APPENDIX A. SUPPLEMENTARY

Life cycle assessment of community-based sewer mining: Integrated heat recovery and fit-for-purpose water reuse

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Keywords

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Water reuse

S1. Scenario description

This study is based on a hypothetical community of 30,000 people aimed to be built as an urban infill development within the City of Edmonton, Alberta, Canada. The environmental performance integrating an ambient district heating system with community-based wastewater treatment for water reuse is determined by three scenarios: (1) Business-As-Usual (BAU), (2) District Energy System (DES) from Sewage Heat Recovery, and (3) DES with MBR Treatment.

Table S 1 LCA study scenarios.

Scenario category	Heating system	Water treatment system	Wastewater treatment system	Wastewater Reuse	Water Use Application
BAU	Conventional gas furnace and water heater	Conventional water treatment plant	Conventional wastewater treatment plant	x	IR
					IR+TF
					IR+TF+CW
DES	Sewage heat recovery for district heating	Conventional water treatment plant	Conventional wastewater treatment plant	x	IR
					IR+TF
					IR+TF+CW
DES+MBR	Sewage heat recovery for district heating	Membrane bioreactors		✓	IR
					IR+TF
					IR+TF+CW

BAU: Business-as-usual; DES: District energy system; MBR: Membrane biological reactor; IR: Irrigation; TF: Toilet flushing; CF: Clothes washing

The system boundaries for this study are limited to the construction and operation of heating, water treatment, and wastewater treatment systems for each scenario, in addition to the conveyance system of recycled wastewater from the membrane bioreactors to buildings. Gravity transport wastewater collection systems and sludge collection and use were excluded in the study.

BAU

The reference scenario is based on a semi-detached or duplex design (2 units per building) for 30,000 people, representing a design closer to conventional single-detached homes in the City of Edmonton. A conventional combined household wastewater (blackwater and greywater) system was considered in the BAU scenario and is assumed to have the same environmental contributions as the collection systems for the other scenarios. Conventional tap water lines are considered the same for all scenarios.

DES

The scenarios that include a district energy system use a design based on the average Canadian apartment area of 88 m^2. Using the Canadian average of 3 occupants per dwelling, 10,000 units for 30,000 people were assumed (Natural Resources Canada, 2016). A total floor area of 880,000 was used for the hypothetical community of the study using DES. A distribution line is implemented for scenarios that include water reuse, representing additional environmental contributions. Characteristics and a general outline of the distribution system is shown in S7 and Figure S 1, respectively.

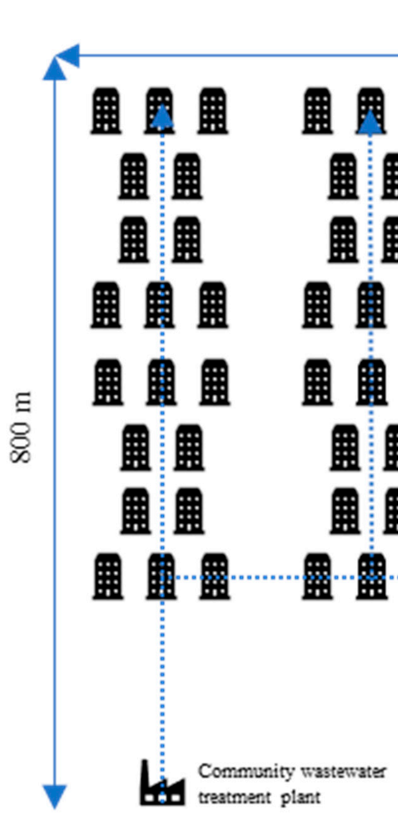

Figure S 1 General recycled water distribution system.

S2. Environmental impact indicators – TRACI

The three impact indicators used for the study are global warming potential (GWP), eutrophication potential (EUP), and human health carcinogenic potential (HHCP) from the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) (Bare, 2012). These impact indicators have been used in water management related LCAs specifically for North American contexts (Jeong et al., 2018; Kobayashi et al., 2020; Rahman et al., 2016).

S3. Conventional heating systems

Conventional space and water heating for semi-detached homes are modelled for the baseline scenario. Each household is individually equipped with a furnace and water heater. Inventory data are shown in Table S 2.

Table S 2 Material and operational life cycle inventory data of conventional home heating components.

	Unit	Value	Source
TRANE XE-80 furnace			
Steel	$kg.PE^{-1}.y^{-1}$	4.39E-01	(Blanchard & Reppe, 1998a)
Aluminium	$kg.PE^{-1}.y^{-1}$	3.33E-03	
Polyurethane foam	$kg.PE^{-1}.y^{-1}$	6.00E-03	
Glass	$kg.PE^{-1}.y^{-1}$	1.53E-02	
Paper	$kg.PE^{-1}.y^{-1}$	9.33E-03	
A.O. Smith 32000 BTU/HR input water heater			
Steel	$kg.PE^{-1}.y^{-1}$	1.11E+00	(Blanchard & Reppe, 1998a)
Aluminium	$kg.PE^{-1}.y^{-1}$	2.00E-02	
Plastic	$kg.PE^{-1}.y^{-1}$	1.11E-02	
Polyurethane foam	$kg.PE^{-1}.y^{-1}$	1.11E-02	
Glass	$kg.PE^{-1}.y^{-1}$	5.11E-02	
Operational requirements			
Electricity	$kWh.PE^{-1}.y^{-1}$	1.35E+02	(Blanchard & Reppe, 1998a)
Natural gas	$GJ.PE^{-1}.y^{-1}$	9.42E+00	

S4. District energy system and sewer heat recovery

This study aims to optimize the resource recovery potential of combined municipal wastewater by recovering heat energy and treating the wastewater at a community-scale for various water reuse purposes. The heat recovery system used for this study was adapted from a sewer heat exchange system in the City of Vancouver managed by the Southeast False Creek Neighbourhood Energy Utility (SFCNEU) (City of Vancouver, 2020). The SFCNEU system recycles waste heat captured from sewage and wastewater to provide heating and hot water for buildings. Of the energy requirements of the district heating system, 70% is supplied from sewage heat recovery (320% efficiency) and 30% is supplied from gas boilers (efficiency of 83%). 3% is attributed to thermal distribution loss with 2.5% ancillary electrical. The inventory data used for this study is shown in Table S 3.

Sewage is screened and pumped into a central heat pump at 25 C and returns to the sewage pump station at 20 C. The heated refrigerant is upgraded using a compressor with a coefficient of performance (CoP) of 3.5. Thermal energy is then transferred into the district heating distribution system with an outgoing water temperature of 65 C. A back-up system consisting of a peaking boiler that is gas fired is used. The Vancouver system uses sewage heat recovery to provide 3 megawatts (MW) of baseload capacity – requiring electricity for the heat pumps but yields 3.2 times the energy output. An additional 16 MW of natural gas capacity is provided for back-up and peak capacity needs. Space heating for the hypothetical district energy system is based on hydronic radiant floor/ceiling systems (City of Edmonton, 2017b). The design of the Vancouver district heating system is based on multi-unit buildings with lower expected energy consumption per household in comparison to detached single family home designs used for the baseline conventional scenario (City of Vancouver, 2020).

This study uses the development of Blatchford in Edmonton, AB, Canada as a general reference case for the scale of feasibility within the City of Edmonton. The concept of Blatchford as an infill development or redeveloping an area that was previously an airport is to create the first large scale net zero and carbon neutral community in Canada. Blatchford aims to have a District Energy Sharing System (DESS), a centralized heating and cooling distribution system for the various building types of the community. A geoexchange field is expected to harness shallow geothermal energy using 570 boreholes at a depth of 150 m. Similar to a geo*thermal* system, a geo*exchange* field takes advantage of constant shallow underground temperatures to allow thermal energy transfer and storage for both heating and cooling. The sewer trunk main used for wastewater extraction is located at a depth of approximately 17 m, with a lift station designed for approximately 20 m deep according. The Blatchford area of 536 acres (2 169 115 m^2) aims to house approximately 30 000 residents.

Table S 3 Southeast False Creek system – material inventory data for the sewer heat recovery and district heating system.

	Unit	**Value**
Boiler plant		
Stainless steel	$kg.PE^{-1}.y^{-1}$	6.36E-02
Carbon steel	$kg.PE^{-1}.y^{-1}$	1.12E-02
Cast iron	$kg.PE^{-1}.y^{-1}$	2.12E-03
Bronze	$kg.PE^{-1}.y^{-1}$	9.07E-05
District heat		
Carbon steel	$kg.PE^{-1}.y^{-1}$	1.53E-02
Cast iron	$kg.PE^{-1}.y^{-1}$	3.00E-03
Bronze	$kg.PE^{-1}.y^{-1}$	3.33E-04
Sewage heat recovery		
Stainless steel	$kg.PE^{-1}.y^{-1}$	5.67E-02
Carbon steel	$kg.PE^{-1}.y^{-1}$	5.67E-02
Cast iron	$kg.PE^{-1}.y^{-1}$	1.65E-02
Bronze	$kg.PE^{-1}.y^{-1}$	6.05E-05
Sewage wet well		
Stainless steel	$kg.PE^{-1}.y^{-1}$	9.13E-04
Sewage pump station		
Cast iron	$kg.PE^{-1}.y^{-1}$	2.21E-03
Stainless steel	$kg.PE^{-1}.y^{-1}$	5.17E-03
Plant ventilation and odour control [a]		
Galvanized steel	$kg.PE^{-1}.y^{-1}$	4.25E-03
Stainless steel	$kg.PE^{-1}.y^{-1}$	7.94E-03
Cast iron	$kg.PE^{-1}.y^{-1}$	5.60E-04
Bronze	$kg.PE^{-1}.y^{-1}$	9.37E-05
Distribution pipe system [b]		
Steel	$kg.PE^{-1}.y^{-1}$	1.64E-01
Polyurethane foam	$kg.PE^{-1}.y^{-1}$	2.75E-05
Excavation	$m^3.PE^{-1}.y^{-1}$	9.10E-03
Operational requirements [c]		

Electricity	$kWh.PE^{-1}.y^{-1}$	3.71E+02
Natural gas	$GJ.PE^{-1}.y^{-1}$	2.65E-01

N/I: Not included

[a] Plant ventilation and odour control was limited to the wet well odour control system, chilled water pumps, heating coil pumps, and hot water tanks.

[b] Per unit equivalent of the distribution pipe system is based on the South East False Creek system and the region being serviced. HDPE pipe casing was not included in the analysis.

[c] Operational requirements are collected from the South East False Creek system and the region being serviced. As operational energy varies annually, an annual average of 10 years of operation was considered for this study. Sewage heat recovery for this system provides approximately 70% of energy requirements for district heating provision and the remaining 30% from gas boilers as of 2019.

S5. Conventional wastewater treatment system

The conventional wastewater treatment system used in the Business-As-Usual (BAU) scenario includes primary treatment, biological treatment, and ultraviolet disinfection based on the existing local wastewater treatment plant (EPCOR, 2020b). The ecoinvent dataset was used for construction and demolition of the plant (Wernet et al., 2016).

Table S 4 Conventional wastewater treatment chemical and operational inventory.

	Unit	**Value**
Chemical components		
Alum	$kg.PE^{-1}.y^{-1}$	2.91E-01
Polymer	$kg.PE^{-1}.y^{-1}$	1.14E-02
Bleach	$L.PE^{-1}.y^{-1}$	5.47E-02
Caustic	$kg.PE^{-1}.y^{-1}$	3.29E-02
Operational energy		
Natural gas	GJ/L treated WW	5.1714E-07
Electricity	kWh/L treated WW	4.9823E-04

S6. Water use and reuse

In evaluating the benefits of water recycling, various scenarios are used to simulate different types of water reuse. The basis of water use and reuse for this study is based on household water consumption averages in the City of Edmonton as shown on Table S 7. The major household water consumption types of irrigation, toilet flush, and clothes washing was chosen, as well as a combination of the three (Table S 8). These values also correspond to the avoided volumes to tap water production.

Table S 7 Edmonton household water consumption characteristics.

Type of consumption	**Fraction of household water consumption (%)** [a]	**Volume per person per year ($m^3.PE^{-1}.y^{-1}$)** [b]
Showers / baths	34	23.0826
Outdoor	5	3.3945
Kitchen / cleaning	13	8.8257
Clothes washing	19	12.8991
Toilets	29	19.6881

[a] Fraction of household water consumption for the City of Edmonton (City of Edmonton, 2017a; Kobayashi et al., 2020).
[b] Daily household water consumption for Edmonton is 186 L/person/day (EPCOR, 2020a).

Table S 8 Water use / reuse scenarios.

Water use / reuse	**Total volume of water per year ($m^3.y^{-1}$)**
Irrigation	101835
Toilet flush	590643
Clothes washing	386973
Irrigation + toilet flush	692478
Irrigation + toilet flush + clothes washing	1079451

Local guidelines and previous research suggest a minimum diameter of 150 mm for main pipes and 20 mm for service pipes used (City of Edmonton, 2017a). Header PVC pipes are estimated to be more than 7.11 mm thick with an outside diameter of 168 mm and an assumed weight of 5.25 kg/m. Branch pipes are estimated to be more than 2.87 mm thick with an outside diameter of 26.7 mm and an assumed weight of 0.313 kg/m. Pipe lengths are shown in Table S 9. Pumping energy for the distribution pipes were estimated using EPANET 2 (Rossman, 2000).

Table S 9 Recycled water distribution inventory.

	Material	**Unit**	**Value**
Service line [a]	PVC	$kg.PE^{-1}.y^{-1}$	1.13E-02
Main pipe [b]	PVC	$kg.PE^{-1}.y^{-1}$	6.65E-03
Pumps	Cast iron	$kg.PE^{-1}.y^{-1}$	1.09E-04
	Bronze impeller	$kg.PE^{-1}.y^{-1}$	1.20958E-05
Operation			
Electricity		$kWh.m^{-3}$	6.18E-02

[a] Estimated 108,400 m length of service lines.
[b] Estimated 3,800 m of main pipelines.

S7. Tap water production

The construction and demolition of the conventional water treatment system used in this study is from the ecoinvent database (Wernet et al., 2016). Operational requirements for the production and distribution of tap water were estimated from the averages of the 2017 and 2018 annual waterworks report of the local tap water supplier (EPCOR, 2018). The inventory data used for these processes are shown on Table S 8 based on per volume of water produced as varying water volumes are being modelled.

Table S 10 Life cycle inventory data of conventional tap water production.

Material	Unit	Value	Source
Aluminium sulfate	$mg.L^{-1}$	44.4666	(EPCOR, 2018)
Filter polymer - Magnafloc LT 2AG	$mg.L^{-1}$	0.273	
Carbon chemical	$mg.L^{-1}$	61.9333	
Sodium hypochlorite	$mg.L^{-1}$	3.25	
Aqua ammonia	$mg.L^{-1}$	0.565	
Caustic soda	$mg.L^{-1}$	8.8	
Fluoride	$mg.L^{-1}$	0.725	
Sodium bisulfite	$mg.L^{-1}$	21.85	
Energy usage			
Energy consumption for treatment and pumpage	$kWh.L^{-1}$	0.000666055	(EPCOR, 2018)
Gas consumption for treatment and pump stations	$GJ.L^{-1}$	7.65738E-07	

S8. Community-based wastewater treatment – Membrane bioreactor

This study uses MBRs to effectively treat municipal wastewater for various water reuses after the sewage heat recovery process. As the first stage of the wastewater has already been screened (1-3 mm capacity) through prior to the heat recovery unit, influent is passed through directly into containers containing ultrafiltration membrane cassettes with porous membranes typically consisting of cellulose or other polymer materials (Cascadia Green Building Council, 2011; Jeong et al., 2018). MBRs have the advantage of producing high quality effluent while minimizing footprint, but at the cost of greater energy demands and greater operator attention (Cashman et al., 2018; Zenon, 2006).

Table S 11 Life cycle inventory data for MBR. [a]

	Material	Unit	Value
Pre-treatment fine screen	Steel	$kg.m^{-3}.y^{-1}$	1.97E-02
Concrete pad	Concrete	$m^3.m^{-3}.y^{-1}$	2.99E-02
Steel container	Steel	$kg.m^{-3}.y^{-1}$	9.69E-03
Mixer	Steel	$kg.m^{-3}.y^{-1}$	2.17E-03
Aeration system piping	PVC	$kg.m^{-3}.y^{-1}$	9.32E-05
Aeration system rubber piping	Rubber-silicon based	$kg.m^{-3}.y^{-1}$	3.94E-04

Pump	Steel	$kg.m^{-3}.y^{-1}$	1.05E-03
MBR reactor steel housing	Steel	$kg.m^{-3}.y^{-1}$	1.09E-03
Membranes	Polyvinylidene fluoride [b]	$kg.m^{-3}.y^{-1}$	3.28E-04
Recycle pump	Steel	$kg.m^{-3}.y^{-1}$	7.22E-04
Air blower	Cast iron	$kg.m^{-3}.y^{-1}$	1.03E-03
Controls/portable instruments	Polyester	$kg.m^{-3}.y^{-1}$	6.57E-05
Operational requirements			
Membrane cleaning	Sodium hypochlorite	$kg.m^{-3}.y^{-1}$	4.90E-02
Electricity		$kWh.m^{-3}$	1.9611

[a] Inventory data sourced from literature and is based on per volume of water produced (Cascadia Green Building Council, 2011). The excavation process was not included as it is considered to have negligible impacts for the associated scale.
[b] Polyvinyl fluoride was used instead of polyvinylidene fluoride for this study (Kobayashi et al., 2020).

S9. Lifespan

The lifespans of the associated components used for this study has been taken from previous studies and manufacturer sources and are shown in Table S 13.

Table S 13 Lifespan of LCA components.

	Unit	Value	Notes
Conventional systems			
Conventional wastewater treatment plant	years	50	(Cascadia Green Building Council, 2011)
Conventional water treatment plant	years	50	(Cascadia Green Building Council, 2011)
Conventional home heating components (gas furnace and water heater)	years	15-50	(Blanchard & Reppe, 1998b; Vignali, 2017)
District energy system			
Sewage heat recovery and district energy	years	30	(Kerr Wood Leidal Associates LTD., 2013)
Distribution pipes	years	30	(Fröling et al., 2004; LOGSTOR, 2020)

Sewage wet well	years	100	Assumed lifespan of steel gates before disposal or recycling.
Sewage pump station, heat pumps, water pumps	years	15	(Hydraulic Institute et al., 2001)
Boilers	years	15	(Vignali, 2017)
Wet well odour control	years	35	Contacted manufacturer
Membrane bioreactor system			
Screen (pretreatment)	years	50	(Cascadia Green Building Council, 2011)
MBR reactor	years	50	
Membrane	years	10	
Pump	years	10	
Mixer	years	10	
Air blower	years	15	
Controls	years	25	

S10. Electricity mix

A sensitivity analysis was conducted using the projected electricity mix in 2040 and a hypothetical fully renewable mix based on the assumption of projected growth rates in the province of Alberta (Alberta Utilities Commission, 2020; National Energy Board, 2016).

	AB2018	**AB2040**	**Renewable**
Hydro	2.3%	3.2%	3.2%
Wind	5%	10.1%	61.2%
Biomass/biogas	2.4	1.9%	18.4%
Solar	0.03%	0.8%	17.2%
Coal	42%	13.2%	
Natural gas	48%	70.4%	
Oil	0.4%	0.4%	

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