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Life Cycle Assessment of Community-Based Sewer Mining: Integrated Heat Recovery and Fit-For-Purpose Water Reuse

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Abstract: Municipal sewage contains significant embedded resources in the form of chemical and thermal energy. Recent developments in sustainable technology have pushed for the integration of resource recovery from household wastewater to achieve net zero energy consumption and carbon-neutral communities. Sewage heat recovery and fit-for-purpose water reuse are options to optimize the resource recovery potential of municipal wastewater. This study presents a comparative life cycle assessment (LCA) focused on global warming potential (GWP), eutrophication potential (EUP), and human health carcinogenic potential (HHCP) of an integrated sewage heat recovery and water reuse system for a hypothetical community of 30,000 people. Conventional space and water heating components generally demonstrated the highest GWP contribution between the different system components evaluated. Sewage-heat-recovery-based district heating offered better environmental performance overall. Lower impact contributions were demonstrated by scenarios with a membrane bioreactor (MBR) and chlorination prior to water reuse applications compared to scenarios that use more traditional water and wastewater treatment technologies and discharge. The LCA findings show that integrating MBR wastewater treatment and water reuse into a district heating schema could provide additional environmental savings at a community scale.

Keywords: life cycle assessment; heat recovery; membrane bioreactor; water reuse; community-based wastewater treatment

1. Introduction

Emerging wastewater treatment technologies permit application of waste-to-resource approaches, particularly in the recovery of various products from municipal wastewater. This idea has historically been exhibited through the production of compost and fertilizer for agriculture, but increasingly complex processes have been developed enabling the recovery of resources in the form of chemical energy and heat [1,2]. Sewage heat recovery systems are an attractive waste-to-resource approach that has been gaining interest in recent years [3,4]. Sewage heat can be captured and optimized for a district heating system wherein reductions in CO_2 emissions can be demonstrated from the conversion of fossil-fuel-sourced-electricity-heated homes to community-based heating from alternative energy sources [5,6], particularly since domestic space heating and hot water provision represent the largest share of energy consumption associated with residential building operations [7].

Global water insecurity has resulted in emerging wastewater reclamation initiatives and applications in recent years [8–10]. The concept of extracting wastewater from an existing sewer to be reclaimed as reusable water (sewer mining) emerged largely from the need to reduce pressure on water resources in Australia [11]. Now it is a concept that can play a role in the transition of conventional sanitation systems to systems that support circularity and sustainable development. Community-based wastewater treatment using aerobic membrane bioreactors (MBRs) and chlorine disinfection is assumed to be a mature and available technology to produce effluent suitable for water reuse purposes [12,13].

Previous studies have explored the integration of water, waste, and energy management systems in various cases, i.e., Curauma, Chile [14], as well as energy and nutrient recovery in municipal wastewater [1,15–17]. However, few studies exist that have evaluated the environmental performance of integrated systems [18], and we did not find any research that evaluated the cumulative environmental impact of combining a sewage heat recovery system with community-based wastewater treatment for various water reuse applications.

Environmental burdens associated with products and processes based on material and energy uses and releases to the environment can be quantified using life cycle assessment (LCA), which has commonly been used to assess wastewater treatment and resource recovery systems [18–21] and building heating [22]. Recent research has generally found positive environmental performances from the recovery of heat energy from municipal sewage, with limitations attributed to supply distances and regulations/policies [23]. In principle, municipal sewage could provide space and water heating for buildings, particularly since operational energy requirements account for 80–90% of the life cycle energy needs of a building [24]. Sewers have also been reported to be the largest source of heat loss from buildings [25]. It is probable that operational energy requirements to maintain comfortable conditions and day-to-day maintenance of a building are higher for cold regions that require longer periods of space heating, making sewage heat recovery a more attractive alternative for winter cities.

This paper contributes to the understanding of maximizing the environmental performance of residential communities by incorporating a decentralized sanitation and resource recovery scheme, consisting of sewage heat recovery and community-based wastewater treatment for water reuse. While the environmental evaluation of different fuels for district heating has been investigated, very few studies have looked at the evaluation of sewage heat recovery, as only a few full-scale systems exist to date [21,26,27]. Water reuse benefits considered include a reduced need for drinking water production [28].

Here, we present the environmental performance of applying integrated resource recovery technologies from wastewater serving a hypothetical community development of 30,000 people, using previously identified key parameters [29] to determine possible benefits of decentralized water and wastewater infrastructure compared to business as usual.

2. Materials and Methods

2.1. Community System and Problem Framing

The greenfield community modelled was assumed to consist of individual homes for a 30,000 person-equivalent (PE) population in Edmonton (53.54° N, 113.49° W), Canada. The life cycle approach followed the ISO14044 [30] methodology. The overall research framework and approach are illustrated in Figure 1.

2.2. Life Cycle Inventory (LCI) and Life Cycle Assessment (LCA)

The LCA calculations were performed with OpenLCA ver. 1.8.0 [31] using the TRACI 2.1 impact assessment method developed for North America [32] and the approach previously described by Schoen et al. [13]. The environmental impact indicators included global warming potential (GWP) in kg CO_2-eq.$PE^{-1}.y^{-1}$, eutrophication potential (EUP) in kg N-eq.$PE^{-1}.y^{-1}$, and human health carcinogenic potential (HHCP) in kg benzene-eq.$PE^{-1}.y^{-1}$.

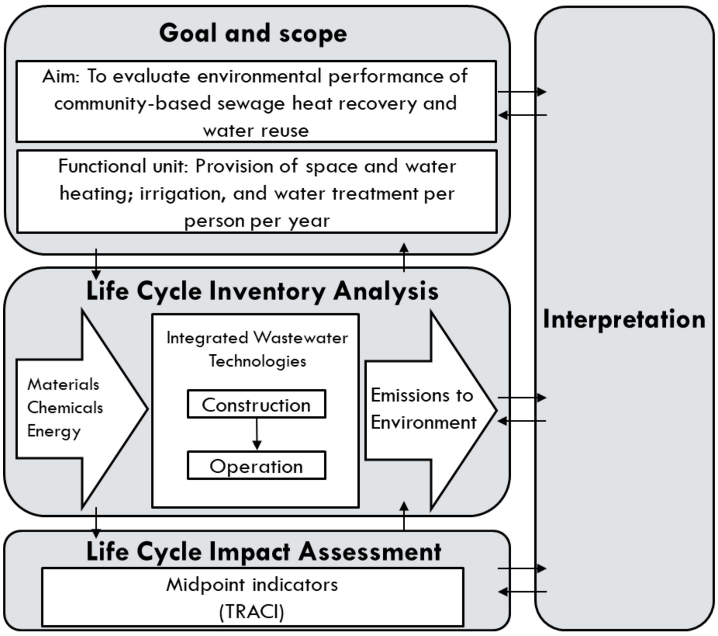

Figure 1. Overall research framework and approach.

The materials that comprised the different components and technologies in this study were identified primarily based on full-scale systems and manufacturer specifications, and through literature review. The ecoinvent database, version 3.5 [33], was used for much of the background inventory data. Additional details on LCI are provided in the Supplementary Materials.

The functional unit chosen was the annual provision of the following services per person: home space heating, hot water, and various types of water uses such as irrigation (IR), toilet flushing (TF) and clothes washing (CW).

2.3. Scenarios

2.3.1. Business as Usual (BAU)

The BAU scenario used in this study consisted of single-family homes with water and space heating using an conventional furnace and gas-fired water boilers (natural gas), tap water provision from a conventional water treatment plant (coagulation, flocculation, and filtration) with disinfection (free chlorine, ultraviolet disinfection, and monochloramine for distribution) [34], and conventional sanitation services using a centralized municipal wastewater treatment plant including primary treatment, biological secondary treatment, and ultraviolet (UV) disinfection [35,36]. Conventional space and water heating systems were considered for the BAU scenarios using data from the literature (Supplementary Materials, Table S2). The conventional municipal wastewater system was based on the operational conditions of the local wastewater treatment plant (WWTP) [36], which is the wastewater treatment provider for communities within the City of Edmonton, Canada. Major inventory components for the WWTP and drinking water production were sourced from the literature and the ecoinvent database [33,35].

2.3.2. Sewage Heat Recovery and District Energy System (DES)

Domestic hot water and space heating for the modelled district energy system scenario was assumed to use heat pump evaporators located above a major sewer main in the community for heat recovery. The design was adapted from a system in Vancouver, Canada, which provides 70% of domestic hot water and space heating for the community of Southeast False Creek [5], with further details for the LCA for the hypothetical community in Edmonton provided in the Supplementary Materials (Section S5).

2.3.3. Community-Based Membrane Bioreactor (MBR) for Water Reuse

The community-based configuration used for this study included screening as pre-treatment, ultra-filtration for the main treatment, and chlorination for disinfection. A simplified recycled water distribution system was assumed with its associated additional material and operational process requirements (Supplementary Materials, Section S8). Three water reuse volumes were modeled: irrigation (IR) at 101,835 $m^3.y^{-1}$, irrigation and toilet flush (IR + TF) at 692,478 $m^3.y^{-1}$, and irrigation, toilet flush, and clothes washing (IR + TF + CW) at 1,079,451 $m^3.y^{-1}$ (Table 1) based on local household water consumption averages (Supplementary Materials, Section S6).

Table 1. LCA study scenario types.

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	×	IR
					IR + TF
					IR + TF + CW
DES	Sewage heat recovery for district heating	Conventional water treatment plant	Conventional wastewater treatment plant	×	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.

2.4. System Assumptions

Main assumptions:

- Material transport was generalized using the ecoinvent global market databases (v3.5) to account for transport impacts.
- 10,000 detached housing units representing 30,000 EP based on standard community developments for the City of Edmonton (Supplementary Materials, Section S1).
- Heating distribution building components, such as radiant floor/ceiling systems used for the district heating system and conventional building heating distribution components, were excluded from the analysis.
- Conveyance of recycled water within buildings was excluded from the study.
- Sludge management and gaseous operational emissions for individual components were excluded from this study.
- The end-of-life phase was not considered, as impact contributions have been found to be minimal relative to the construction and operational phases for the technologies used [28,37].

Sensitivity Analysis

Operational requirements, such as electricity production, largely affect the environmental impact contributions of water management and heating systems [38,39]. The 2018 Alberta electricity mix was used as the default alongside a 2040 projected electricity mix, and a hypothetical 100% renewable energy mix [40,41]. Specific electricity mixes used are available in the Supplementary Materials (Section S13).

3. Results

3.1. Comparison of Different Water Reuse Scenarios

In general, the BAU scenario had the highest GWP values, while EUP and HHCP had similar values between BAU and DES, and all three indicator values were the lowest for the DES+MBR scenario (Figure 2). Irrigation as a choice of water use (101,835 $m^3.y^{-1}$) for the community produced little to no difference in the EUP and HHCP indicators values across three the three scenarios; however, as water use volumes increased to include toilet flushing and clothes washing, greater environmental savings were calculated when community-based wastewater treatment and water reuse systems were included.

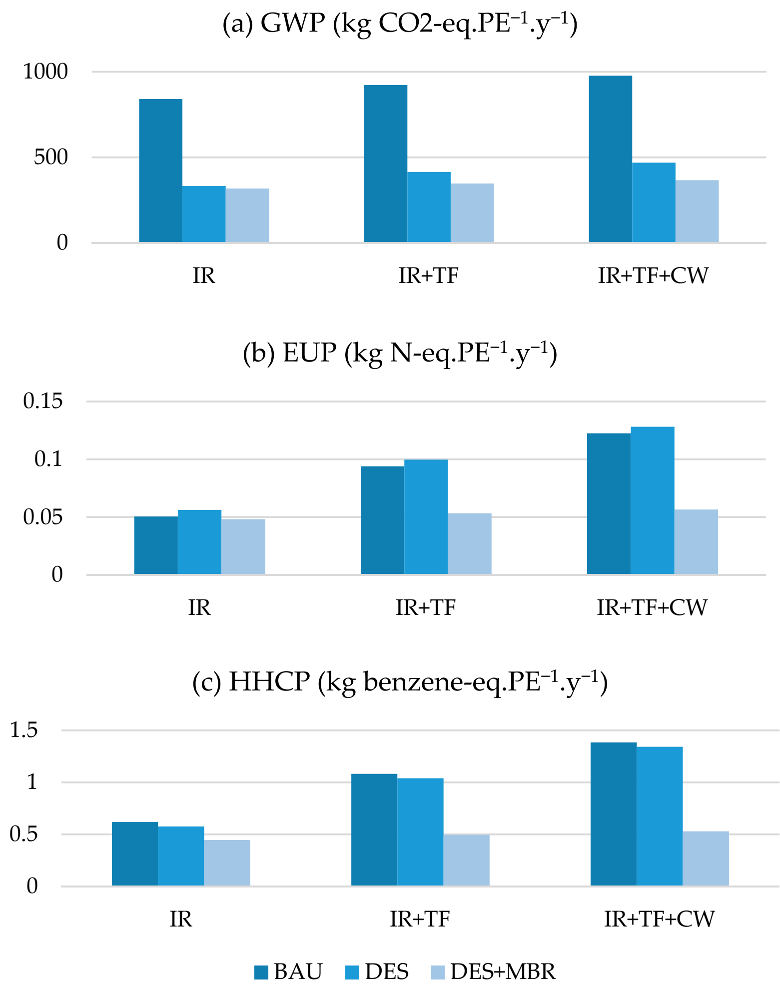

Figure 2. Comparison of business as usual (BAU), district energy system (DES) and district energy system with membrane bioreactor treatment (DES+MBR) for impact categories: (**a**) global warming potential (GWP); (**b**) eutrophication potential (EUP), and (**c**) human health carcinogenic potential (HHCP) for different water reuse scenarios.

Relative to the combined impacts of water treatment, wastewater treatment, space and water heating, and MRB systems, the DES+MBR system exhibited the least variation in impacts as water use volumes increased. Overall, impact contributions from the operational phase dominated over the construction phase for GWP (>98%), EUP (>96%), and HHCP (>85%) (Table 2). Construction phase contributions were generally in the range of 1–15% for each impact category. BAU scenarios tended to have greater contributions associated with the construction phase compared to DES and DES+MBR scenarios.

Table 2. Impact contributions of construction and operational phases of system components for BAU, DES, and DES + MBR applications under various water reuse options.

		BAU			DES			DES + MBR		
		IR	**IR + TF**	**IR + TF + CW**	**IR**	**IR + TF**	**IR + TF + CW**	**IR**	**IR + TF**	**IR + TF + CW**
GWP (kg CO_2-eq.PE^{-1}.y^{-1})										
Water Treatment System	CON	6.71×10^{-1}	6.75×10^{-1}	6.78×10^{-1}	6.71×10^{-1}	6.75×10^{-1}	6.78×10^{-1}	---	---	---
	OPR	1.07	7.29	1.14×10^{1}	1.07	7.29	1.14×10^{1}	---	---	---
Space and Water Heating System	CON	2.86	2.86	2.86	5.73×10^{-1}	5.73×10^{-1}	5.73×10^{-1}	5.73×10^{-1}	5.73×10^{-1}	5.73×10^{-1}
	OPR	8.17×10^{2}	8.17×10^{2}	8.17×10^{2}	3.12×10^{2}	3.12×10^{2}	3.12×10^{2}	3.12×10^{2}	3.12×10^{2}	3.12×10^{2}
Wastewater Treatment System	CON	5.85	5.85	5.85	5.85	5.85	5.85	---	---	---
	OPR	1.30×10^{1}	8.86×10^{1}	1.38×10^{2}	1.30×10^{1}	8.86×10^{1}	1.38×10^{2}	---	---	---
MBR System	CON	---	---	---	---	---	---	4.12×10^{-1}	2.59	4.02
	OPR	---	---	---	---	---	---	5.85	3.98×10^{1}	6.20×10^{1}
Water Reuse Savings		---	---	---	---	---	---	−1.07	−7.29	-1.14×10^{1}
Total		8.41×10^{2}	9.23×10^{2}	9.76×10^{2}	3.33×10^{2}	4.15×10^{2}	4.69×10^{2}	3.18×10^{2}	3.48×10^{2}	3.67×10^{2}
EUP (kg N-eq.PE^{-1}.y^{-1})										
Water Treatment System	CON	1.01×10^{-4}	1.02×10^{-4}	1.03×10^{-4}	1.01×10^{-4}	1.02×10^{-4}	1.03×10^{-4}	---	---	---
	OPR	1.80×10^{-4}	1.22×10^{-3}	1.91×10^{-3}	1.80×10^{-4}	1.22×10^{-3}	1.91×10^{-3}	---	---	---
Space and Water Heating System	CON	6.78×10^{-4}	6.78×10^{-4}	6.78×10^{-4}	1.16×10^{-4}	1.16×10^{-4}	1.16×10^{-4}	1.16×10^{-4}	1.16×10^{-4}	1.16×10^{-4}
	OPR	4.09×10^{-2}	4.09×10^{-2}	4.09×10^{-2}	4.72×10^{-2}	4.72×10^{-2}	4.72×10^{-2}	4.72×10^{-2}	4.72×10^{-2}	4.72×10^{-2}
Wastewater Treatment System	CON	1.32×10^{-3}	1.31×10^{-3}	1.32×10^{-3}	1.32×10^{-3}	1.31×10^{-3}	1.32×10^{-3}	---	---	---
	OPR	7.32×10^{-3}	4.98×10^{-2}	7.76×10^{-2}	7.32×10^{-3}	4.98×10^{-2}	7.76×10^{-2}	---	---	---
MBR System	CON	---	---	---	---	---	---	1.08×10^{-4}	6.82×10^{-4}	1.06×10^{-3}
	OPR	---	---	---	---	---	---	9.56×10^{-4}	6.50×10^{-3}	1.01×10^{-2}
Water Reuse Savings		---	---	---	---	---	---	-1.80×10^{-4}	-1.22×10^{-3}	-1.91×10^{-3}
Total		5.05×10^{-2}	9.40×10^{-2}	1.22×10^{-1}	5.62×10^{-2}	9.97×10^{-2}	1.28×10^{-1}	4.82×10^{-2}	5.32×10^{-2}	5.66×10^{-2}
HHCP (kg benzene-eq.PE^{-1}.y^{-1})										
Water Treatment System	CON	3.72×10^{-3}	3.74×10^{-3}	3.76×10^{-3}	3.72×10^{-3}	3.74×10^{-3}	3.76×10^{-3}	---	---	---
	OPR	3.17×10^{-3}	2.16×10^{-2}	3.37×10^{-2}	3.17×10^{-3}	2.16×10^{-2}	3.37×10^{-2}	---	---	---
Space and Water Heating System	CON	3.41×10^{-2}	3.41×10^{-2}	3.41×10^{-2}	7.44×10^{-3}	7.44×10^{-3}	7.44×10^{-3}	7.44×10^{-3}	7.44×10^{-3}	7.44×10^{-3}
	OPR	4.46×10^{-1}	4.46×10^{-1}	4.46×10^{-1}	4.30×10^{-1}	4.30×10^{-1}	4.30×10^{-1}	4.30×10^{-1}	4.30×10^{-1}	4.30×10^{-1}
Wastewater Treatment System	CON	5.55×10^{-2}	5.55×10^{-2}	5.55×10^{-2}	5.55×10^{-2}	5.55×10^{-2}	5.55×10^{-2}	---	---	---
	OPR	7.66×10^{-2}	5.21×10^{-1}	8.12×10^{-1}	7.66×10^{-2}	5.21×10^{-1}	8.12×10^{-1}	---	---	---
MBR System	CON	---	---	---	---	---	---	2.51×10^{-3}	1.67×10^{-2}	2.61×10^{-2}
	OPR	---	---	---	---	---	---	9.37×10^{-3}	6.37×10^{-2}	9.93×10^{-2}
Water Reuse Savings		---	---	---	---	---	---	-3.17×10^{-3}	-2.16×10^{-2}	-3.37×10^{-2}
Total		6.19×10^{-1}	1.08	1.39	5.77×10^{-1}	1.04	1.34	4.46×10^{-1}	4.97×10^{-1}	5.29×10^{-1}

CON: construction; OPR: operation; BAU: business as usual; DES: district energy system; MBR: membrane biological reactor; IR: irrigation; TF: toilet flushing; CF: clothes washing.

3.2. Comparison of the Different System Components

Space and water heating systems for all scenarios (67–98%) were the major source of environmental contributions, attributed to their greater energy consumption relative to other processes like water treatment, wastewater treatment, and MBR systems (Figure 3). As expected, increasing volumes for water use correspondingly increased the contributions of wastewater treatment and MBR systems. However, the DES+MBR scenarios generally showed a lower overall GWP contribution from wastewater-treatment-related processes using the MBR system, as opposed to the BAU and DES scenarios. While water treatment systems for the BAU and DES generally accounted for less than 3% of GWP contributions, avoiding this contribution in the DES+MBR scenario due to community-based wastewater treatment and reuse offered additional environmental savings.

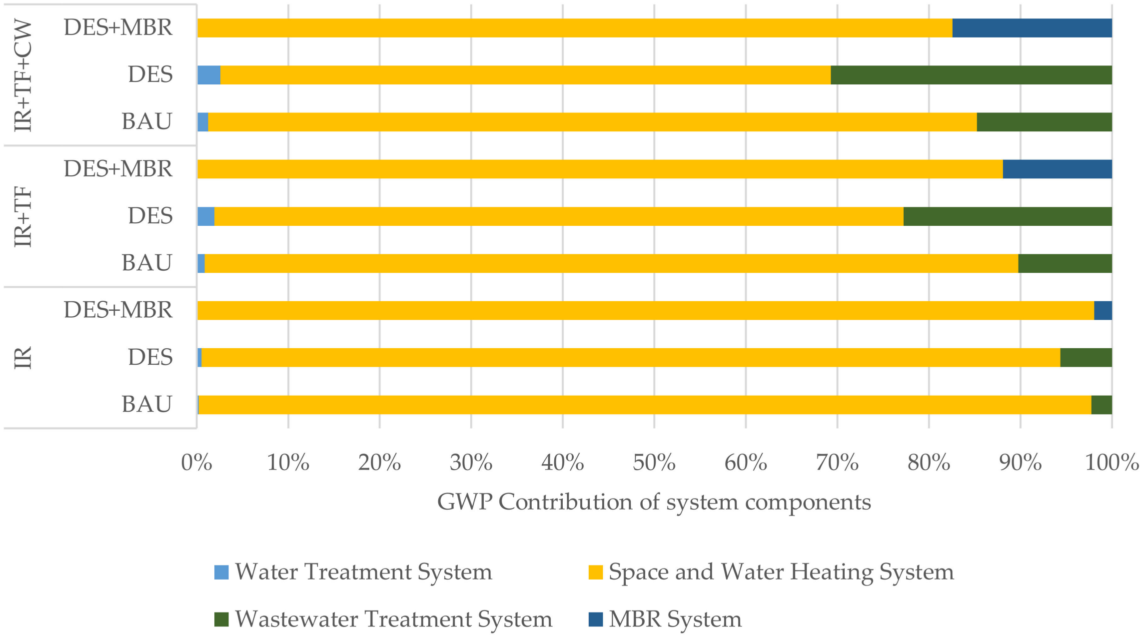

Figure 3. Global warming potential (GWP) impact contribution of system components for the three study scenarios and water reuse options: business as usual (BAU), district energy system (DES), and district energy system with membrane bioreactor (DES+MBR); irrigation (IR), toilet flushing (TF), and clothes washing (CW).

The EUP and HHCP impact categories showed similar contributions across system components, with the exception of slightly lower EUP contributions for the space and water heating system (Figure 4), and a slightly higher HHCP contribution for water treatment (Figure 5). Larger EUP and HHCP impact contributions from the wastewater treatment systems were observed for DES and BAU, particularly as water reuse volumes increased across the options, attributable to increases in operational needs. All scenarios indicated lower impacts relative to the overall contributions for the MBR systems compared to traditional centralized wastewater treatment.

The space and water heating system for the DES scenarios yielded lower GWP and HHCP impacts as compared to the BAU scenarios. However, slightly higher EUP values for the DES scenarios were attributed to natural gas requirements from the sewage heat recovery system to meet community district heating needs.

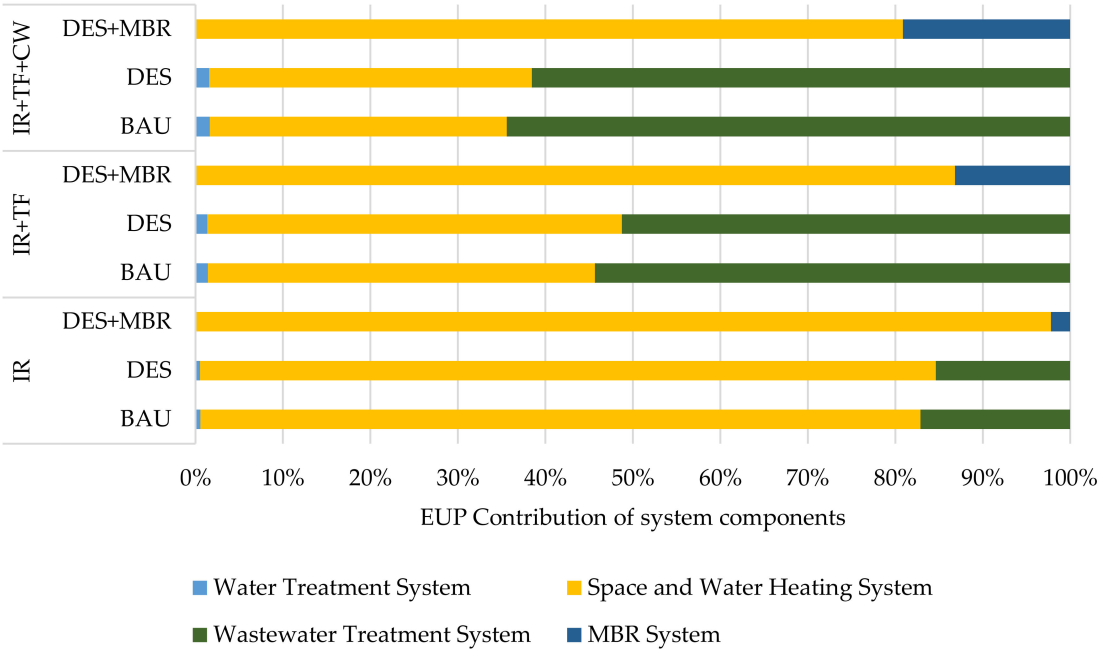

Figure 4. EUP impact contribution of system components for the three study scenarios and water reuse options: business as usual (BAU), district energy system (DES), and district energy system with membrane bioreactor (DES+MBR); irrigation (IR), toilet flushing (TF), and clothes washing (CW).

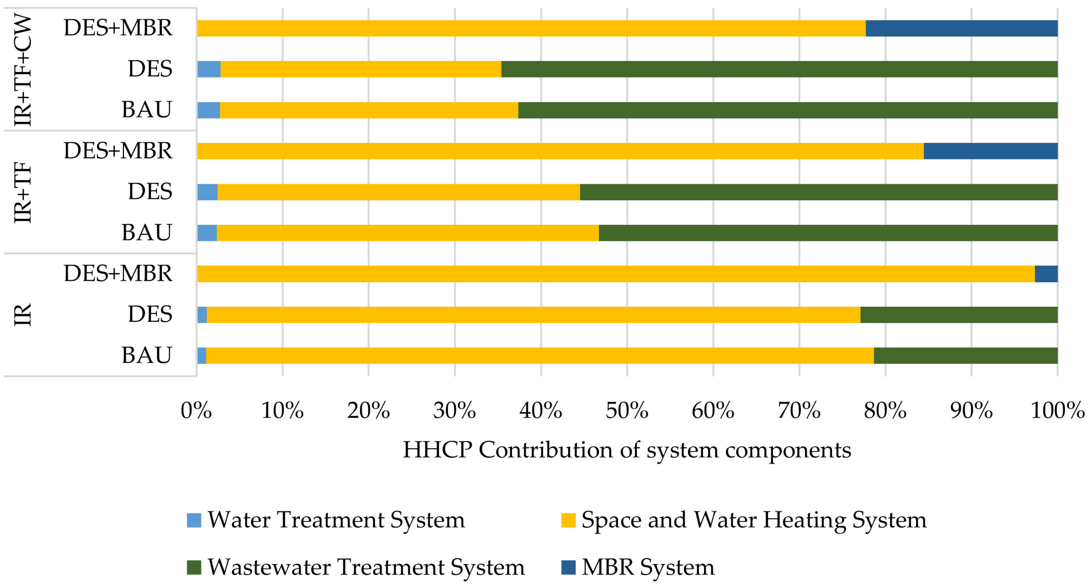

Figure 5. HHCP impact contribution of system components for the three study scenarios and water reuse options: business as usual (BAU), district energy system (DES), and district energy system with membrane bioreactor (DES+MBR); irrigation (IR), toilet flushing (TF), and clothes washing (CW).

3.3. Sensitivity Analysis—Alternative Electricity Mixes

The GWP values were highest in the BAU scenarios, with lower impacts in the 2040 and renewable electricity mixes relative to the default (fossil fuel) electricity mix. Impacts increased with rising water reuse volume across the different applications modelled (Figure 6a). However, even with the largest water reuse volume (IR+TF+CW), using a renewable electricity mix resulted in lower impact values than in the case of the IR+TF water reuse volume, using either a 2018 or projected 2040 electricity mix.

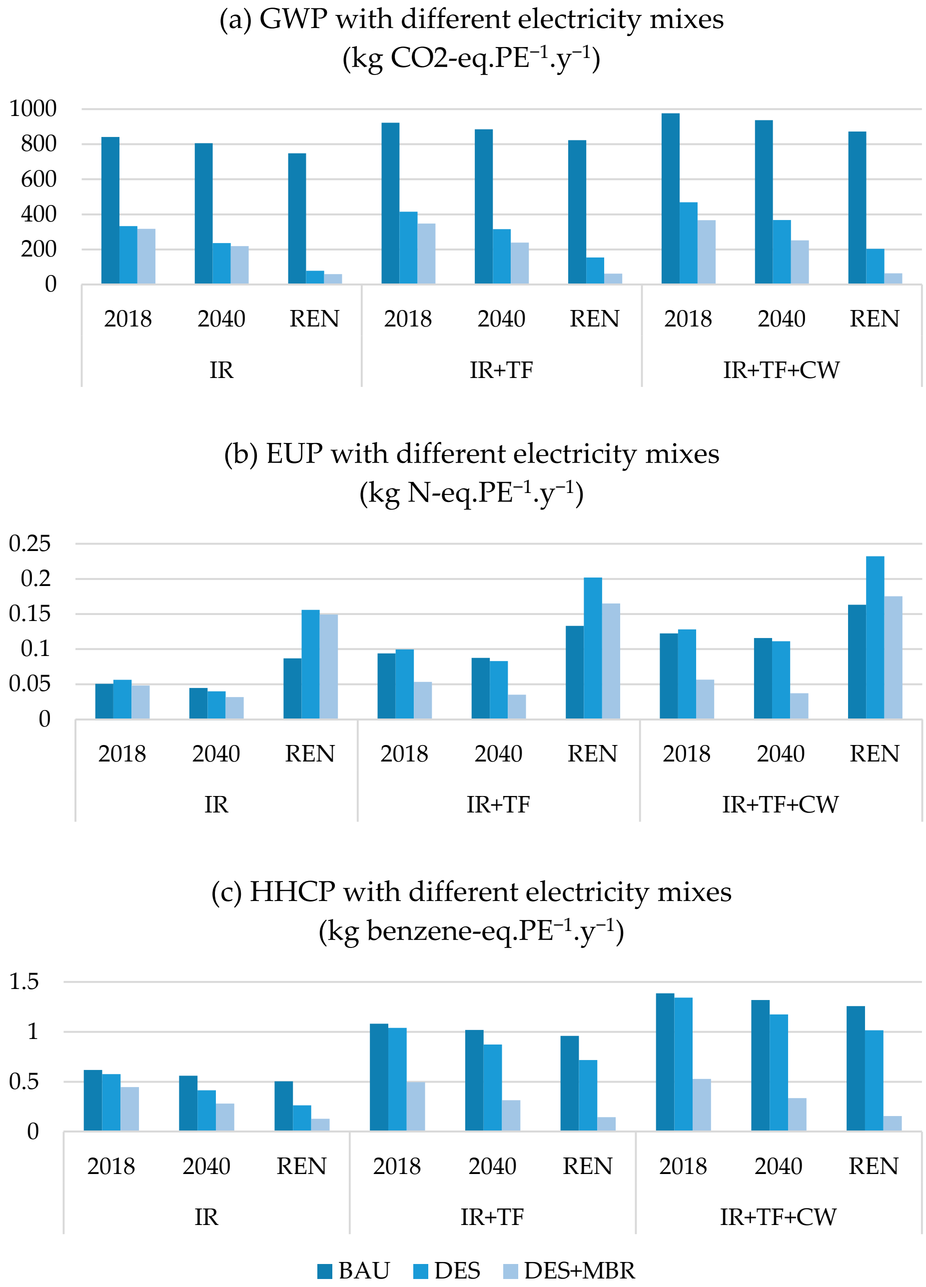

Figure 6. Impact categories (**a**) GWP, (**b**) EUP, and (**c**) HHCP for different electricity mixes across the three systems modelled: 2018, 2040, and renewable (REN); irrigation (IR), toilet flushing (TF), and clothes washing (CW).

A decreasing trend for HHCP was also observed for the 2040 and renewable electricity mixes (Figure 6c). However, the DES+MBR scenarios show a >50% decrease in HHCP compared to the BAU and DES scenarios, particularly as water reuse volumes increased, as energy consumption from conventional water and wastewater treatment processes was avoided.

The renewable electricity mix was associated with larger EUP values for all three scenarios compared to 2018 and 2040 electricity mixes. As EUP generally increased with greater water reuse volumes, the DES+MBR scenarios remained lower for the 2018 and 2040 electricity mixes due to the reduction of water and wastewater treatment processes. The greater impact associated with the renewable electricity mix was attributable to the 18.4% use of biomass/biogas compared to the 2018 and 2040 electricity mixes at 2.4% and 1.9%, respectively.

4. Discussion

In striving for improved provision of urban water services, various options for hybrid centralized/distributed systems have been identified, some using novel technologies [42]. However, most of these innovative solutions have not been considered economically feasible, and there are significant practical challenges in adapting them to major city centers [43,44]. Here, we presented a modular approach to facilitate reconfiguration of water service infrastructure. The core interest in the current study was the environmental impact of a transitional design whereby sewage heat recovery is used for district heating alongside community-based wastewater treatment for water reuse. Such transitional designs may facilitate more realistic applications of innovative technologies.

Our results indicate that the use of a sewer-heat-recovery-based district heating system integrated with community-based wastewater treatment and water reuse can reduce environmental (GWP and EUP) and human health (HHCP) impacts by over half in comparison with conventional systems. Since space and water heating systems comprise over 70% of the GWP for conventional systems, the focus on shifting to district-energy-based systems facilitates the initial step in optimizing environmental performance and sustainability for community structures. Based on the default electricity mix, the largest contributors to the environmental impact indicators of the study are electricity and natural gas consumption. Yet, even with a transition to renewable energy sources, DES and local water reuse options appear more advantageous than BAU systems (Figure 6).

Compared to the BAU scenarios, impacts for DES applications were reduced due to lower overall energy and chemical use. While the MBR system showed higher energy requirements compared to conventional wastewater treatment systems, overall impacts were still lower because of the lower chemical consumption (alum and polymer) associated with MBR and the reduction of tap water production through water reuse. MBR-associated scenarios also achieved lower life cycle impacts for the construction phase compared to BAU, as previously noted [45,46].

The sensitivity analysis showed that environmental and human health impacts are largely dictated by variations in the chosen electricity mixes. Greater EUP for the renewable electricity mix, for instance, was attributed to the higher use of biogas/biomass electricity production versus the conventional and projected electricity mixes. The EUP would otherwise be much lower using DES+MBR applications, due to lower overall impacts from the electricity mix.

Sewage-heat-recovery-based district heating systems can yield additional environmental savings with community-based wastewater treatment and water reuse, particularly when a greater volume of wastewater is utilized. Conventional wastewater and water treatment systems consistently demonstrated over 20% increases in EUP and HHCP contributions from IR to IR+TF and from IR+TF to IR+TF+CW, while the use of community-based MBR treatment showed consistently lower impacts in the three water reuse scenarios examined, making it a sustainably effective alternative to the use of conventional drinking water.

Water reuse applications for irrigation, toilet flushing, and clothes washing for the hypothetical community in the DES+MBR applications were consistently the most effective across the three impact categories examined. While studies have already shown the environmental favorability of district heating systems compared to conventional systems [6,26], research in community-based wastewater treatment and reuse is at an early stage of development [28,47]. The reduction in impacts from sewage-heat-recovery-based district heating systems can yield additional environmental savings with community-based wastewater treatment and water reuse, particularly when a greater volume of wastewater is used in the process.

Overall, integrating water reuse in environmentally optimized solutions like district heating systems appears to facilitate thinking towards community-based approaches and more localized sustainability. As demonstrated here, current sewage systems can thus be utilized to decrease environmental impacts, while the shift towards decentralized systems may be planned for future growth/rebuilds accordingly.

4.1. Limitations

The heat recovery potential of urban wastewaters varies significantly between regions because of different environmental conditions and sewage characteristics [48,49]. Changes in the structure of sewage systems, in addition to variations in peak water consumption, must be identified on a case-to-case basis to evaluate heat recovery potential. This study was limited to the construction and operational phases, and excluded direct operational emissions of individual system processes. Future studies should consider modified material and waste transport processes unique to the study region.

4.2. Future Research

4.2.1. Other Resource Recovery and Future Technologies

Increased methane production potential and COD (chemical oxygen demand) removal efficiency using anaerobic membrane bioreactors (AnMBR) for sewer mining may be studied to optimize the environmental performance of sustainable community-based systems [50], however, upflow anaerobic sludge blanket (UASB) technology may have a better environmental performance, due to the associated environmental impacts of AnMBR membrane fouling [51]. Various other technologies based on circular economy thinking may be modelled to further improve the environmental performance of sanitation options, such as nutrient recovery [52,53], biogas production from urban organic waste [54,55] and blackwater [17,56–58], and water reuse from source-diverted greywater [59].

Other renewable energy sources, such as geothermal, can also be considered for a district heating system [60], such as that of the planned Blatchford development in Edmonton, Alberta. The development aims to use geothermal and sewage heat recovery for its district energy system. This study provides the framework to evaluate such systems before and after full-scale construction and operation is complete to better understand the applicability of such technologies in other similar regions and conditions.

Water and energy conservation can be improved with UV-LED disinfection systems [61,62], an alternative to the chlorine disinfection techniques that form the basis of conventional tap water production systems. While there are benefits of using chlorine disinfection, such as the provision of residuals in the water distribution system [63], more effective controls may be achieved using UV technologies [61–64] for fit-for-purpose water reuse.

4.2.2. Scales of Implementations

Future investigation should consider the environmental performance of transitional alternatives for different sizes of communities to identify the optimal extent of each application. Understanding the environmental impacts of various community scales based on density or area may better inform the feasibility of full-scale applications of these technologies. Comparative assessments based on different scales of application have been undertaken using LCA for greywater treatment technologies [28,65], municipal wastewater systems [66], and combined heat and power plants [67].

4.2.3. Comparisons of Transitional Designs

The framework presented should also be applicable to evaluate the environmental performance of alternative water and district heating innovations for both greenfield and infill developments. Additional options for transitional designs can be assessed based on the needs and available resources for specific regions. Sewage heat recovery designs are largely dictated by sewage properties like flow and temperature, and suitable technologies that continue to evolve for full-scale applications [49].

5. Conclusions

Integrated sewage heat recovery and community-based wastewater treatment offers a realistic means of applying a transitional approach to achieving a circular economy. The ability to harness existing energy from existing trunk sewers to heat a community showed improved environmental performance compared to conventional systems.

The main conclusions from the study are:

- Compared to BAU centralized water services, the lowest impacts modeled were for scenarios with community-based MBR wastewater treatment and water reuse.
- Conventional space and water heating components typically contributed the most to GWP values among the system components. A sewage-heat-recovery-based district heating system offered the best environmental performance of the systems modelled.
- Integrating MBR wastewater treatment and water reuse into a district heating schema provides additional environmental savings at a community scale, and under future scenarios utilizing renewable energy mixes.

The framework developed should prove useful for future analyses of other emerging wastewater treatment and resource recovery technologies and can be used to evaluate the environmental performance of the systems used for other regional contexts. Additional data regarding direct operational emissions for such sewer heat recovery systems may be included in future studies to provide a more robust environmental impact analysis.

Supplementary Materials: The following are available online at http://www.mdpi.com/2076-3298/7/5/36/s1, Figure S1: General recycled water distribution system., Table S1: LCA study scenarios., Table S2: Material and operational life cycle inventory data of conventional home heating., Table S3: Southeast False Creek system—material inventory data for the sewer heat recovery and district heating system., Table S4: Conventional wastewater treatment chemical and operational inventory., Table S7: Edmonton household water consumption characteristics., Table S8: Water use/reuse scenarios., Table S9: Recycled water distribution inventory., Table S10: Life cycle inventory data of conventional tap water production., Table S11: Life cycle inventory data for MBR [a]., Table S13: Lifespan of LCA Components.

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