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INVENTORY OF EMERGING TECHNOLOGIES AND INNOVATIONS TO REDUCE GHG EMISSIONS IN DRINKING WATER SERVICES

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DISCLAIMER

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This project was conducted under the mentorship of Metro Vancouver staff. The opinions and recommendations in this report and any errors are those of the author and do not necessarily reflect the views of Metro Vancouver or the University of British Columbia.

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1. Background

The disastrous effects of climate change in recent decades have driven global efforts to reduce greenhouse gas (GHG) emissions. The Paris Agreement and the United Nations Sustainable Development Goals (SDGs) are examples of international consensus for such efforts. In the Paris Agreement 2015, more than 140 countries, including Canada, pledged to an ambitious "net zero" target by 2050[1]. More than 70% of global GHG emissions are from cities as they are the hubs of economic activities and corresponding resource consumption, including water and energy[2]. Water utilities, providing water supply and wastewater collection services, are a significant source of carbon emissions contributing to over 50% of all infrastructure emissions[3]. The primary source of emissions from water utilities is energy consumption. On a global scale, urban water utilities account for around 1-2% of total energy use and GHG emissions[4]. Many water utilities worldwide, like Denver Water, Sonoma Water, Thames Water, Metropolitan Water District of Southern California, etc., have successfully decarbonized their systems.

Metro Vancouver is interested in identifying emerging technologies that may facilitate their decarbonization efforts. The purpose of this project is to summarize the emerging technologies and innovations specific to water services in the form of an inventory and evaluate their possible inclusion in Metro Vancouver systems and policy decisions.

2. Objectives and scope

2.1. Objectives

The objectives of the project include:

- Assemble a list of activities involved in managing drinking water in the regional water utilities. The inventory will serve as a foundation for identifying potential areas for applying emerging technologies to reduce GHG emissions.
- Conduct a literature review to identify and document emerging technologies and innovations in drinking water services that could lead to GHG emissions reductions.
- Prepare an Excel-based inventory of such technologies with specific details to inform options assessment and decision-making for ongoing GHG reduction initiatives and/or potential pilot studies of Metro Vancouver.

2.2. Scope

The project's overall scope encompasses the following activities:

- Prepare a list of water services activities in the regional water utilities. These activities broadly include planning, procurement, construction, operation, maintenance, decommissioning, and waste management. This will provide the basis for the investigation and help identify areas for technology application.
- Categorize the activities or sub-activities based on their GHG emission contribution. Shortlist 5-10 activities/functions in the drinking water utilities system lifecycle that can offer significant GHG emissions reductions.
- Conduct a literature review to identify alternative emerging technologies or innovations available for the shortlisted activities for reductions in GHG emissions.
- Perform a high-level assessment of GHG savings offered by each available alternative and list potential additional benefits, costs, and risks.

3. Methodology

A literature review was conducted to prepare an inventory of emerging technologies and innovations for reducing GHG emissions from water services. Figure 1 shows an overview of the adopted methodology.

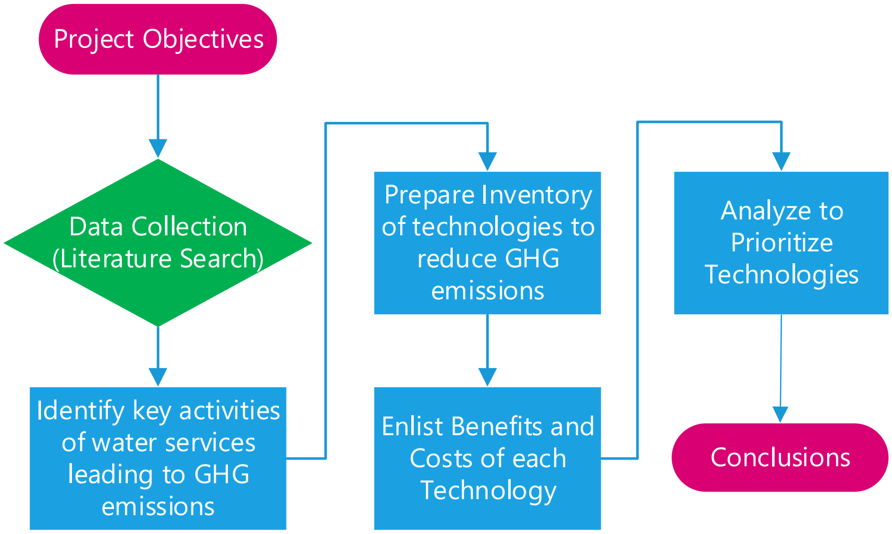

Figure 1. The overall methodology adopted for meeting project objectives

4. Water Services Activities and GHG Emissions

Energy consumption is water utilities' primary source of GHG emissions[5]. Various activities at different system life cycle stages may contribute to GHG emissions. The following sub-sections describe such activities associated with each project life cycle stage.

4.1. Planning Activities

Energy Assessment and Technology Selection

A typical water utility relies on energy-intensive infrastructure and equipment to transport water from its source to customers. This includes pumps, motors, buildings, and disinfection equipment, all of which consume energy to treat and deliver clean drinking water. By evaluating the energy usage and carbon footprint of these components, utilities can select more efficient, low-energy pumps for water extraction, transmission, distribution, and treatment. Energy assessments can also be applied to Heating, Ventilation, and Air Conditioning (HVAC) systems and other building energy uses. During the planning phase of projects or policy development, incorporating an options assessment that prioritizes energy consumption as a key decision criterion can significantly and sustainably reduce greenhouse gas (GHG) emissions across the entire water supply system.

Design consideration

Incorporating a sustainability perspective into design leads to low-carbon water infrastructure that minimizes energy and chemical consumption. Examples of energy-efficient designs and processes include utilizing gravity-fed supply and transmission where feasible, opting for alternative filtration techniques like contact or direct filtration instead of energy-intensive membrane filtration, and implementing effective pre-treatment before membrane processes when necessary. Additionally, selecting low-energy and low-carbon construction methods, such as trenchless technology for pipe installation, can reduce greenhouse gas (GHG) emissions by up to 85% compared to traditional construction methods[6].

Sustainable Material Selection

Choosing materials for pipes and chemicals for water treatment during the project planning phase can have a significant impact on greenhouse gas (GHG) emissions throughout both construction and operation. For example, Ductile Iron (DI) pipes have higher life cycle GHG emissions compared to High-Density Polyethylene (HDPE) pipes, which in turn have higher emissions than Polyvinyl Chloride (PVC) pipes. Similarly, using polymers and Poly-aluminum Chloride (PAC) as coagulants in water treatment results in greater life cycle GHG emissions than using Alum or Iron salts.

Life cycle analysis

Performing a life-cycle analysis of projects is another effective approach to identifying and selecting the most sustainable alternatives. This tool assesses total carbon emissions throughout the entire lifespan of a project—from resource consumption and construction to operation, maintenance, decommissioning, recycling, and disposal—and compares them with alternative options. This method provides theoretical and practical insights that would support optimizing water systems and attaining low-carbon management.

4.2. Construction Activities

Emissions from construction activities are primarily linked with energy consumption.

Excavation and earthwork

Emissions from heavy machinery and equipment used for excavation and earthmoving are significant contributors to carbon output. Construction machinery like excavators, bulldozers, and cranes typically run on diesel or other fossil fuels, generating substantial carbon emissions. Additionally, earthmoving activities can release carbon stored in the soil, further contributing to overall emissions.

Material production and transport

The extraction of raw materials and the production of infrastructure components such as concrete, steel, PVC, and HDPE involve energy-intensive processes that frequently depend on fossil fuels. Additionally, vehicles used to transport materials, equipment, and personnel to and from the construction site contribute to carbon dioxide emissions.

Water Management

Water usage and energy consumption during construction can contribute to emissions, particularly when pumps and motors used for managing groundwater and other water sources rely on fossil fuel-based energy.

Waste management

Waste materials from construction activities, such as excess soil, rock, and debris, are typically transported and disposed of using fuel-powered vehicles, which contribute to carbon emissions.

Testing and commissioning

Energy consumption and emissions during the testing and commissioning of new water systems, including activities such as leakage and hydraulic testing, flushing, and disinfecting newly constructed lines, are significant contributors to overall emissions due to the energy used by pumps and other equipment.

4.3. Operation and Maintenance Activities

Water Abstraction

Emissions related to water abstraction are primarily from energy consumption by electricity-driven pumps and motors. In addition, some direct yet insignificant emissions of GHGs, like methane, are also expected from storage reservoirs/lakes.

Water Treatment

Water treatment processes require significant energy, especially for moving water through various stages of treatment. If this energy comes from fossil fuels, it directly contributes to carbon emissions. Filtration and disinfection, which often rely on pumps and equipment, can be particularly energy-intensive, especially when methods like ultraviolet (UV) light, ozonation, or chlorination are used.

The use of chemicals such as chlorine, coagulants, and pH adjustment agents also have a carbon footprint. The production, transportation, and dosing of these chemicals involve energy use, which can contribute to emissions. Additionally, managing the byproducts, like sludge, typically involves energy-intensive processes and fuel-powered vehicles for transport and disposal, further adding to the carbon emissions associated with water treatment.)

Water Distribution/Transmission

Energy consumption is significant in the pumping and pressurizing of water throughout the network. Centrifugal pumps, commonly used in distribution and transmission systems, rely on electricity, thereby contributing to CO_2 emissions associated with production of electricity.

Buildings, fleet, others

Buildings and fleet operations within the system also have an environmental impact. Energy used for HVAC systems, lighting, and other utilities in buildings, along with emissions from fuel-powered utility vehicles, further contribute to the overall carbon footprint.

4.4. Maintenance Activities

Pump and Motor Maintenance

Emissions from energy consumption occur during the maintenance and operation of pumps and motors, as well as from fuel-powered maintenance vehicles.

Leak detection and repair

Energy is consumed during the maintenance of valves and pipes, including activities like excavation, repairs, and leak detection using electronic or acoustic equipment. Routine tasks such as cleaning, inspecting, and repairing pipe breaks or leaks also require energy, contributing to emissions.

Valve and pipe maintenance

Energy is used during the maintenance of valves and pipes, including excavation and repair work, while emissions are generated from fuel-powered maintenance vehicles.

4.5. Decommissioning Activities

Equipment/Infrastructure dismantling, Site restoration, Recycling and waste management

Emissions from energy consumption during dismantling of treatment plant buildings, pipe infrastructure, etc., site restoration, and disposal of construction debris. Large-scale hydraulic structures such as reservoirs and water diversion projects (tunnels) have longer service lives, and the main structures are not demolished after being decommissioned.

Considering the life cycle components of water supply systems and associated GHG emissions, it is imperative to identify interventions to reduce the GHG emissions from each stage/component. The following section provides an overview of such interventions.

5. Emerging Technologies and Innovations

An inventory of specific emerging technologies and innovations aimed at reducing GHG emissions from various sources has been compiled, supplemented with case studies from water utilities that have already adopted these solutions. The complete inventory is presented in the tabular format in **Appendix 1**, which lists available technologies, their estimated GHG reductions, and unit costs.

Below is an overview of these technologies and innovations.

5.1. Alternate Energy Sources

Switching to alternative and renewable energy sources is the most common strategy adopted by water utilities to reduce GHG emissions. Solar energy, wind power, and hydropower are the primary alternatives. Small-scale solar power plants installed at the administrative or plant buildings, parking lots, and even floating on lakes can supply partial or full electricity needs for treatment plants and pumping stations. In-line micro-hydro systems, where water passing through pipelines turns turbines to generate electricity, are another viable option. Compared to coal, estimated GHG emissions from solar, wind, and hydropower are reduced by 90%, 97%, and 97%, respectively[7].

Installing solar power plants is more common among water utilities to supplement the energy needs of pumping stations, treatment plants, and administration buildings. Denver Water met an organizational goal for “net zero” annual energy consumption in 2020, generating more than the required energy for pumping stations and treatment plants from carbon-free sources: hydropower and solar power [8]. Additional examples include the Sonoma Water, Denver Water, the *San Diego County Water Authority (SDCWA), The City of Phoenix Water Services Department, the Southern Nevada Water Authority (SNWA), the Las Vegas Valley Water District (LVVWD), Inland Empire Utilities Agency (IEUA), Denver Water,* [9–14].

Interconnection agreements while installing solar or wind power may be challenging. A utility (*SDCWA*) suggested owning the installation of solar infrastructures, while another (*Sonoma Water*) suggested engaging in a power purchase agreement (PPA). Hence, the advantages of a utility owning vs. not owning the solar infrastructure appear to be case-dependent. The advantages of switching to alternative energy sources are apparent; however, a feasibility study should be conducted to assess the financial viability of such projects, and capital cost, payback, and annual savings should be estimated.

5.2. Reducing Fleet Emissions

Another significant source of GHG emissions is the fuel consumed by utility fleets. These emissions can be reduced by switching to Zero Emission Vehicles (ZEVs), using greener fuels, and optimizing fleet efficiency.

Greener fuel alternatives include Biodiesel and Compressed Natural Gas (CNG), with B100 (100% Biodiesel) being 90 and 94% less carbon intensive than diesel and gasoline, respectively[15]. Using renewable fuels is a common approach adopted by water utilities. For instance, 97% of the diesel purchased by the *East Bay Municipal Utility District (EBMUD) in 2020* [16] and 96-97% of the total diesel purchased in 2023 by *MWDSC* was renewable.

Another common method adopted by utilities is switching to zero-emission vehicles (ZEVs). Electric vehicles (EVs) are the most common ZEV option, but for larger utility vehicles where EV options may be limited, plug-in hybrids and hybrids are also viable. Depending on the energy source, GHG emissions from EVs are 60-80% lower than those from gasoline vehicles[17]. Examples of water utilities switching to ZEVs include Sonoma Water, Los Angeles Department of Water and Power (LADWAP), and Denver Water, among others [13,18,19].

Implementing telematics and routing software to optimize fleet operations is another attractive option to reduce GHG emissions and lower fleet expenses. Utilities have attained significant fuel and GHG emission reductions through such interventions, e.g., a 42% reduction in fleet emissions by *EBMUD,* and *LADWP* is avoiding 1,909 tCO_2 emissions per year. To opt for fleet optimization, telematics systems need to be installed in all on-road vehicles to collect driving utilization data. These data would help in selecting the correct vehicles for the energy-efficient vehicle transitions.

5.3. Improvements in Pumping Operations

Interventions to reduce GHG emissions at pumping stations include automated pump operations using Supervisory Control and Data Acquisition (SCADA), Variable Frequency Devices (VFDs), Plant Information Assessment Framework (PI-AF), and hybrid linear and multi-objective optimization. In addition to optimizing the operations, pump overhauling and replacement when needed has proved to be a significant method of energy and GHG emission reductions[20].

Employing the above-mentioned interventions, particularly pump overhauling and refurbishing, can reduce energy and GHG emissions significantly. For example, a simple refurbishing of a large-capacity pump by the *Massachusetts Water Resources Authority (MWRS)* led to a reduction of 133,000 kWh/year of energy consumption and $12,000/year of cost savings [20]. Obtaining real-time pump efficiency data with these technologies helps adjust the pumping loads to better understand which pumps need repairs or replacement and when installing variable frequency drives (VFDs) makes sense.

5.4. Reducing Energy Consumption in Buildings

Energy optimization for buildings and greener building design can significantly impact the building's GHG emissions. For example, a major retrofit at the Marston Treatment Plant in southwest Denver, saves over $10,000 and nearly 205,000 kilowatt-hours of electricity annually, while reducing carbon dioxide emissions by an impressive 161 tons each year. Similarly, the *MWDSC* converted 49% of interior and exterior lighting at all Metropolitan facilities to LED technologies. They aim to convert 100% of lights to LED by 2045 [18]. Greener building design and LEED certification are similar approaches through which the administration and operations of buildings of a water utility may significantly reduce carbon emissions.

5.5. Emissions Reduction through Water Conservation

The GHG emissions from a water utility are directly related to the amount of water extracted, transmitted, treated, or distributed. Usually, the emission footprint of water utilities is expressed as kg CO_2 per m^3 of water. For instance, in the US, average emissions are 0.4 $kgCO_2e/m^3$ of water. Hence, the amount of water conserved would directly lead to corresponding CO_2 reduction.

The potential to reduce GHG emissions through water conservation lies more with regional water utilities, as they have the chance to engage and mobilize their municipalities to have a greater overall impact. For example, the *Sonoma-Marin Saving Water Partnership* is a regional collaboration providing water use efficiency programs to customers of 13 local water utilities. The lead partner of this collaboration is Sonoma Water, a regional utility. Since its establishment in 2009, the partnership has been effective at lowering water demands. Regional per capita water demand has been reduced consistently to 93 gallons per capita per day (gpcd) in 2022 as compared to 160 gpcd in 1995 (42% reduction) [13].

Leakage control is another potential source of water conservation and reducing associated energy and GHG emissions. Water utilities such as *LVVWD* focus on leakage control. The use of artificial intelligence (AI), the Internet of Things (IoT), and other technological developments is helping leakage control efforts and water conservation initiatives of *LVVWD*.

5.6. Modifications in Water Treatment Processes

Certain modifications in the water treatment processes can lead to reduced GHG emissions. For example, selecting contact filtration (with a coagulation-flocculation process) instead of direct filtration (without the flocculation step) may reduce the energy consumption of the overall filtration process [21]. Similarly, optimizing the filtration backwash sequence would result in fewer backwashes. Since a major energy-consuming component in filtration is backwashing, it may result in a significant reduction in energy consumption and GHG emissions [4].

UV disinfection and Ozonation are also some of the major energy-consuming treatment processes. Hence, significant energy and GHG emission reductions may be attained by optimizing the UV/ozone dose based on variable water quality, using efficient electrical components, and flow-paced UV systems [4,22]. Chlorination is another essential disinfection method to maintain residual disinfectant in the distribution network. The research has shown that onsite chlorination is a more cost-effective and sustainable option as it will eliminate transportation-related emissions [23]. Reducing the chemical consumption at a treatment plant may result in the reduction of indirect GHG emissions. The Chemical Reduction Program of *SNWA* has reduced chemical consumption by optimizing disinfection, fluoridation, and corrosion control and has reduced its carbon footprint by 309 tCO_2 eq [11].

5.7. Construction Modifications

Some factors related to the design and construction of various water supply system components offer a reasonable GHG emissions reduction. Concrete is the largest CO_2 emissions-producing activity (>50%) in WTP construction. Hence, using greener or low-carbon concrete would significantly reduce CO2. *PWB's* Water Filtration Plant has planned to use low-carbon concrete for facility process basins and structures to help reduce supply-chain greenhouse gas emissions [24].

Similarly, trenchless pipe construction and replacement technologies have reduced construction energy consumption and carbon footprint to varying degrees relative to the open-cut method. A study, conducted jointly by researchers in China and the US, reveals various levels of GHG emission reduction by trenchless methods, for example, 6-56% for Horizontal Directional Drilling (DDD), 26-56% for Horizontal Auger Boring

(HAB), 38-68% for Impact Moling (IM), 14-86% for Pipe Jacking (PJ), and 6-62% for Pipe Ramming (PR), respectively [6].

Different pipe materials also have various levels of life-cycle emissions. A research case study based on Life Cycle Analysis (LCA) in *Arizona, US* indicated that molecular-oriented PVC (PVC-O) provides the best environmental savings compared to PVC, HDPE, and DI in the demonstration of the potable water project. Life cycle CO_2 emissions are in order of PVC-O < PVC < HDPE < DI [25]. However, the overall emission reductions of PVC-O were only around 4 % less than DI pipes. Hence, the decision to select pipe material may not only be based on carbon emissions but other important factors such as cost, longevity, chemical leaching, etc.

6. Conclusions

Many of the water utilities across the world are making efforts to decarbonize their systems. However, some water utilities are leading the cause and are way ahead in attaining lower GHG emissions. A few like *Denver Water* have also attained the ambitious net zero emissions target. There are plenty of technologies and innovations for reducing GHG emissions from water services. Every water utility has different scenarios and a carbon footprint. They may adopt the suitable and relevant ones from the inventory. It is concluded based on the literature review, discussions, and lessons from case studies that the most potential for reducing GHG emissions is for alternative/renewable energy sources including hydropower, solar, wind, and in-line micro hydro. Following the installation of hydropower plants where feasible, Solar power is the most commonly adopted alternative energy source by water utilities. Wind and solar power plant installation requires precisely predicting estimated energy production at a particular site. Therefore, a high-precision weather production model should be used when possible. In-line micro hydro may particularly be considered as it is feasible where gravity water transmission is available like in metro Vancouver. Sites with existing vaults and pressure-reducing valves would be suitable for a micro-hydro generator.

Fleet emissions are usually the largest source of GHG emissions for those utilities that have already decarbonized their energy systems. Reducing fleet emissions can be attained through switching to alternative fuels (Biodiesel and NG), ZEVs (EVs, plug-in hybrid, and hybrid options), and optimizing fleet efficiency. Switching to greener fuels should immediately be adopted until all the fleet can be converted to ZEVs. The success of ZEVs requires the availability of sufficient fueling/charging infrastructure. With such transitions, it is also important that the fleet remains resilient and can respond in an emergency, including a power outage. Fleet Challenge Canada or other organizations that specialize in optimizing vehicle fleets can be engaged to develop better plans to switch to ZEVs. Various Government subsidy initiatives are available in Canada and BC including, but not limited to, Green Municipal Fund Canada, Clean BC Go Electric, the Fleet Charging Program of BC, and the ZEV program of Transport Canada.

Improving the pumps' energy efficiency would contribute to significant reductions in energy consumption and associated GHG emissions. This improvement may be attained by pump refurbishing/overhauling, using VFDs, SCADA, and other IT-based optimization systems. An energy audit of pumping stations would be an excellent start to this initiative. Real-time monitoring data (e.g., pump efficiency, speed, suction/discharge pressure, flow, etc.) should be collected to determine pump performance. Energy efficiency audits and comprehensive metering of pump stations are recommended to examine the relative health of each station pump. The resulting data can be used to determine which pumps should be operated more and which pumps need to be refurbished or replaced.

In addition to the above-mentioned innovations, several other technologies and innovations, as outlined in Appendix 1, including water conservation programs, energy optimization for buildings, use of cleaner construction materials (low-carbon concrete) and methods (trenchless construction), selection of less energy-intensive and less chemical-intensive treatment methods (where feasible), optimization of high energy treatment systems like UV and Ozonation, etc., can be adopted, as long-term goals, to attain ultimate sustainability. Special considerations should be given to policy-making related to adopting low carbon practices at the planning and design phases of projects as they impact the GHG emissions from operation and maintenance activities. Conducting an LCA study at the planning and feasibility stages of new projects is an effective way to ensure sustainability and prioritize project components with reduced life cycle GHG emissions.

7. APPENDIX-1

Inventory of Technologies/Innovations to reduce GHG Emissions from various components of Water Services

GHG Emission Source/Activity	Technology/Innovation for GHG emission reduction	Detail/Description	GHG Reduction Potential	Unit Cost
Fleet emissions	**Conversion ZEVs**	Electric ZEVs should be preferred. If ZEVs are not readily available or operationally feasible, near-zero emission vehicles, including plug-in hybrids *and* hybrid models, should be considered.	Gasoline produces 2.3 kg CO_2/L, Diesel produces 2.7 kg CO_2/L[26]. While EVs in BC produce no emissions, so a 100% reduction[27]	CAD 8,000 more to own an electric vehicle compared to a gas vehicle[28]
				The cost of charging EVs is less than the cost of gas for an equivalent gas-powered vehicle and requires much less maintenance[29].
			Depending on the electricity source, the life cycle emissions of EVs are 60-80% less than those of gasoline or diesel vehicles in the United States [17].	
	Switching to alternative greener fuels	***Renewable diesel or Biodiesel***	B100 (100% Biodiesel) produces 74% lower emissions than gasoline[30]	US Fuel Rates (USD) as of April 2024[31]: ▪ Gasoline 3.65/gallon, ▪ Diesel 4.07/gallon, ▪ CNG 2.90/gallon, ▪ LNG 3.85/gallon, ▪ B100 4.57/gallon CNG is relatively cheaper, while biodiesel is a little expensive.

			B100 is 90-94% less carbon intensive than diesel and gasoline[15]	Biodiesel costs are currently 70% to 130% higher than petrol and diesel on the wholesale market depending on the crop used according to a study in Europe[32]
		CNG		CNG is relatively cheaper than gasoline and diesel[31]
	Improve fleet efficiency (Operational changes)	***Telematics and Routing Software***	Thames Water attained a 10% decrease in fuel consumption, which amounts to 429 tons of annual CO_2 reduction[33].	Cost can be obtained from organizations providing such services.
Energy Consumption	**Alternative energy sources**	***Solar energy:*** Small-scale solar power plants to provide partial or full electricity needs of treatment plants or pumping stations.	Lifecycle GHG emissions of Solar energy are 85 tCO_2/GWh, which are 90% and 88% less than that of Coal (888 tCO_2/GWh) and Oil (735 tCO_2/GWh), respectively [7]	CAD 2650 per kW up to 10 kW and less for larger systems[34]
			Lifecycle GHG emissions of Solar energy are 48 gCO_2/kWh, which is 90% less than that of Coal (820 gCO_2/kWh) on average. However, the min-max range varies a lot[35].	CAD 2500 per watt (BC Hydro)[36]
			Canadian: Coal 1001, NG 461-465, Solar <50, Wind 12, Hydro 2-17 tCO_2/GWh[37]	CAD 1800 in 2017, and 1449 per kW in 2024 estimated (Utility-scale)[38]
		Wind power	Lifecycle GHG emissions of Wind power are 26 tCO_2/GWh, which are 97% and 96% less than that of Coal and Oil respectively [7]	CAD 1600 in 2017 and 1466 estimated in 2024 (Utility-scale)[38]
			Lifecycle GHG emissions (IPCC). Coal 820, Gas 490, Solar 48, Hydro 24, Wind 12	

			gCO$_2$/kWh. Varies a lot min-max[35]	
		In-line micro-hydro: As water passes through the pipeline, it turns the turbine and generates electricity.		A 5-kW micro hydro turbine system for residential or commercial sites typically costs between USD 15,000 to 55,000[39]
		Dam ***Hydropower*** Generation		
Pumping	**Improving Pump energy efficiency**	***Pump overhauling, and replacement*** of inefficient pumps/parts.	Refurbishing of just one of the ten 3500 HP pumps at MMWRA reduced the electricity consumption by 133,000 kWh/year.[20]	The cost for refurbishing the Pump at MWRA was USD 126,000 (Refer to section 6.3)[20].
	Better/automated pump operations	***VFDs***	The total calculated energy savings from these VFDs installed by MWRS was USD1,066,285 kWh/year[20]	
			30% to 35% cost reductions (in terms of energy reduction) with VFDs. The same proportion would be the GHG reduction[40].	VFD installation cost: USD 19,000 per 100 HP of pumping system[40].
			Swansea Water District in southern Massachusetts enjoys over USD 14,000 in cost savings annually due to motor replacement and updated motor controls[40].	
	Operational Optimization	***SCADA***	Small improvements in pump efficiency are likely to yield significant reductions in energy consumption with consequential reductions in carbon emissions.	SCADA system installation costs for a small to medium-sized system, anywhere from USD 10,000 to 100,000[41]

		Use of PI-AF: The PI System collects, stores, and manages data from your plant or process and stores it in the PI Archive. Data Asset Framework (AF) organizes and enhances the data. Users consume the data by the use of a tool of the PI Visualization Suite (PVS) such as PI Vision.		
		Hybrid linear and multi-objective optimization approaches can be used to identify key energy consumption elements in a water supply system and evaluate the amount of investment needed to achieve significant operational gains at those points in the supply network.		
Water Demand/Consumption	**Water Conservation and leakage control**	***IoT and data solutions for Leakage control:*** Any water loss in the system will require more energy later to replace and treat the water for end users. Therefore, the less water loss in the system, the less water that must be treated and the less GHG emissions generated from the treatment stage.		

		Acoustic leak detection system for leakage control: To help track leaks down before they become a problem, the acoustic leak detection system "listens" for water leaking underground and pinpoints where leaks are occurring.		
		Water conservation programs	In California, a 24.5% water consumption decrease relative to the 2013 baseline in 2015-16, translates into 1830 GWh energy saving, and a GHG emissions reduction of 521 000 MT CO_2e[42]	Water conservation may cost 67% less as compared to Infrastructure upgrades to meet future demands[43].
			In the US, average emissions are 0.4 $kgCO_2e/m^3$ of water. Hence, reducing water consumption would reduce CO2 correspondingly [44].	Results of a study by the University of California at Davis (UCD) with the LADWP showed that water conservation programs were largely cost-competitive (and in some cases more cost-effective than direct energy efficiency programs)[42]
Water Treatment Processes	**Filtration: Backwash Optimization**	How the ***filter backwash sequence*** is initiated in conventional filtration can affect the frequency of backwashing. The more times filters are backwashed, the more energy is consumed during the process. Therefore, it is critical to optimize the backwashing sequence so that filters are not excessively backwashed.		

		The more optimal the sequence, the less GHG emissions generated from the treatment stage.		
	Filtration: Process selection	Use ***Contact Filtration (CF) instead of Direct Filtration (DF)***.	The results of a study show that the carbon footprint from operations is five times larger for the DF with Al coagulant compared to the CF with Fe coagulant[21].	Operational costs covering chemicals and energy are almost 30% higher for the DF using Al coagulant. [21]
	UV Disinfection: Optimizing energy consumption for Ultraviolet disinfection	The ***dose*** (as impacted by water turbidity), ***control, and maintenance*** can be optimized to minimize GHG emissions while meeting minimum disinfection requirements.		
		Flow-Paced UV Systems: the minimum number of lamps needed to meet disinfection objectives		
		More ***efficient electrical components*** from transformers to ballasts.		
	Chlorination: Onsite Chlorine Generation (OSCG)	**OSCG** is a more sustainable option than traditional chlorination methods. Reducing transportation requirements reduces the plant's carbon footprint because less fossil fuel is needed to supply it with disinfectant. Additionally, on-site generation eliminates the waste of empty chemical containers.		The sodium hypochlorite generation system is expensive compared to conventional transport systems, but its operating cost is more appropriate. To conclude, a feasibility analysis, including a Life Cycle Cost Analysis (LCCA), is required [45].

Energy consumption in Buildings	**Energy Optimization for Buildings**	***Switching to LED lights*** is a simple yet effective way to reduce a building's energy consumption and carbon emissions.	LED lights are at least 75% more energy efficient than incandescent bulbs[46].	The cost per LED light varies in Vancouver from CAD 99.99 to 369.99[47]
			Replacing lights with LEDs at a Filtration plant by Denver Water is saving 161 tons of CO_2 emissions each year[18]	
	Green Building Designs	***LEED Certification:*** Design to maximize sunlight yet minimize heat and glare. An underflow air distribution system results in huge energy savings. Wall insulation (mulch post-industrial blue jeans). Water recycling system. Low flow plumbing fixtures. Energy star-rated equipment and appliances.		
Indirect Emissions (Chemical usage, material selection, construction, etc.)	**Sustainable material selection**	***Sustainable pipe selection:*** Use of pipes based on life cycle emissions.	3 to 5 % reduction in life cycle CO_2 emissions using PVC instead of DI pipes.[25]	PVC pipes are 7% cheaper than DI pipes. However, durability, longevity, and chemical leaching concerns must be considered[48].
				PVC costs 40% to 30% less than DI pipes for sizes 12" to 24"[49].
	Reduce chemical consumption	***Reduced*** use of chemical treatment or ***chemical consumption***		
	Green Construction	***Trenchless construction***	GHG emission reductions for various trenchless methods range from 6% to 86% [6]	Construction costs of Cured-in-Place Pipe (CIPP) renewal are 57%, 63%, and 18% less as compared to the open-cut pipeline replacement for small, medium, and large-

				diameter sanitary sewer pipes, respectively[50]
			Trenchless Technology produces 97% less life cycle emissions than open-cut pipeline construction[51].	Trenchless Technology may provide savings of up to 79% of the cost of the open-cut installation method[51]
		Low-carbon concrete: Concrete is the largest CO_2 emissions-producing activity (>50%) in Water Treatment Plant (WTP) construction. Hence using greener or low-carbon concrete would have a great impact on overall CO_2 reduction.	Low-carbon concrete leads to a 30% reduction in carbon footprint.[52]	Low-carbon concrete at the same rate/price as conventional concrete is available from different companies like Dufferin Concrete[53].
			GHG reduction of various low-carbon concrete methods ranges from 9 to 43%).[54]	

8. References

1. UN. (2024). *For a livable climate: Net-zero commitments must be backed by credible action*. United Nations. https://www.un.org/en/climatechange/net-zero-coalition
2. IPCC, I. C. (2013). *Contribution to the IPCC Fifth Assessment Report, Climate Change 2013: The physical science basis*.
3. Johnston, A. H., & Karanfil, T. (2013). Calculating the greenhouse gas emissions of water utilities. *Journal-American Water Works Association*, *105*(7), E363–E371. https://doi.org/10.5942/jawwa.2013.105.0073
4. Ballard, S., Porro, J., & Trommsdorff, C. (2018). *The roadmap to a low-carbon urban water utility: An international guide to the WaCCliM approach*. IWA Publishing. https://library.oapen.org/bitstream/handle/20.500.12657/24825/wio9781780409924.pdf?sequence=1&isAllowed=y.
5. Vince, F., Aoustin, E., Bréant, P., & Marechal, F. (2008). LCA tool for the environmental evaluation of potable water production. *Desalination*, *220*(1–3), 37–56.
6. Lu, H., Matthews, J., & Iseley, T. (2020). How does trenchless technology make pipeline construction greener? A comprehensive carbon footprint and energy consumption analysis. *Journal of Cleaner Production*, *261*, 121215. https://doi.org/10.1016/j.jclepro.2020.121215
7. WNA. (2011). *Comparison of Lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources*. World Nuclear Association. https://world-nuclear.org/images/articles/comparison_of_lifecycle.pdf
8. Tod Hartman. (2022). *Battling climate change with solar, hydro and a shifting fleet*. https://www.denverwater.org/tap/battling-climate-change-solar-hydro-and-shifting-fleet?size=n_21_n
9. WUCA. (2024). *Wind Power, Solar and Battery Storage: Inlad Empire Utilities Agency*. Water Utilities Climate Alliance. https://www.wucaonline.org/assets/pdf/greenhouse-gas-case-study-ieua.pdf
10. SDCWA. (2024). *Pursuing Cutting-Edge Renewable Energy Projects*. San Diego County Water Authority. https://www.sdcwa.org/projects-programs/programs/energy/
11. SNWA. (2024). *Sustainability Projects*. Southern Neveda Water Authority. https://www.snwa.com/environment/sustainability/index.html
12. CoP. (2017). *Lake Pleasant Solar Generation Facility*. City of Phoenix. https://betterbuildingssolutioncenter.energy.gov/sites/default/files/Renewable%20Energy%20Fuels%20Clean%20Water_Phoenix.pdf
13. Sonoma. (2024). *Energy & Sustainability Projects*. Sonoma Water. https://www.sonomawater.org/energy-sustainability-projects
14. LVVWA. (2024). *Using sustainable energy*. Las Vegas Valley Water Dsitrict. https://www.lvvwd.com/water-system/sustainable-energy/index.html#:~:text=More%20than%2085%20percent%20of,the%20Government%20Green%20Fleet%20Awards
15. Navius Research. (2023). *Biofuels in Canada 2023*. Navius Research Inc. https://advancedbiofuels.ca/wp-content/uploads/Biofuels-in-Canada-2023-2023-11-01.pdf

16. WUCA. (2024). *Reducing Fleet Emissions: East Bay Municipal Utility District*. Water Utilities Climate Alliance. https://www.wucaonline.org/assets/pdf/greenhouse-gas-case-study-ebmud.pdf

17. Blink. (2023). *How EVs Are Reducing Carbon (CO2) Emissions*. https://blinkcharging.com/blog/how-evs-are-reducing-carbon-co2-emissions

18. Tod Hartman. (2019). *Denver Water brings energy savings into the light*. https://www.denverwater.org/tap/denver-water-brings-energy-savings-light?size=n_21_n

19. MSRC. (2023). LADWP Cleans Up SoCal Skies with Eight New Heavy-Duty CNG Vehicles. *Clean Transportation Funding from MSRC*. http://www.cleantransportationfunding.org/news/2023/ladwp-cleans-socal-skies-eight-new-heavy-duty-cng-vehicles

20. WUCA. (2024). *Pumping Efficiencies: Massachusetts Water Resources Authority*. Water Utilities Climate Alliance. https://www.wucaonline.org/assets/pdf/greenhouse-gas-case-study-mwra.pdf

21. Pellikainen, P., Eikebrokk, B., & Vahala, R. (2023). Importance of process design on carbon footprint from drinking water treatment by enhanced coagulation-filtration. *Water Practice & Technology*, *18*(11), 2653–2663.

22. Nicola Elardo. (2021). *Improving the Sustainability of UV Systems*. https://uvsolutionsmag.com/articles/2021/improving-the-sustainability-of-uv-systems/

23. Beth Kenedy. (2010). Sustainable Water Disinfection. *Wastewater Digest*.

24. PWB. (2024). *About the Bull Run Filtration Project*. Portland Water Bureua. https://www.portland.gov/water/bullruntreatment/filtration/about

25. Piratla, K. R., Ariaratnam, S. T., & Cohen, A. (2012). Estimation of CO 2 emissions from the life cycle of a potable water pipeline project. *Journal of Management in Engineering*, *28*(1), 22–30. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000069

26. NRC. (2014). *Learn the facts: Emissions from your vehicle*. Natural Resources Canada. https://natural-resources.canada.ca/sites/nrcan/files/oee/pdf/transportation/fuel-efficient-technologies/autosmart_factsheet_9_e.pdf

27. CER. (2018). *Market Snapshot: How much CO2 do electric vehicles, hybrids and gasoline vehicles emit?* Canada Energy Regulator. https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/market-snapshots/2018/market-snapshot-how-much-co2-do-electric-vehicles-hybrids-gasoline-vehicles-emit.html

28. Isabella Zavarise. (2024). Buying an EV can save you money the longer and farther you drive it: UBC study. *CTV News*. https://bc.ctvnews.ca/buying-an-ev-can-save-you-money-the-longer-and-farther-you-drive-it-ubc-study-1.6805794

29. BC Hydro. (2024). *How much does owning an eletric vehicle costs?* BC Hydro Power smart. https://electricvehicles.bchydro.com/learn/costs-of-electric-vehicles

30. U.S. DOE. (2024). *Biodiesel Vehicle Emissions*. U.S. Department of Energy. https://afdc.energy.gov/vehicles/diesels-emissions

31. U.S. DOE. (2024). *Alternative Fuel Price Report*. U.S. Department of Energy. https://afdc.energy.gov/fuels/prices.html

32. Trans and Env. (2022). *Billions wasted on biofuels: Biofuels are a harmful and expensive distraction to road transport decarbonisation*. Transport and Environment. https://www.transportenvironment.org/uploads/files/202206_Billions_wasted_on_biofuels_TE.pdf

33. Inseego. (2024). *Thames Water improve fleet efficiency*. https://inseego.com/uk/resources/case-studies/thames-water/

34. Solar Reviews. (2024). *Solar panel cost Vancouver: Prices & data 2024*. https://www.solarreviews.com/solar-panel-cost/washington/vancouver#:~:text=Solar%20panel%20cost%20Vancouver%3A%20Prices%20%26%20data%202024&text=As%20of%20Jun%202024%2C%20the,solar%20tax%20credit%20now%20available.

35. Zazala Quist. (2024). *The CO_2 footprint of different energy sources*. https://ecochain.com/blog/the-co%E2%82%82-footprint-of-different-energy-sources/

36. BC Hydro. (2024). *Solar Panel*. BC Hydro Power smart. https://www.bchydro.com/powersmart/residential/tips-technologies/solar-panels.html

37. WPC. (2024). *What makes waterpower a clean energy source?* Water Power Canada. https://waterpowercanada.ca/wp-content/uploads/2021/12/WPC_What-makes-waterpower-a-clean-energy-source.pdf

38. CER. (2023). *Market Snapshot: The cost to install wind and solar power in Canada is projected to significantly fall over the long term*. Canada Energy Regulator. https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/market-snapshots/2018/market-snapshot-cost-install-wind-solar-power-in-canada-is-projected-significantly-fall-over-long-term.html

39. SUNECO. (2024). *Renewable Energy Solutions*. SUNECO Hydro Turbines. https://www.sunecohydro.com/10kw-hydro-turbine/

40. MDC. (2022). *Cost Savings with Variable Frequency Drives*. Munro Distributing Company, Inc. https://www.munroelectric.com/silvereclipse/images/content/Cost%20Savings%20with%20VFDs.pdf

41. Andrew Erickson. (2023). *What Price Should You Expect for SCADA Systems and Maintenance?* https://www.dpstele.com/blog/scada-price-maintenance-cost.php

42. Spang, E. S., Holguin, A. J., & Loge, F. J. (2018). The estimated impact of California's urban water conservation mandate on electricity consumption and greenhouse gas emissions. *Environmental Research Letters*, *13*(1), 014016.

43. Jennifer Wong and Susanne Porter-Bopp. (2009). *Water Conservation Planning Guide For British Columbia's Communities*. https://poliswaterproject.org/wp-content/blogs.dir/162/files/sites/162/2009/03/Water-Conservation-Planning-Guide-for-British-Columbias-Communities.pdf

44. Zib III, L., Byrne, D. M., Marston, L. T., & Chini, C. M. (2021). Operational carbon footprint of the US water and wastewater sector's energy consumption. *Journal of Cleaner Production*, *321*, 128815. https://doi.org/10.1016/j.jclepro.2021.128815

45. ÇELİK, E. Ö., AKDEMİR, Ü. Ö., & ÇELİK, H. (2017). *Liquid, Gas Chlorine and On-site Generation in Drinking Water Facilities Design Consideration and Comparison of Operating Costs*.

46. BC Hydro. (2024). *LED Light Bulbs*. BC Hydro Power smart. https://www.bchydro.com/powersmart/residential/tips-technologies/led-light-bulbs.html

47. Van Lighting. (2024). *Ceiling LED*. Vancouver Lighting. https://vancouverlighting.ca/collections/ceiling-led-1

48. Anthony Wallace. (2024). *America Is Replacing Its Pipes: Is Ductile Iron Pipe a Good Alternative for Plastic?* https://www.beyondplastics.org/news-stories/pvc-versus-iron-water-pipes-

49. JM Eagle Inc. (2024). *PVC vs Ductile Iron Pipe Installed Cost Comparison Calculator*. https://www.jmeagle.com/pvc-vs-ductile-iron-pipe-installed-cost-comparison-calculator

50. Kaushal, V., Najafi, M., Serajiantehrani, R., Vacanas, Y., Danezis, C., Singh, A., & Yazdani, S. (2020). Sanitary sewer construction cost comparison between trenchless cipp renewal and open-cut replacement. *Proceedings of International Structural Engineering and Construction*, *7*(1).

51. Apeldoorn, S. (2010). Comparing the costs-trenchless versus traditional methods. *International Society for Trenchless Technology Conferencie, Australasian Society for Trenchless Technology, Sidney*, *8*.

52. Zachary Lovett, David Diedrick, and David Figurski. (2024). *Advancing sustainable construction: Specifying low-carbon concrete*. https://www.constructionspecifier.com/building-resilience-and-decarbonization-concrete-solutions/

53. Dufferin Concrete Inc. (2023). *Ontario Price List*. https://dufferinconcrete.ca/wp-content/uploads/2022/10/Dufferin-Concrete-2023-Ontario-Price-List_condensed-1.pdf

54. Delaney Khung. (2022). *Life Cycle Assessment (LCA) and Cost-Benefit Analysis for Low Carbon Concrete and Cement Mix Designs*. https://irp.cdn-website.com/be6d1d56/files/uploaded/Low%20Carbon%20Concrete%20LCA%20and%20Cost-Benefit%20Whitepaper%20Final.pdf