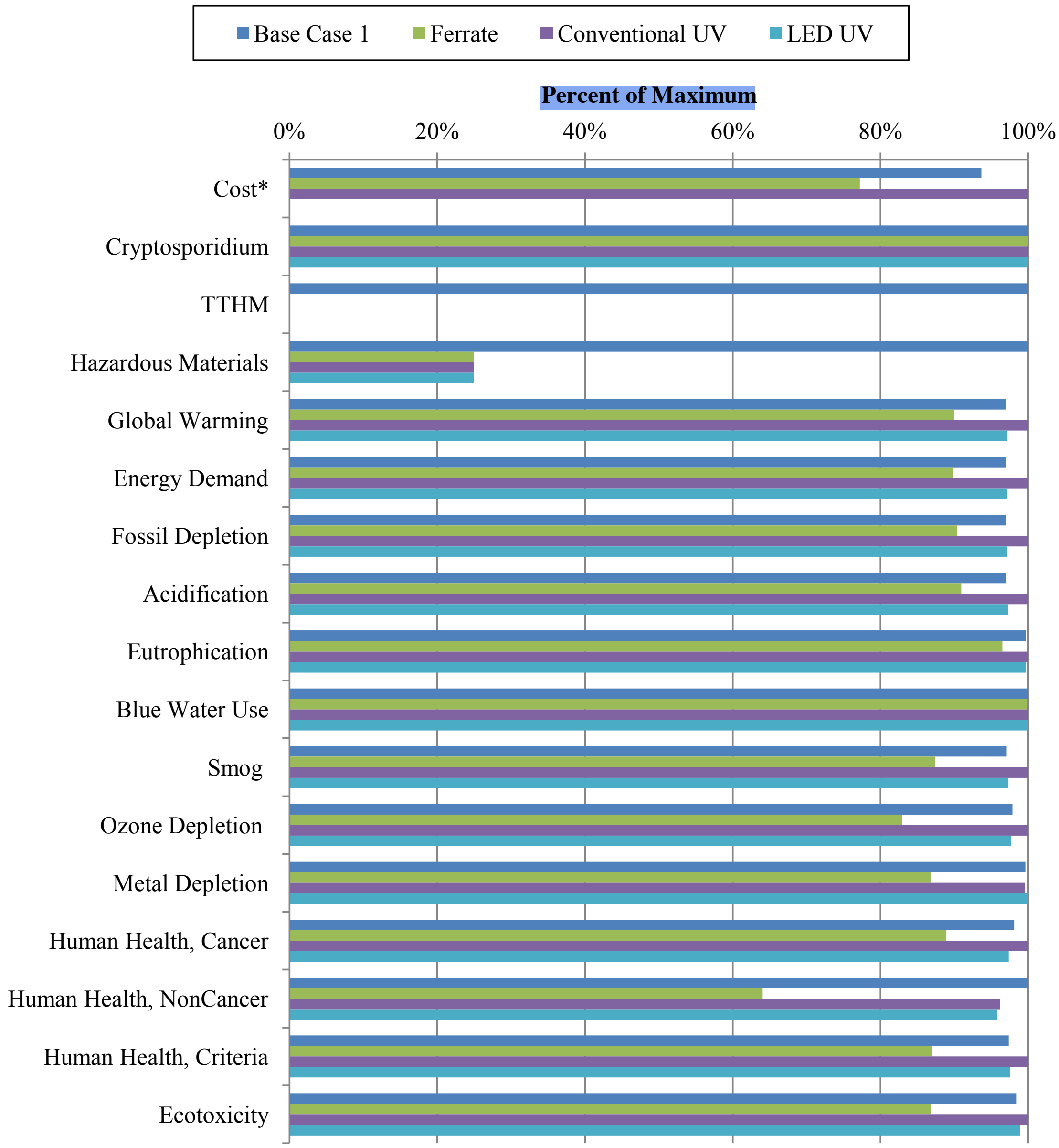
- Cost: this category displays cost by life cycle stage. The costs are shown as a percentage of the highest cost system (in this case conventional UV).
- Normalized by impact: this category presents the normalized impact assessment results by impact category. Impact categories have been normalized using TRACI v2.1 normalization factors.[24] The results are shown as a percentage of the highest normalized impact system (in this case conventional UV).
- Normalized & weighted by impact: this category presents the normalized and weighted impact assessment results by impact category. Impact categories have been normalized using TRACI v2.1 normalization factors and have been weighted using NIST weighting factors.[24], [25] The results are shown as a percentage of the highest normalized impact system (in this case conventional UV).
- Normalized by stage: this category presents the normalized impact assessment results by life cycle stage. Life cycle stages have been normalized using TRACI v2.1 normalization factors.[24] The results are shown as a percentage of the highest normalized impact system (in this case conventional UV).

Only impacts with TRACI normalization factors are shown in Figure 34. Blue water use, metal depletion, cumulative energy demand, and fossil depletion are excluded due to lack of available normalization factors. Additional water treatment metrics included (TTHM and hazardous materials) are not shown since they also do not have associated normalization factors. Cost results for LED UV are also not shown in Figure 34 due to lack of available cost data for this technology. Some findings of note from Figure 34:

- Weighting increases the relative importance of global warming potential.
- In all cases, conventional UV has the highest overall normalized impact, normalized and weighted impact, and cost.
- Impact assessment results' correlate with cost results.

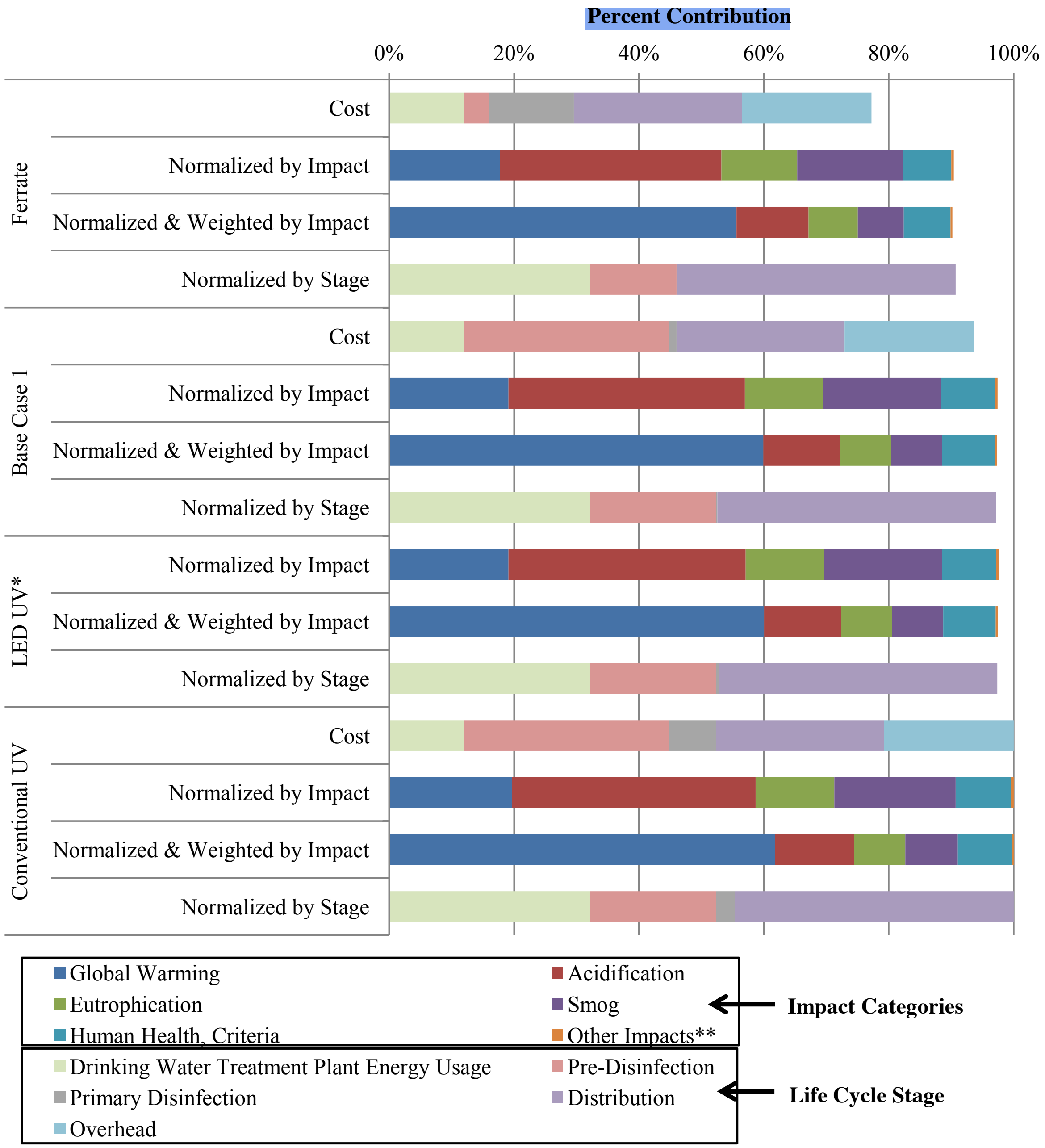
[24] Ryberg, M., Vieira, M.D.M., Zgola, M., Bare, J., and Rosenbaum, R.K., 2014. Updated US and Canadian normalization factors for TRACI 2.1. Clean Techn Environ Policy, 16: 329-339.

[25] Gloria, T.P., Lippiatt, B.C., and Cooper, J. 2007. Life cycle impact assessment weights to support environmentally preferable purchasing in the United States. Environ. Sci. Technol, 41, 7551-7557.



*No cost data available for LED UV

Figure 33. Summary comparative results of alternative disinfection technologies.



**No cost data available for LED UV*
***"Other Impacts" includes human health noncancer, human health cancer, ozone depletion, and ecotoxicity*

Figure 34. Normalized comparative results for different drinking water treatment disinfection technologies.

8. POINT-OF-USE ALTERNATIVE DISINFECTION TECHNOLOGIES

EPA investigated the impacts and costs associated with point-of-use drinking water technologies. EPA focused this analysis on point-of-use technologies that may be used by hospitals to reduce pathogen exposure for immune-compromised individuals. EPA did not investigate point-of-use alternatives for home use. Because point-of-use technologies will not change unit processes at the drinking water plant, EPA did not compare point-of-use LCA results to the base case model. Instead, EPA reported the life cycle impacts of each point-of-use technology and compared the impacts to the additional pathogen removal provided by the technology.

Hospitals draw water from the municipal water supply. Although water is disinfected at the treatment plant and chlorine is added to maintain an appropriate residual throughout the distribution system, microorganisms can be present in water at the tap due to residual bacteria in the distribution systems. Hospitals may use additional technologies to prevent pathogen exposure. Typically, *Legionella* and *Pseudomonas* bacteria are of greatest concern to hospitals. Hospitals may use technologies that are implemented for the water system as a whole at the point water enters the building from the municipality and prior to distribution throughout the facility. However, EPA's analysis focused on point-of-use filters that could be installed at or near the faucet.

EPA investigated use of Pall-Aquasafe™ 31-day point-of-use filters for waterborne microorganisms. According to Pall's website, filters can be used for up to 31 days and use a double-layer sterilizing grade membrane to reduce *Legionella* and *Pseudomonas* and other gram-negative bacteria.[26] The cost per filter ranges from $39 to $79, depending on the volume purchased by each customer. Since the point-of-use filter is an additional level of drinking water treatment and does not replace any processes in the base case water treatment scenario, the filter cost does not change any of the costs associated with water treatment in the base case.

An additional point-of-use technology examined was LED UV. As discussed in Section 7.3, Aquionics' current LED UV system is for point-of-use applications. Aquionics notes that this system may be used for stand-alone point of use, healthcare equipment, laboratory research equipment, and autocalves among other uses. This system is not installed directly on the faucet, but rather more likely installed in the pipe system right before the faucet.

8.1 System Boundaries

The system boundaries for the point-of-use disinfection technologies are displayed in Figure 35. Prior to point-of-use disinfection, all processes are equivalent to base case 1. The drinking water at the hospital then undergoes further disinfection via either the point-of use faucet filter (Pall) or the LED UV technology (Aquionics). The system boundaries end at consumption of the water by an immune-compromised adult.

[26] Pall Corporation Aquasafe Medical Filters. See: http://www.pall.com/main/medical/product.page?id=45154#

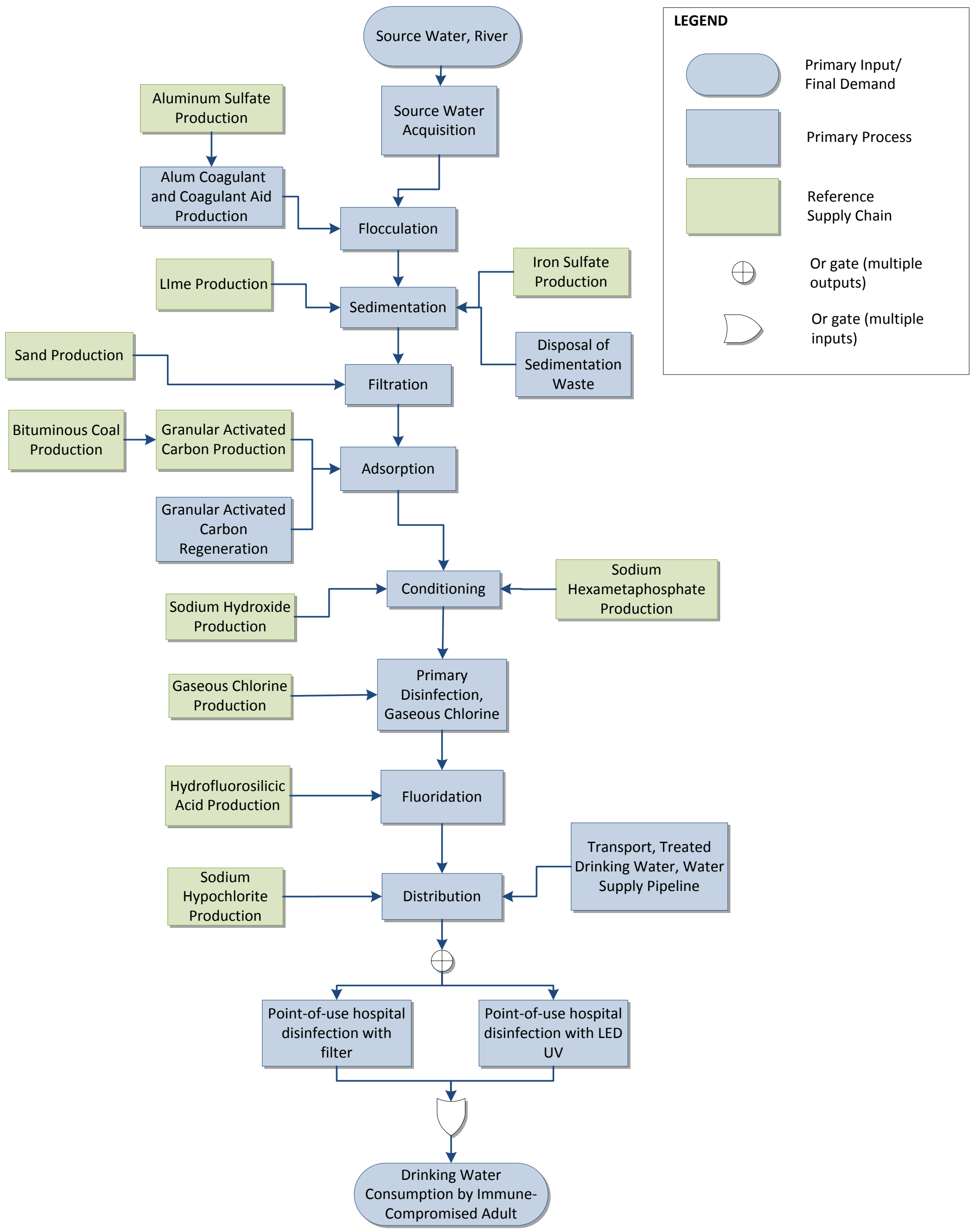


Figure 35. System boundaries for hospital point-of-use drinking water treatment.

8.2 <u>Pall Point-of-Use Filter</u>

8.2.1 *LCA Model*

EPA made the following assumptions for the point-of-use filter analysis:

- For the point-of-use LCA model, only the primary disinfection stage is changed from the base case DWT model.
- Water treated per filter unit is highly dependent upon the water use patterns in a given hospital. Thus, it is assumed that an individual faucet and filter are used on average 12 hours per day for one month. The faucet and filter is assumed to flow at a rate of 8.33 liters of treated water per minute, which is based on the standard maximum flow for faucets in the U.S. set by the U.S. Department of Energy and is within the rate of disinfection for the Pall Aquasafe 31-day filter as reported on their website.[27,28]
- Point-of-use filter infrastructure requirements were modeled based on the publicly available Declaration of Compliance for the Aquasafe 31-day filter, specifications for the QPoint™ filter published on the Pall Corporation website, and personal communication with Pall representatives.[29,30,31] This study identified the background ecoinvent datasets and associated quantities utilized in the life cycle inventory model, which were replicated in this LCI model.
- Disinfection with point-of-use filters removes 100% of *Legionella* and *Pseudomonas* present in drinking water delivered to the hospital. This is based on field evaluation reports on the Pall Aquasafe 31-day filter.[32]

8.2.2 *Unit Processes*

The specific unit processes added for the point-of-use filter LCA model are identified below.

Infrastructure

1. **Point-of-Use Hospital Filter, Infrastructure**. Infrastructure inputs for the point-of-use hospital filter are aggregated in this unit process. Infrastructure processes included are the production of the filter itself, production of a tap adapter, and corrugated packaging for distribution of the filters to hospitals.
2. **Point-of-Use Hospital Filter, Production.** Filters are manufactured from a variety of plastic resins.
3. **Tap Adapter for Point-of-Use Hospital Filter.** The faucet adapter, made of nickel-plated brass connects the point-of-use filter to a standard faucet for use in a hospital.
4. **Packaging for Point-of-Use Hospital Filter.** Filters are shipped to hospitals in corrugated boxes with 12 filers per box.

[27] U.S. Department of Energy: Buildings Technology Program. Oct 2013. Faucets. Accessed at: http://www1.eere.energy.gov/buildings/appliance_standards/product.aspx/productid/64

[28] Pall Corporation. Pall-Aquasafe™ AQ31F1S and AQ31F1R Filters for Waterborne Microorganisms. Accessed at: http://www.pall.com/main/medical/product.page?id=45154

[29] Pall Corporation. March 2013. Declaration of Compliance: Pall-Aquasafe™ Disposable Water Filter 31 Day Use – Tap Application. Accessed at: http://www.pall.com/pdfs/Medical/AQ31F1R-Declaration-of-Compliance.pdf

[30] Pall Corporation. Nov 2012. QPoint™ Tap Water Filter – USA. Accessed at: http://www.pall.com/main/consumer-water/product.page?lid=h8pw157j

[31] Pall Medical North American Sales Representatives Personal Communication. February 24, 2014.

[32] Pall Corporation. Feb 2009. Pall-Aquasafe™ Disposable Water Filter – Tap (AQ31F1S and AQ31F1R) Field Evaluation Report.

Use

5. **Drinking Water Consumption, Base Case, at Hospital with Point-of-Use Filter.** The point-of-use filter removes *Legionella* and *Pseudomonas* and other gram-negative bacteria from drinking water at the tap.

Table 25 displays the data sources used for the point-of-use hospital filter in addition to the data sources used in the base case model (See Table 3). Some data on components and weight of the filter were gathered from Pall. For upstream processes that would not be known by Pall such as information on resin production, EPA used information from the National Renewable Energy Laboratory's U.S. Life Cycle Inventory Database (U.S. LCI), a publically available life cycle inventory source.[33] Where data were not available from Pall or the U.S. LCI, ecoinvent v2.2, EPA used a private Swiss LCI database with data for many unit processes.[34]

Table 25. Point-of-Use hospital filter data sources.

Process	**Data Source**
Point-of-use hospital filter production	Information from Pall
Corrugated for filter packaging	ecoinvent v2.2
Nickel-plated brass tap adapter	ecoinvent v2.2
Polycarbonate for filter	ecoinvent v2.2
High-density polyethylene resin for filter	U.S. LCI
Synthetic rubber for filter	ecoinvent v2.2
Polypropylene for filter	U.S. LCI
Injection molding of plastic components of filter	ecoinvent v2.2

8.2.3 *Results*

Table 26 displays results for the base case and base case plus the point-of-use hospital filter per cubic meter of drinking water delivered to the immune-compromised person. Figure 36 presents summary results by life cycle stage for Base Case with the additional point-of-use disinfection with the Pall Aquasafe 31-day filter. As previously mentioned, no cost data was available for point-of-use filtration, so this is excluded from the figure. Overall point-of-use filter results show minimal increases in impacts compared to the base case results.

[33] National Renewable Energy Lab. US LCI Database. See: http://www.nrel.gov/lci/database/default.asp.

[34] Ecoinvent Centre (2010), ecoinvent data v2.2. ecoinvent reports No. 1-25, Swiss Centre for Life Cycle Inventories.

Table 26. Base case and Base case plus point-of-use hospital filter results per m^3 drinking water delivered to the consumer.

Results Category	Unit	Base Case 1	Base Case 1 plus Point-of-Use Hospital Filter
Hazardous Materials	*kg* Cl_2	*0.0018*	*0.0018*
Global Warming	*kg* CO_2 *eq*	*1.04*	*1.04*
Energy Demand	*MJ*	*19.8*	*19.9*
Fossil Depletion	*kg oil eq*	*0.36*	*0.36*
Acidification	*kg H+ mole eq*	*0.48*	*0.48*
Eutrophication	*kg N eq*	*9.7E-04*	*9.7E-04*
Blue Water Use	m^3	*1.20*	*1.20*
Smog	*kg* O_3 *eq*	*0.067*	*0.067*
Ozone Depletion	*kg CFC-11 eq*	*2.8E-08*	*2.8E-08*
Metal Depletion	*kg Fe eq*	*0.036*	*0.036*
Human Health, Cancer, Total	*CTU*	*2.9E-11*	*2.9E-11*
Human Health, NonCancer, Total	*CTU*	*3.2E-11*	*3.2E-11*
Human Health, Criteria	*kg PM10 eq*	*0.0015*	*0.0015*
Ecotoxicity, Total	*CTU*	*4.4E-04*	*5.9E-04*

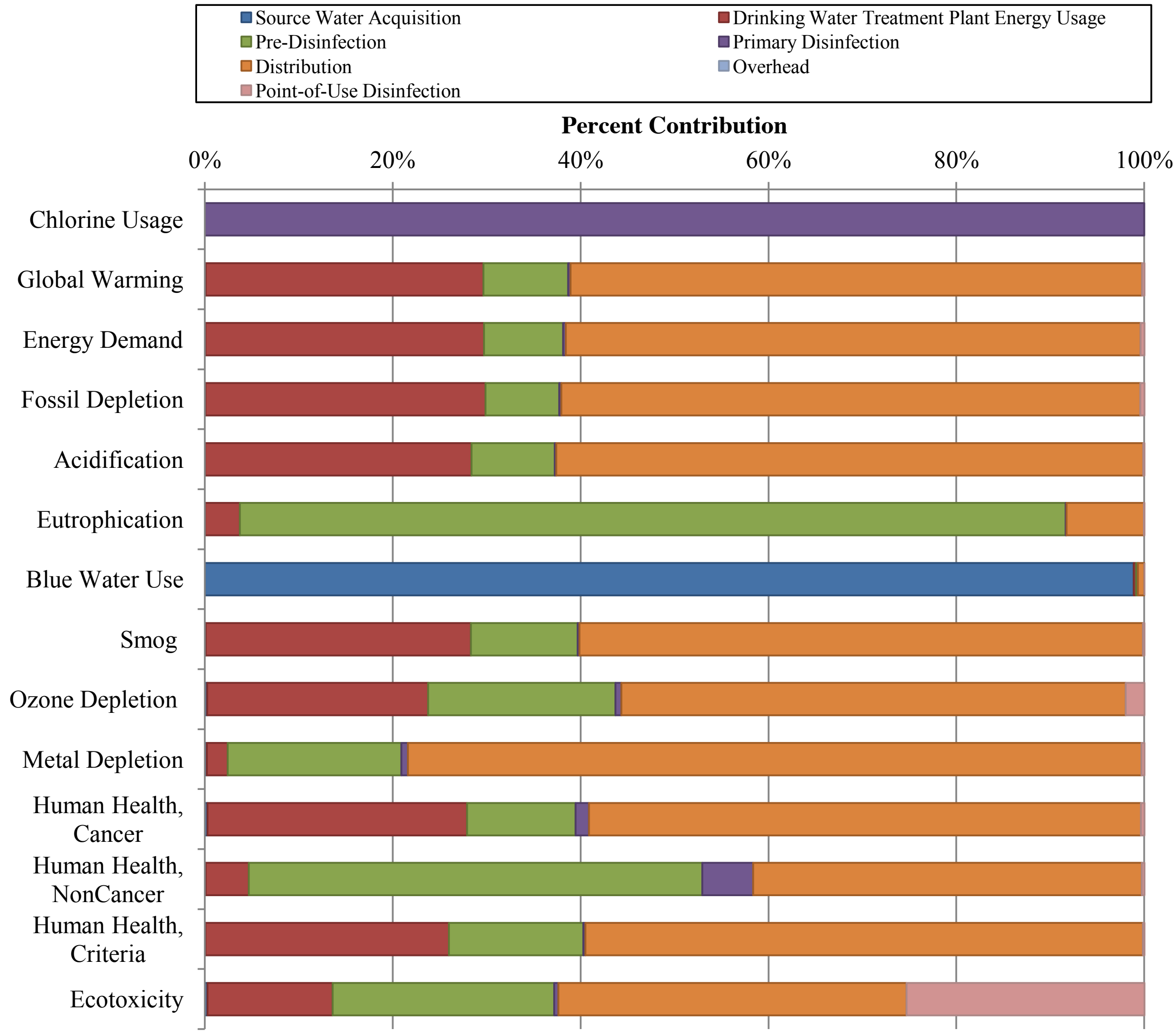


Figure 36. Base Case 1 plus point-of-use hospital filter contribution analysis results.

Because the point-of-use filter results are dependent on the assumption regarding water use per day (base case assumed 12 hours per day), additional analyses were conducted assuming 1 hour use per day and 24 hour use per day. The percent change in impacts for the base case plus the point-of-use hospital filter compared to the base case without the point-of-use hospital filter was calculated for the three different use scenarios. The results of this analysis are displayed in Figure 37. Ecotoxicity is excluded, since it has a comparatively large increase and makes it difficult to interpret other impact changes graphically. Ecotoxicity impacts are largely driven by upstream fungicide and pesticide use during potato farming for the potato starch in the corrugated boxes used to distribute the filters. Overall, impacts increase with less water treated per day, since this means more filters are required per volume of water.

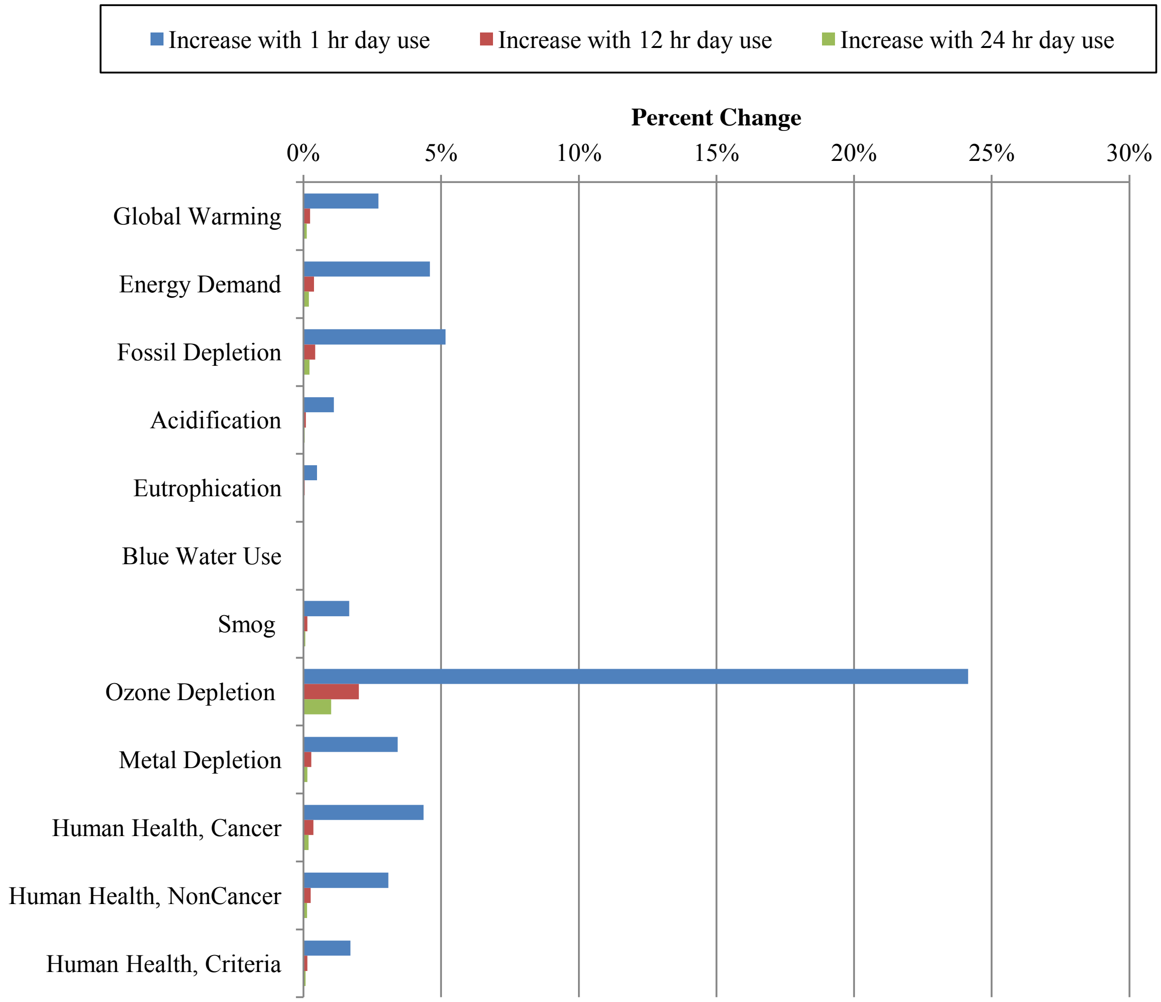


Figure 37. Base case percent change with point-of-use filter.

8.3 LED UV Point-of-Use Filter

8.3.1 *LCA Model*

EPA made the following assumptions for the point-of-use LED UV analysis:

- The LED UV system modeled is identical to that modeled in Section 7.3, with the following exceptions.
  - Instead of being housed in a stainless steel vessel with electronic controls, it is assumed the LED lamp is within a 6 pound unit that is primarily polypropylene with stainless steel pipe attachments.[35]

[35] The unit is 6 lb per Aquionics website: http://www.aquionics.com/main/pearl-brand2/pearlaqua/. EPA assumed the plastic housing was polypropylene due to lack of specific composition data.

- Based on Aquionics' website, it is assumed that 1 LED lamp treats 60,000 gallons of water over its lifetime.[36]

8.3.2 *Unit Processes*

The specific unit processes added for the point-of-use LED UV unit LCA model are identified below.

Disinfection

1. **Disinfection, Point-of-Use LED UV**. Primary disinfection with LED UV. The inputs to this unit process include operation and infrastructure requirements for the UV units.
2. **Point-of-Use LED UV Drinking Water Treatment, Operation**. This process covers electricity usage associated with operation of the point-of-use UV units.
3. **Point-of-Use LED UV Drinking Water Treatment, Infrastructure**. Infrastructure inputs for the UV units are aggregated in this unit process. Infrastructure processes included are the LED die fabrication, LED packaging assembly, three-inch sapphire wafer manufacture, and the point-of-use UV vessel.
4. **Point-of-Use UV Vessel.** Production of the plastic and steel vessel used to house the LED UV lamps.

Use

5. **Drinking Water Consumption, Base Case, at Hospital with Point-of-Use LED UV**. Final delivery of water, which is disinfected with LED UV, to an immune-compromised adult. This unit process aggregates the other main life cycle stages and is used to build the final product system. There are no actual impacts associated with the drinking water consumption life cycle stage itself.

Table 27 displays the data sources used for the point-of-use LED UV model in addition to the data sources used in the base case model (See Table 3). Aquionics' equipment specifications were used to determine operational energy requirements. Upstream infrastructure was primarily modeled based on a DOE LCA of LEDs.[20] This study identified the background ecoinvent data sets and associated quantities utilized in the DOE LCI and EPA replicated this LCI model. Aquionics' equipment specifications were also used to determine the materials and weights of the UV vessel.

[36] Aquionics. PearlAqua™. Accessed at: http://www.aquionics.com/main/pearl-brand2/pearlaqua/ (February 10. 2014).

Table 27. Point-of-Use LED UV data sources.

Process	Data Source
Point-of-Use LED UV disinfection operation	Aquionics' equipment specifications
Infrastructure for UV lamp	DOE LED LCA[20]
Infrastructure for Point-of-Use UV vessel	Aquionics' equipment specifications
Three-Inch Sapphire Wafer Manufacture	DOE LED LCA[20]
LED Die Fabrication	DOE LED LCA[20]
LED Packaging Assembly	DOE LED LCA[20]
Materials for LED production	ecoinvent v2.2
Energy for LED production	ecoinvent v2.2

8.3.3 *Results*

Table 28 presents results for the base case and base case plus the point-of-use hospital LED UV system per cubic meter of drinking water delivered to the immune-compromised person. Figure 38 shows summary results by life cycle stage for Base Case with the additional point-of-use disinfection with the LED UV unit. As previously mentioned, no cost data was available for LED UV, so this is excluded from the figure. A notable increase in overall impacts is seen for the addition of point-of-use LED UV disinfection. While some of this increase is due to electricity requirements for LED UV disinfection, the majority of increased impacts are driven by production of the LED UV lamps. The LED UV lamp infrastructure (e.g., sapphire wafer manufacture, die fabrication) is complex, and the lamps are assumed to be produced in China, which generates much of its electricity from coal, a relatively high impact energy source. The electricity mix in China is modeled based on ecoinvent v2.2 data specific to China, with 78.6% of the electricity sourced from hard coal, followed by 15.9% sourced from hydropower, 2.9% sourced from oil, and 2.1% sourced from nuclear.[12] Such LED UV infrastructure burdens are not seen for the large-scale LED UV analysis, as that analysis assumes 200 million gallons of water is able to be treated per lamp compared to the 60,000 gallons of water treated per lamp in this point-of-use analysis.

Table 28. Base case and Base case plus point-of-use hospital LED UV disinfection results per m^3 drinking water delivered to the consumer.

Results Category	**Unit**	**Base Case 1**	**Base Case 1 plus Point-of-Use Hospital LED UV Disinfection**
Hazardous Materials	*kg* Cl_2	*0.0018*	*0.0018*
Global Warming	*kg* CO_2 *eq*	*1.04*	*1.47*
Energy Demand	*MJ*	*19.8*	*25.6*
Fossil Depletion	*kg oil eq*	*0.36*	*0.48*
Acidification	*kg H+ mole eq*	*0.48*	*0.67*
Eutrophication	*kg N eq*	*9.7E-04*	*1.4E-03*
Blue Water Use	m^3	*1.20*	*1.21*
Smog	*kg* O_3 *eq*	*0.067*	*0.101*
Ozone Depletion	*kg CFC-11 eq*	*2.8E-08*	*4.0E-08*
Metal Depletion	*kg Fe eq*	*0.036*	*0.075*
Human Health, Cancer, Total	*CTU*	*2.9E-11*	*4.6E-11*
Human Health, NonCancer, Total	*CTU*	*3.2E-11*	*5.0E-11*
Human Health, Criteria	*kg PM10 eq*	*0.0015*	*0.0023*
Ecotoxicity, Total	*CTU*	*4.4E-04*	*1.8E-03*

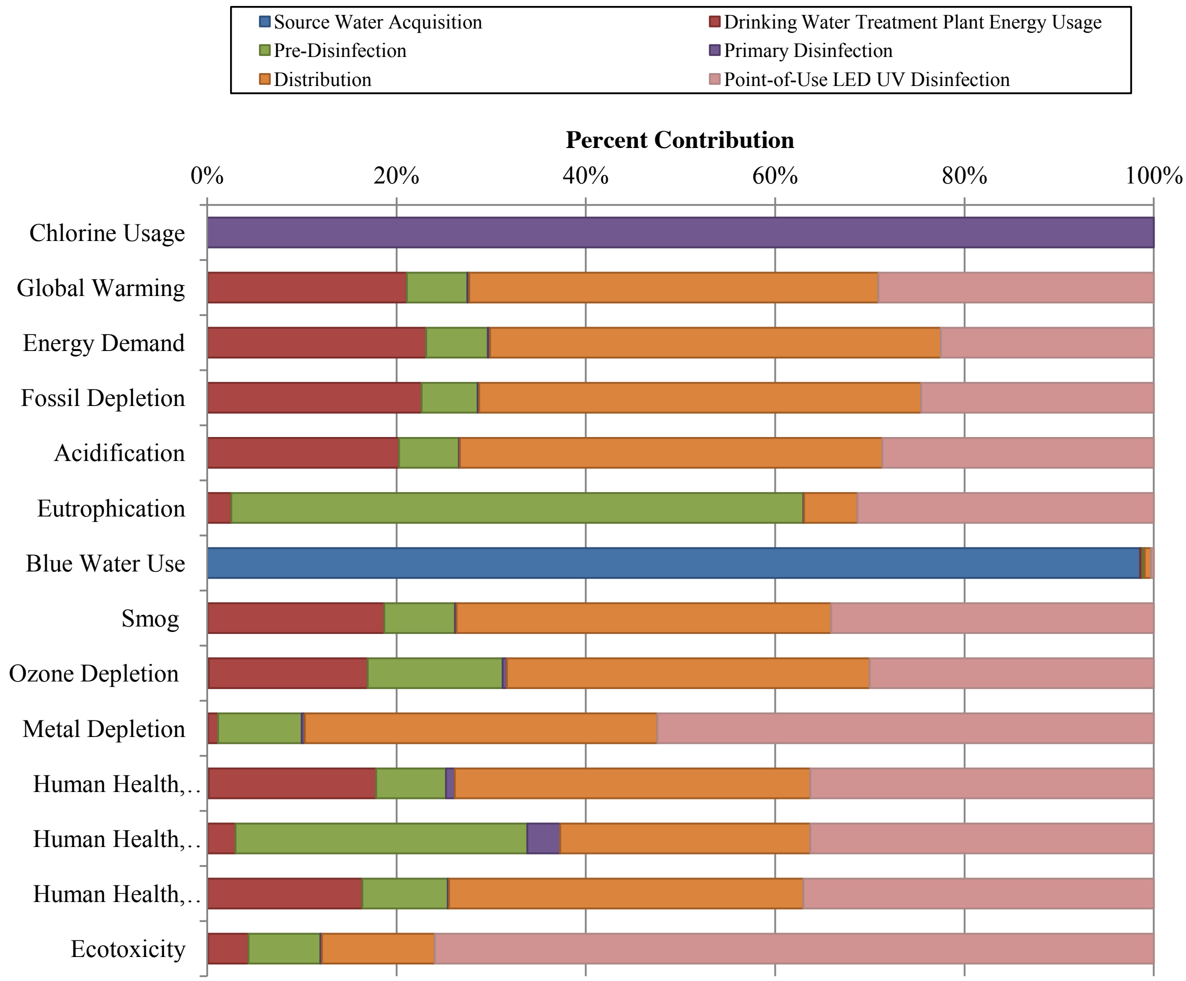


Figure 38. Base Case 1 plus point-of-use hospital LED UV disinfection contribution analysis results.

8.4 Comparative Results

Figure 39 illustrates the comparative results for the different hospital point-of-use disinfection technologies. Both point-of-use technologies are examined as an addition to Base Case 1 (disinfection with gaseous chlorine). In this figure, results are normalized to the point of use technology with the highest impact in the category under examination. In all cases, the LED UV point-of-use technology has the greater impacts compared to the Pall point-of-use tap filter. The LED UV system requires some electricity for operation; whereas, the filter does not require electricity for generation. The production of the LED UV lamp in China is relatively more burdensome for the impacts examined compared to the infrastructure production requirements of the Pall filter.

While a direct comparison is made here between these two point-of-use disinfection technologies, there are some key distinctions between them. The Pall filter is designed for application to the faucet; whereas, the LED UV system is designed for application prior to the faucet. Any pathogens formed near the faucet may not be treated by the LED UV system. Additionally, the Pall filter is designed specifically for hospital use; whereas, Aquionics notes that healthcare is just one of many applications for the point-of-use LED UV system. This analysis is provided to begin to understand the potential impact differences between these two systems, and it is not intended to provide a recommendation on use of either of the technologies.

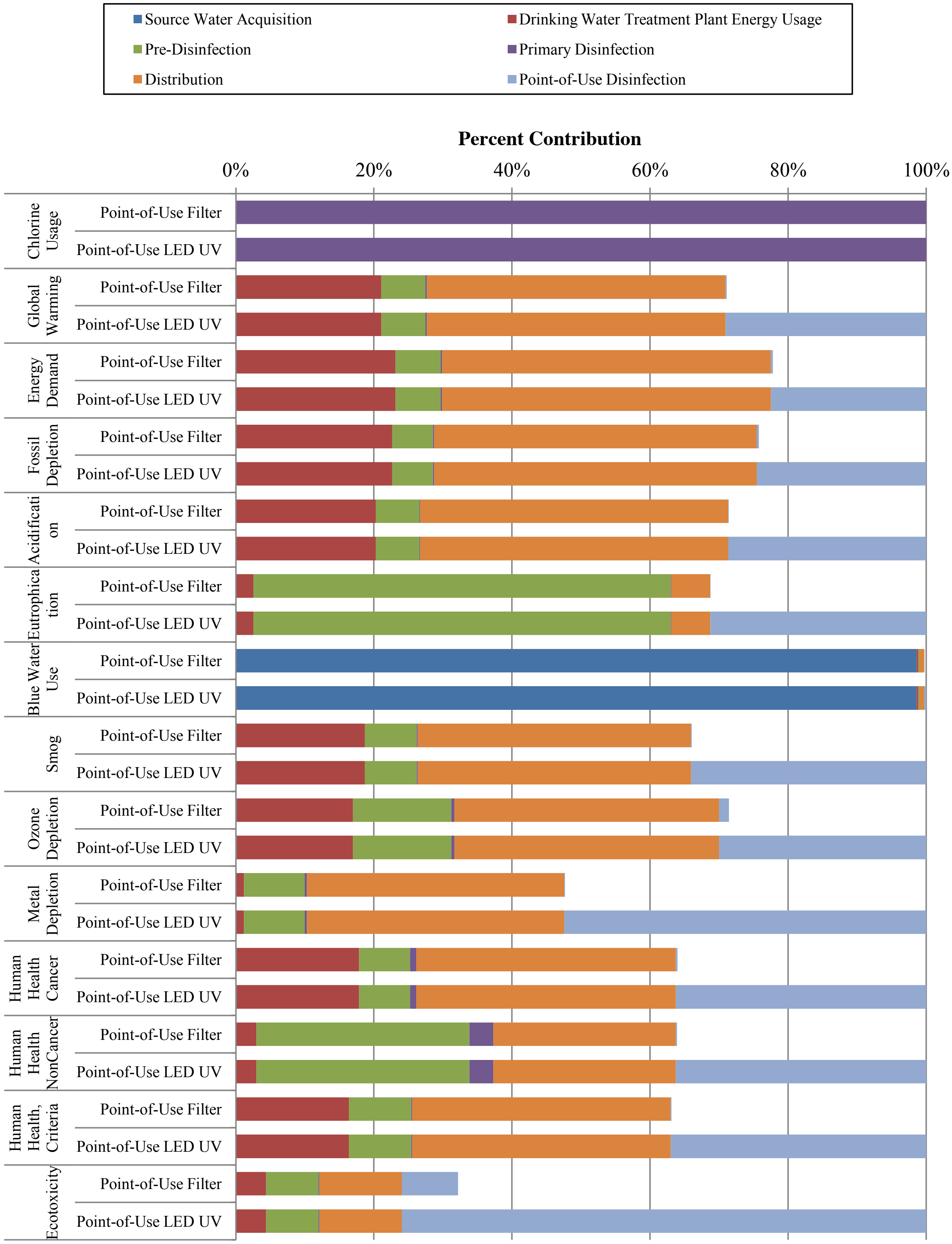


Figure 39. Comparative results for different hospital point-of-use disinfection technologies.

9. OVERALL RESULTS SUMMARY

Results of the base case drinking water analysis with disinfection via gaseous chlorine show impacts are largely driven by electricity consumption at the drinking water treatment plant and during distribution to the consumer. Overall, primary disinfection with gaseous chlorine only contributes zero to five percent to the total life cycle impacts of drinking water treatment for the results categories examined. Utilization of ferrate results in environmental, human health, and cost benefits for combined use in the pre-disinfection and primary disinfection stages, since ferrate acts as both a coagulant and disinfectant and only small dosages are required for treatment. Application of UV technology increases impacts during disinfection through increased electricity consumption and through new capital investment, but eliminates the formation of disinfection by-products and greatly reduces hazardous chlorine usage. LED UV is more energy efficient compared to conventional mercury-vapor UV; however, it is currently developed only for point-of-use applications, and not large-scale treatment facilities. For hospital point-of-use disinfection, the LED UV technology has the greater impacts overall compared to the Pall filter. The LED UV system requires some electricity for operation; whereas, the filter does not require electricity for generation and the production of the LED UV lamp in China is relatively more burdensome for the impacts examined compared to the infrastructure production requirements of the Pall filter. In general, this analysis is provided to understand the potential impacts and trade-offs between different drinking water disinfection technologies within the framework of the entire drinking water supply system, and it is not intended to provide a recommendation on whether any technology is superior to other technologies. The LCA model and cost analysis built here can serve as the basis for future assessments of water-related technologies and can be incorporated into broader, sustainable systems analyses of water technologies.

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