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A Decision Framework for Designing Sustainable Wastewater-Based Resource Recovery Schemes

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Abstract: The availability of sufficient water supply is a challenge many municipalities have faced in recent decades and a challenge that is expected to intensify with time. While several choices remain for selecting alternatives to freshwater sources, water reclamation offers an opportunity for sustainable resource recovery. Nonetheless, tradeoffs exist in the selection of the most sustainable technology for recovering resources from wastewater when long-term impacts are taken into consideration. This article investigates the factors influencing the environmental and economic impacts of resource recovery technologies through the analysis of life cycle environmental and economic impact case studies. Key characteristics were extracted from life cycle assessment and life cycle cost case studies to evaluate the factors influencing the sustainability of the resource recovery systems. The specific design parameters include the type of resources to be recovered, technology utilized, scale of implementation, location, and end users. The design of sustainable resource recovery systems was found to be largely driven by scale, location (e.g., as it pertains to the energy mix and water quality restrictions), and the scope of the system considered. From this analysis, a decision framework for resource recovery-oriented wastewater management was developed and then applied to an existing case study to demonstrate its usability.

Keywords: wastewater; water reclamation; resource recovery; sustainability

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1. Introduction

Water scarcity has affected 2.3 billion people around the globe [1], which poses a grand challenge to achieve Sustainable Development Goal (SDG) 6 "ensure availability and sustainable management of water and sanitation for all". It also presents critical stressors on our communities as water is needed to maintain human health, agriculture, and many industrial processes. Our communities have been further challenged by the increased intensity of weather events exacerbated by climate change [2,3]. Self-sufficiency can offer empowerment for members of a community [4–6] and plays an even more critical role during disaster situations [7,8]. Fortunately, wastewater serves as a valuable resource that can provide water, energy, and nutrients [9,10], amongst other resources such as precious metals [11,12], to our communities. The true cost of resource recovery, however, must be considered to avoid shifting impacts from one impact category to another.

To evaluate the environmental and economic impacts of a technology, Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) are often employed. By applying these techniques during the design phase, a multi-criteria impact assessment can be conducted to inform strategies for environmental impact and potential cost savings over the system's lifetime. The life cycle impacts of water and wastewater systems have been studied extensively, as evidenced by previously published review articles [13–16]. The methods implemented for evaluating the sustainability of resource recovery systems have been investigated in prior reviews [14,15]. Additionally, frameworks have been developed to guide decision making as it relates to resource extraction from sanitation systems [17] and the design of centralized water reclamation systems in highly urban environments [18].

The previous studies show that the economic and environmental impacts of resource recovery systems are highly driven by the scale of implementation [15,19,20], selection of treatment technology and treatment train [15,19], location and topography [20], and end uses [21,22]. Several previous studies have focused on different aspects of the design for wastewater-based resource recovery systems (e.g., treatment techniques and system scales), with the purpose of providing guidance for municipalities. However, lack of a systematic decision framework that can be used by a variety of stakeholders to plan for the most sustainable resource recovery scheme in their water service area is evident.

Given the trends in the environmental and economic impacts of wastewater-based resource recovery systems [10], the objective of this article is to provide a decision framework for sustainable resource recovery as stakeholders choose *how* to recover resources from their wastewater systems and decide *where* to send those resources to. This framework will serve to facilitate the decision-making process for the design of sustainable resource recovery systems and can be applied by researchers and municipalities alike. The article seeks answers to the following research questions: (1) What factors are driving the greenhouse gas emissions and costs of resource recovery systems? and (2) How can prior case studies inform the decision-making process? An analysis of existing life cycle case studies is conducted to support the development of this framework. The scope of this research considers water, energy, and nutrient recovery from domestic wastewater.

2. Materials and Methods

Life cycle environmental and economic impact case studies were analyzed in this research for wastewater-based resource recovery systems. In all, 21 water reclamation, 26 energy recovery, and 29 nutrient recovery life cycle assessments (LCAs) were analyzed (see the Appendix A for the list of articles). The analysis of the environmental impact assessments focused on greenhouse gas (GHG) emissions as this impact category was consistently reported across the LCAs. For the life cycle cost (LCC) case studies, 16 water reclamation, 10 energy recovery, and 10 nutrient recovery case studies were assessed. Key characteristics were extracted from these data samples to conduct the statistical analysis as described in the sections that follow.

2.1. Resource Recovery Processes

2.1.1. Water Reclamation

The characteristics that were extracted from the water reclamation case studies included the scale of implementation, the location of the system, the technology used for resource recovery, the end use of the reclaimed water, water quality parameters, the life cycle phases considered in the assessment, and the physical scope of the study (e.g., treatment and distribution). A variety of wastewater treatment trains were used within the case studies and they were categorized by secondary and tertiary treatment processes (see Figure 1a). Activated sludge (AS), absorption/bio-oxidation (AB), oxidation ditch (OD), anaerobic/anoxic/oxic (A2O), membrane bioreactor (MBR), upflow anaerobic sludge blanket (UASB), and septic tank (ST) are treatment technologies based on suspended growth. Rotating biological contactor (RBC) is a type of attached growth technology. Wastewater stabilization ponds and vertical flow constructed wetlands (VFCW) are considered lagoon-based technologies. These aforementioned treatment technologies are categorized as secondary biological treatment (2^{nd}Bio). Tertiary treatment technology is applied after secondary treatment (2^{nd}Bio) to obtain a better effluent quality for water reuse. Enhanced nitrogen and/or phosphorus removal are tertiary biological treatment processes (3^{rd}Bio). Flocculation, coagulation, adsorption (e.g., granular activated carbon [GAC]), and filtration (e.g., sand filtration [SF] and media filtration [MF]) are categorized as tertiary physical and/or chemical treatment (3^{rd}PC). Reverse osmosis (RO), ultrafiltration (UF), and microfiltration (MF) are categorized as membrane filtration (3^{rd}M).

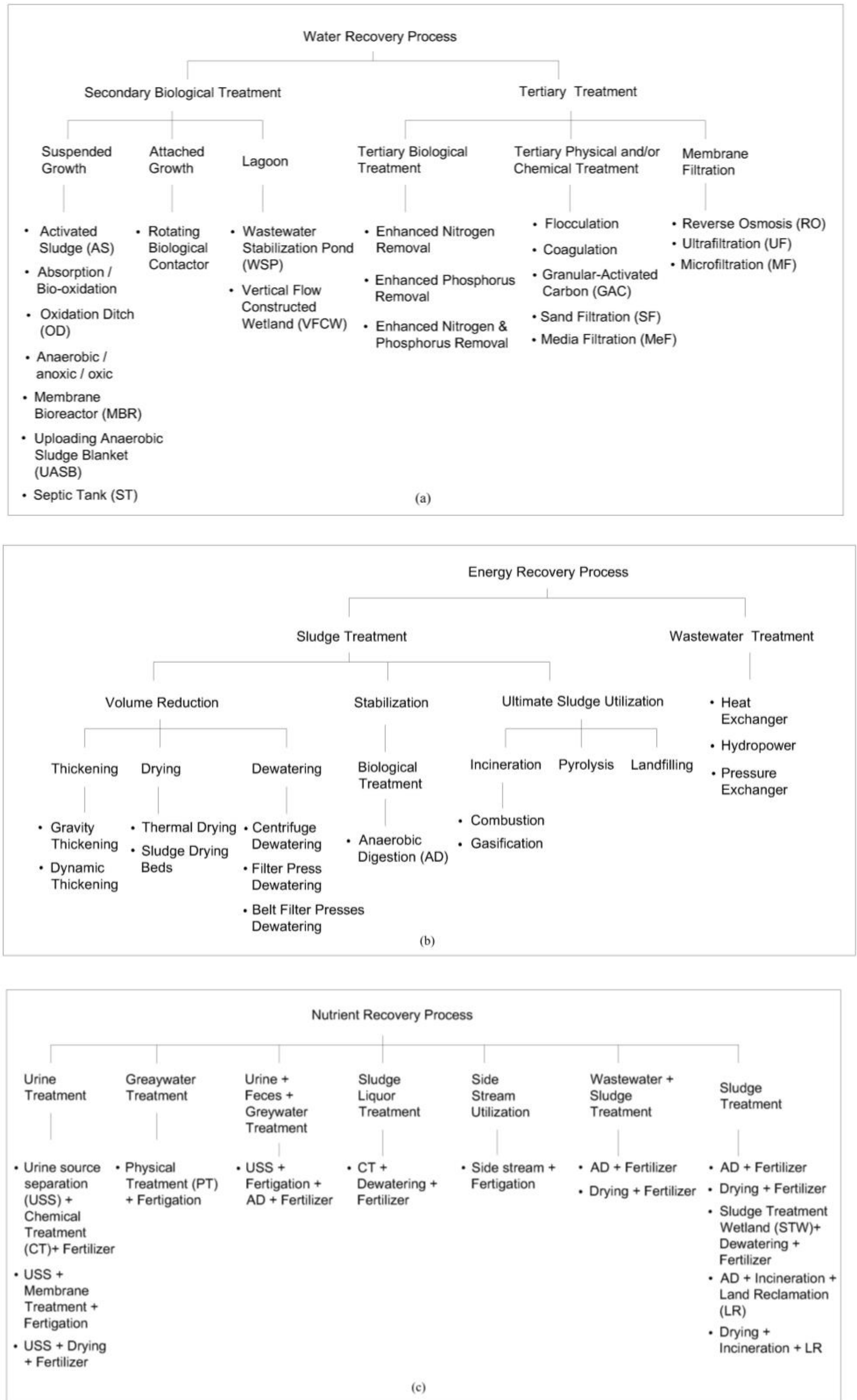

Figure 1. The treatment and/or resource recovery processes considered for (**a**) water reclamation; (**b**) energy recovery; and (**c**) nutrient recovery.

2.1.2. Energy Recovery

Energy, including electricity and heat, can be recovered from sludge treatment through anaerobic digestion (AD), incineration, and composting, and from wastewater through a heat exchanger, hydropower, or pressure exchanger (Figure 1b). The sludge treatment process may include a volume reduction process (V) and stabilization (S) before transferring the sludge for its end use. Gravity thickening, dynamic thickening, thermal drying, sludge drying beds, centrifuge dewatering, filter press dewatering, and belt filter press dewatering are available technologies for volume reduction. Anaerobic digestion, as a reliable stabilization process for biological treatment of the produced sludge, is utilized in most of the articles analyzed. Composting, pasteurization, incineration, combustion, gasification, pyrolysis, and landfilling are the selected processes of ultimate sludge utilization. The sludge utilization step was categorized as either composting, incineration, pyrolysis, or landfilling.

2.1.3. Nutrient Recovery

Nutrient recovery processes include the treatment of the source (e.g., wastewater, urine, sludge) and the ultimate utilization of sludge (Figure 1c). Fertilizer, fertigation, and land reclamation material are common products of nutrient recovery. Nutrient recovery processes were grouped into different sources, including urine, greywater, sludge liquor, side stream, sludge, and a combination of urine, feces, and greywater. For urine as a nutrient recovery source, the available treatment trains are: (1) urine source separation (USS); (2) chemical treatment (Chem), membrane treatment (M), or drying (Dry); and (3) fertilizer or fertigation. Nutrients in greywater can be recovered by a physical treatment process and used for fertigation. For the combination source of urine, feces, and greywater, two recovery processes are considered: (1) USS and fertigation, or (2) AD and fertilizer. Sludge liquor contains an abundance of nutrients and can be recovered as a fertilizer through chemical treatment (Chem) and dewatering (Dew) processes. The side stream of a wastewater treatment plant is a good source for fertigation. AD + fertilizer and Dry + fertilizer are two processes to recover nutrients in wastewater and sludge. Nutrients in sludge can be recovered through four processes of: (1) sludge treatment wetland (STW) + fertilizer; (2) STW + Dew + fertilizer; (3) AD + incineration + land reclamation (LR); and (4) Dry + incineration + LR.

2.2. Statistical Analysis

The effluent quality of reclaimed water for different categories of reuse (non-potable reuse [NPR], indirect potable reuse [IPR], or direct potable reuse [DPR]) must meet water quality regulations. Therefore, the effluent quality and removal rate are considered in the correlation analysis. The representative water quality parameters consist of biological oxygen demand (BOD), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS). The influent and effluent water quality data are obtained from the literature identified in Table A1 of the Appendix A, and the removal rates are calculated quantities.

A bivariate correlation analysis was conducted in Minitab 19 with the life cycle case study data. More specifically, the correlation analysis included the evaluation of relationships between GHG emissions, scale, cost, treatment trains, effluent water quality parameters, removal rates, the type of sewage system, country, and national electrical greenhouse gas emissions. The absolute value of the correlation coefficient, r, closer to 1.0 shows a stronger correlation between variables. The outcomes of the correlation analysis with a p-value less than or equal to 0.05 are highlighted in Table A2 of the Appendix A.

Descriptive statistics were analyzed for sub-sets of GHG emission data within each resource category (water, energy, and nutrients). As the data were found to not be normally distributed, statistically significant differences in the reported environmental impacts were evaluated using the Mann–Whitney U test. Samples of GHG emission data were compared with respect to the case study location, treatment train, reuse type, life cycle phases, and system scope. The U statistic was calculated for pairwise comparisons (see Equations (1) and (2)) where R_1 and R_2 is the sum of the ranks for each data sample, and n_1 and n_2 represent the number of samples. The smaller U value (Equation (3)) was compared to the critical U value when the data samples were less than 20. When the number of samples (n_1 and n_2) exceeded 20, the null hypothesis was rejected for z-scores (see Equation (4)) that were less than −1.96 or greater than 1.96 (a two-tailed test).

$$U_1 = R_1 - \frac{n_1 \times (n_1 + 1)}{2} \quad (1)$$

$$U_2 = R_2 - \frac{n_2 \times (n_2 + 1)}{2} \quad (2)$$

$$U = \min(U_1, U_2) \quad (3)$$

$$z = \frac{U - \frac{n_1 \times n_2}{2}}{\sqrt{n_1 \times n_2 \times \left(\frac{n_1 + n_2 + 1}{12}\right)}} \quad (4)$$

3. Factors Influencing Life Cycle Impacts

This section reports on the outcomes of the correlation analysis to identify the extent to which specific factors influenced the life cycle GHG emissions and LCC of wastewater-based resource recovery systems.

3.1. Correlation Analysis—Water Reclamation

The factors considered for water reclamation systems include the target end use (NPR, IPR, or DPR), the water quality of the influent and effluent, the wastewater treatment process (in most cases, several options can achieve a similar effluent water quality), the redundancy in the treatment train, the design capacity of the treatment system, and the operating scale [15,19,20]. Factors that influence the pumping energy for reclaimed water distribution include the flowrate, the size of the service area for the end users, and the topography of the region [19,20,23]. However, since these parameters were rarely reported consistently in the articles reviewed, this was outside of the scope of this manuscript.

3.1.1. Treatment Train

Specific capital and/or O&M cost (USD 2019/m^3) had a high positive correlation to GHG emissions (kg CO_2-eq/m^3) (r = 0.592, p = 0.026). This demonstrates that systems with high costs tended to result in high GHG emissions, which may be attributed, in part, to the high energy consumption of wastewater treatment technology and distribution pumps [19]. In contrast, specific costs and GHG emissions are both negatively correlated to scale (r = −0.535 and r = −0.453, respectively). Accordingly, large scale systems tend to cost less and produce less GHG emissions on a per unit basis, and thus benefit from economies of scale [15].

3.1.2. Water Quality

The target effluent water quality and removal rate aids in the determination of feasible treatment trains for water reclamation systems. Figure 2 shows the influent and effluent water quality parameters treated by various treatment trains. BOD, COD, TN, and TP were selected as they are representative of key characteristics of the wastewater influent and effluent. Only four treatment trains are discussed due to the limited availability of water quality information. The difference in the influent water quality could be due to variations in the composition of the water consumers (e.g., residential, industrial, or utilities) and the characteristics of the communities across the case studies [21,22,24]. Minor variations are observed in the effluent water quality (see Figure 2); TN and TP in the effluent is predominantly less than 10 mg/L, which aligns with many state regulations for water reuse [25]. Other differences may be attributed to variations in the influent water quality, reuse requirements, and the treatment applied.

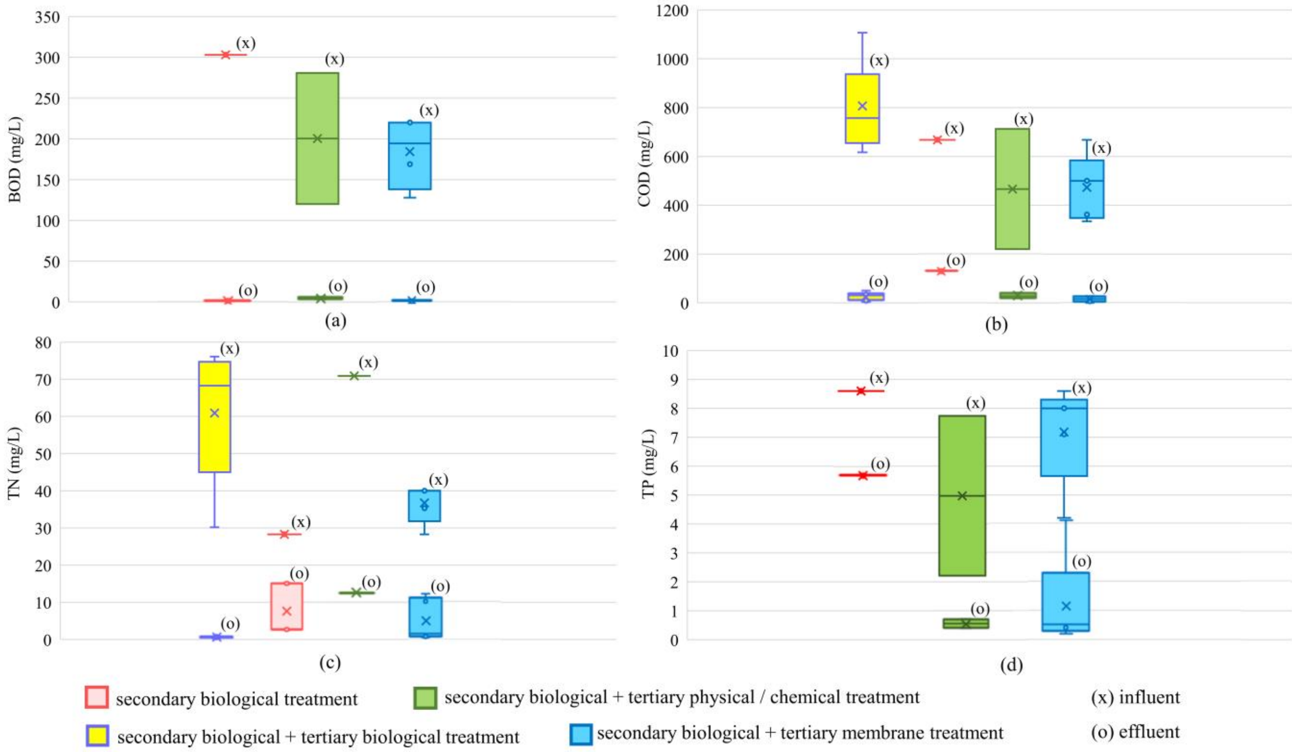

Figure 2. Water quality of the influent and effluent relative to the treatment technologies: (**a**) biological oxygen demand (BOD), (**b**) chemical oxygen demand (COD), (**c**) total nitrogen (TN), and (**d**) total phosphorus (TP).

The water quality parameters were found to have a strong association to the treatment train selected. For example, although the effluent BOD and COD were generally similar for the processes achieving tertiary treatment, biological processes (2^{nd}Bio + 3^{rd}Bio) tended to be selected to treat higher COD influent (r = 0.628 and p = 0.002). Additionally, the selection of this treatment process (2^{nd}Bio + 3^{rd}Bio) was correlated with the TN removal rate (r = 0.518 and p = 0.019). Figure 2 shows that this treatment train was used to treat higher levels of TN in the influent, with an average of approximately 60 mg/L, and provided the best effluent quality among the treatment trains. For total phosphorus management, the trains with tertiary treatment (2^{nd}Bio + 3^{rd}M, 2^{nd}Bio + 3^{rd}PC) had lower effluent TP overall. Significant variation was observed for effluent TP for tertiary membrane treatment (2^{nd}Bio + 3^{rd}M), and thus no correlation between TP and the treatment technologies was identified for the case studies analyzed. When the treatment systems are classified as centralized and decentralized systems, effluent TP was found to be higher for decentralized systems (r = 0.722 and p = 0.004) relative to centralized systems (r = −0.722 and p = 0.004). Table A2 summarizes the outcomes of the correlation analysis in the Appendix A.

3.2. Correlation Analysis—Energy Recovery

Various processes are implemented for wastewater-based energy recovery (e.g., anaerobic digestion, incineration, thermal energy recovery, and hydropower generation). Given this diversity, some factors are more specific to the technology, although the processing rate has been found to influence the resources consumed for energy recovery for most of these systems [15].

Cost (USD 2019/MJ) was found to be negatively correlated to the rate of biosolids processing (r = −0.839 and p = 0), demonstrating the influence of economies of scale. Cost was also negatively correlated to recovery via anaerobic digestion and landfilling (AD + landfilling, r = −0.331 and p = 0), indicating unit costs tended to be lower when this type of energy recovery system was implemented. GHG emissions and AD + landfilling were also correlated, but to a lesser degree (r = 0.274 and p = 0.015), which demonstrates that the treatment technology was not the only factor influencing the GHG emissions.

Other factors that are expected to influence the sustainability of energy recovery systems include climate and topography for thermal energy recovery systems and hydropower generation systems, respectively. For example, Ravichandran et al. [26] evaluated the influence of local conditions on the sustainability of drain water heat recovery systems (DWHRSs) and found it was environmentally and economically beneficial to implement DWHRSs in cold/very cold climates. Similarly, hydropower generation is known to be a function of headloss (influenced by topography and flow rate); however, only a few studies have been conducted [27,28] on the sustainability of wastewater-based hydropower generation systems.

3.3. Correlation Analysis—Nutrient Recovery

For nutrient recovery, the source being processed (i.e., urine, wastewater and sludge, biosolids) highly influenced treatment technology selection (urine treated by urine source separation (USS) and chemical treatment for fertilizer production, r = 0.896, p = 0). Treatment technologies (USS and AD for fertigation and fertilizer) were also correlated with scale (m^3/day) (r = 0.539, p = 0). No correlation was identified for cost; however, GHG emissions were found to be correlated to the source being processed. Specifically, GHG emissions are positively correlated to nutrient recovery from wastewater and sludge (r = 0.28 and p = 0.001), while emissions are negatively correlated to urine as the source for nutrient recovery (r = −0.194 and p = 0.024). This indicates that more GHGs are released when trying to recover nutrients once it has reached an offsite treatment facility, relative to trying to recover nutrients from the source (urine). This finding is in alignment with work from Ishii and Boyer [29] and Landry and Boyer [30] who investigated the life cycle impacts of recovering nutrients via USS and struvite precipitation. A summary of feasible recovery technologies (for water, energy and nutrients) at varied scales can be found in Diaz-Elsayed et al. [10].

4. Informing the Selection of Treatment Technologies

4.1. Life Cycle Costs

The average Specific Net Present Value (*SNPV*) [19] is calculated using Equations (5) and (6) where *NPV* represents the net present value of the system, CF_t the cashflows for time period t, i the discount rate, n the lifespan of the system, and P_t the resources recovered during time period t. Descriptive statistics of the SNPV for the resource recovery systems are presented in Table 1. For water reclamation, biological (2ndBio + 3rdBio) and physical/chemical processes (2ndBio + 3rdBio + 3rdPC) are the least expensive relative to other treatment trains. When membrane treatment is applied, a significantly higher SNPV is attained as 2ndBio + 3rdM and 2ndBio + 3rdM + 3rdPC had an average cost of $2.68 and $7.23 USD 2019/$m^3$, respectively. One benefit to consider for selecting a membrane treatment technology is the improved effluent water quality that can be achieved as discussed in Section 3.1.2.

$$NPV = \sum_{0}^{n} \frac{CF_t}{(1+i)^t} \quad (5)$$

$$SNPV = \frac{NPV}{\frac{1}{n}\int_0^n P_t dt} \quad (6)$$

Table 1. The Specific Net Present Value (SNPV) for resource recovery processes converted to USD 2019 per unit of resource recovered.

Scope of Recovery	Recovery Type or Treatment Process		Mean SNPV	Standard Deviation	Maximum SNPV	Minimum SNPV	No. of Samples
Water	Secondary Treatment	Tertiary Treatment	[USD/m³]	[USD/m³]	[USD/m³]	[USD/m³]	[-]
Wastewater	Bio	N/A	2.90	3.29	12.23	0.05	39
	Bio	Bio + PC	0.19	0.05	0.22	0.13	3
	Bio	PC	0.62	0.51	1.47	0.11	12
	Bio	Bio	0.21	0.05	0.32	0.13	8
	Bio	M	2.68	4.27	10.37	0.08	12
	Bio	M + PC	7.23	0.83	7.78	6.28	3
Energy	Recovery or Treatment		[USD/MJ]	[USD/MJ]	[USD/MJ]	[USD/MJ]	[-]
Wastewater	Hydropower		0.40	0.20	0.75	0.10	25
	Heat exchanger		0.006	0.003	0.008	0.004	2
Wastewater and sludge	AD + composting		0.68	0.81	2.07	0.05	5
	AD + landfilling		24.46	40.48	124.0	0.09	13
Sludge	AD + composting		0.09	0.19	0.43	−0.34	15
	AD + incineration		−0.008 [a]	0.04	0.03	−0.07	6
	AD + landfilling		0.006	0.003	0.008	0.004	2
	AD + pyrolysis		−0.085	n/a	−0.085	−0.085	1
	V + composting		0.20	n/a	0.20	0.20	1
	V + incineration		0.005	n/a	0.005	0.005	1
	V + landfilling		0.126	0.034	0.15	0.10	2
Nutrients	Treatment	End Use	[USD/kg P-eq]	[USD/kg P-eq]	[USD/kg P-eq]	[USD/kg P-eq]	[-]
Urine	USS + Chem	Fertilizer	29.37	46.82	139.32	0.81	14
	USS + M	Fertigation	12.42	12.38	24.40	1.64	4
Sludge	AD	Fertilizer	24.83	61.22	195.35	−21.44	17
	STW	Fertilizer	6.47	0.79	7.20	5.66	4
	STW + Dew	Fertilizer	6.42	2.55	10.68	3.79	5
	AD + Inc.	LR	0.18	0.03	0.21	0.16	3
	Dry + Inc.	LR	−4.74	N/A	−4.74	−4.74	1

[a] Negative values indicate income generated or greater resource recovery relative to consumption. Abbreviations—AD: anaerobic digestion; Bio: biological; Chem: chemical; Dew: dewatering; Dry: drying; LR: land reclamation; PC: physical and/or chemical; M: membrane; STW: sludge treatment wetland; USS: urine source separation; V: Volume reduction process.

For energy recovery from wastewater and sludge, anaerobic digestion with landfilling (AD + landfilling) has the largest range of SNPV, as well as the highest standard deviation, which may be a result of differences in the transportation and labor fees for different locations. The lowest SNPV for AD + landfilling from sludge is due to greater revenue from the recovered product (e.g., electricity and district heating) than spent costs. When sludge is used as the source for resource recovery most treatment technologies resulted in a negative SNPV, which shows the benefit from recovered products. For energy recovery from wastewater as a source, hydropower generation results in a lower SNPV than heat exchangers.

Based on the case studies analyzed, nutrient recovery from urine requires a higher expense than most recovery technologies from sludge. For sludge, anaerobic digestion for fertilizer application (AD + fertilizer) is the most expensive technology with a mean SNPV of 24.46 USD 2019/kg P-eq. This is a result of high energy consumption for pelletization and transportation fees [31,32]. The large standard deviation of AD + fertilizer from sludge is due to the difference in rates for electricity, transportation, construction material, and labor across countries, including Sweden [33], China [32,34], Italy [31], and Japan [35]. Drying, incineration, and land reclamation (Dry + Inc. + LR) provided the lowest SNPV with a mean value of −4.74 USD 2019/kg P-eq. However, only one datum point is available for this technology, which introduces uncertainty for its performance.

In summary, most energy recovery technologies provide a higher revenue than water and nutrient recovery technologies considering the mean SNPV. While treatment of wastewater to some extent is required prior to releasing it back to the environment, a decision can be made on implementation of additional treatment trains to recover more resources (e.g., energy and nutrients). Once the decision is made about which resources to recover and which sources to recover from, the technology can be selected with consideration of the average SNPV shown in Table 1.

4.2. Life Cycle Greenhouse Gas Emissions

This section seeks to identify how the GHG emissions of wastewater-based resource recovery systems are influenced by varied conditions in the case studies evaluated. The correlation analysis revealed a correlation between the GHG emissions of water reclamation case studies with cost, scale, and effluent (BOD and TP) and influent (TN) water quality parameters (see Table A2 in the Appendix A). While GHG emissions and costs were positively correlated (r: 0.588, p: 0.027), economies of scale were verified as increasing the scale of implementation reduced GHG emissions (r: −0.452, p: 0.035). These findings confirm prior findings [15], and reiterate the ability for larger systems to more efficiently consume resources and lower the environmental "cost" relative to smaller systems.

GHG emissions were evaluated relative to the following factors expected to influence the environmental impact of the water reclamation systems (see Figure 3a–c): location, treatment train, reuse type, life cycle phases, and system scope. Statistically significant differences in the outcomes were identified as follows:

- Case studies in Spain resulted in lower GHG emissions than those in the USA (mean of 0.34 kg CO_2-eq/m^3 vs. 1.21 kg CO_2-eq/m^3), which aligns with the reduced dependency on fossil fuels for the Spanish electrical energy mix (0.179 kg CO2-eq/MJ for Spain [36–38], vs. ~0.40 kg CO2-eq/MJ for the USA [36,38–40];
- The inclusion of the construction phase in the LCAs resulted in significantly higher impacts relative to only considering the O&M plus disposal phases (1.62 kg CO_2-eq/m^3 and 0.61 kg CO_2-eq/m^3, respectively);
- In comparing the scope of the water reclamation system, the inclusion of the collection stage resulted in a statistically significant increase in GHG emissions relative to the consideration of only the treatment and water reuse stages (mean: 0.90 kg CO_2-eq/m^3 vs. 0.33 kg CO_2-eq/m^3);
- No statistically significant difference was observed in GHG emissions relative to the reuse type or treatment train. This may be attributed to the dominance of the previously identified factors (i.e., energy mix, life cycle phases, and system scope).

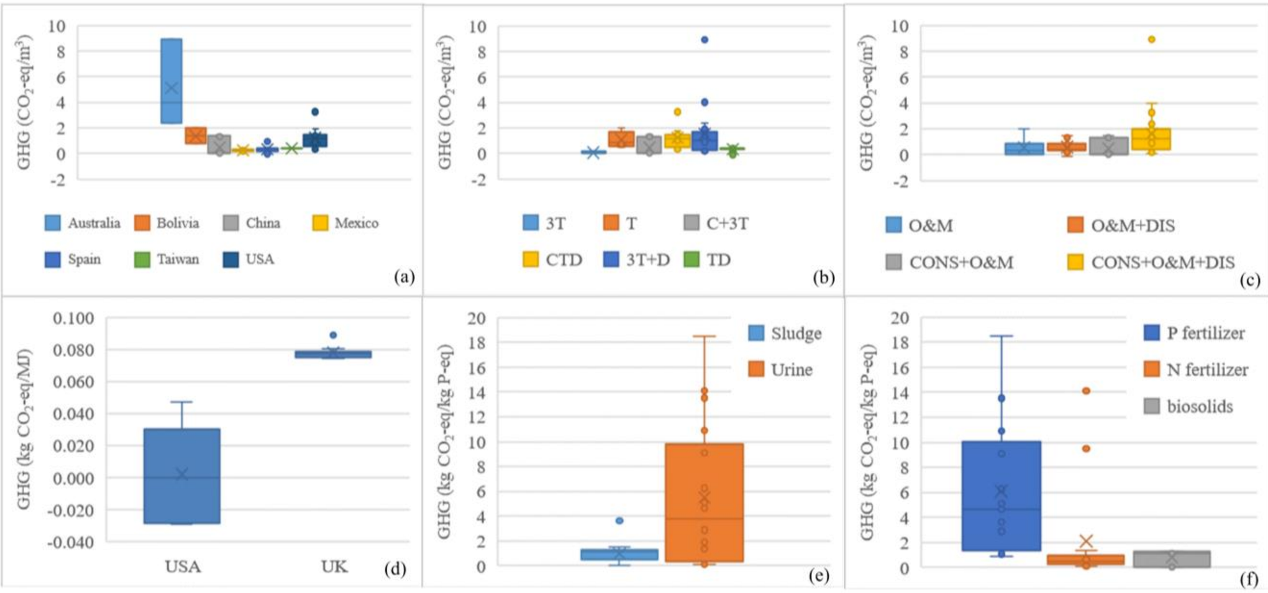

Figure 3. GHG emissions per volume of reclaimed water with reference to (**a**) case study locations; (**b**) treatment stages; and (**c**) life cycle phases; (**d**) GHG emissions per MJ of energy recovered for the USA and UK scenarios; and GHG emissions for nutrient recovery case studies with reference to (**e**) the nutrient source and (**f**) reuse type. Abbreviations—3T: Tertiary Treatment; C: Collection; CONS: Construction Phase; CTD: Collection, Treatment, and Distribution; D: Distribution; DIS: Disposal Phase; N: Nitrogen; O&M: Operation and Maintance Phase; P: Phosphorus; T: Treatment; TD: Treatment and Distribution; UK: United Kingdom; USA: United States of America.

Few LCAs for wastewater-based energy recovery were available, so a comparative analysis was conducted that evaluated data from the following scenarios: (1) natural gas production from anaerobic digestion and landfilling in the USA that considered the construction, O&M, disposal, and recovery life cycle phases for resource recovery from wastewater and biosolids; and (2) a thermal heat exchanger in the United Kingdom that considered the O&M, disposal, and recovery life cycle phases for resource recovery from wastewater. Both sets of scenarios were small-scale case studies, with the former varying from 0.189 to 37.85 m^3/day and the latter ranging from 3.12 to 12.5 m^3/day. The USA scenarios had higher variability (standard deviation: 0.03 vs. 0.004 kg CO_2-eq/MJ of energy recovered), but resulted in lower GHG emissions on average (0.002 vs. 0.08 kg CO_2-eq/MJ) (see Figure 3d). This suggests that high recovery efficiency with reduced environmental impacts can be realized when targeting energy recovery from biosolids, which aligns with its implementation across many WWTPs [10,41].

In a similar vein, the nutrient recovery case studies suggested that, on average, lower GHG emissions resulted from nutrient recovery from biosolids (0.97 kg CO_2-eq/kg P-eq) relative to urine (5.50 kg CO_2-eq/kg P-eq), as shown in Figure 3e. Moreover, the GHG emissions for nitrogen fertilizer tended to result in lower impacts relative to phosphorus fertilizer (mean of 2.09 vs. 5.79 kg CO_2-eq/kg P-eq). The null hypothesis could not be rejected for the comparative analyses of nutrient recovery case studies relative to the life cycle phases, location, degree of centralization, or treatment train with the data acquired.

5. A Framework for Resource Recovery

The framework serves to aid the decision-making process for the design of wastewater-based resource recovery systems. It was developed with guidance from practitioners from the Hillsborough County Florida Public Utilities [42], and is summarized in Figure 4.

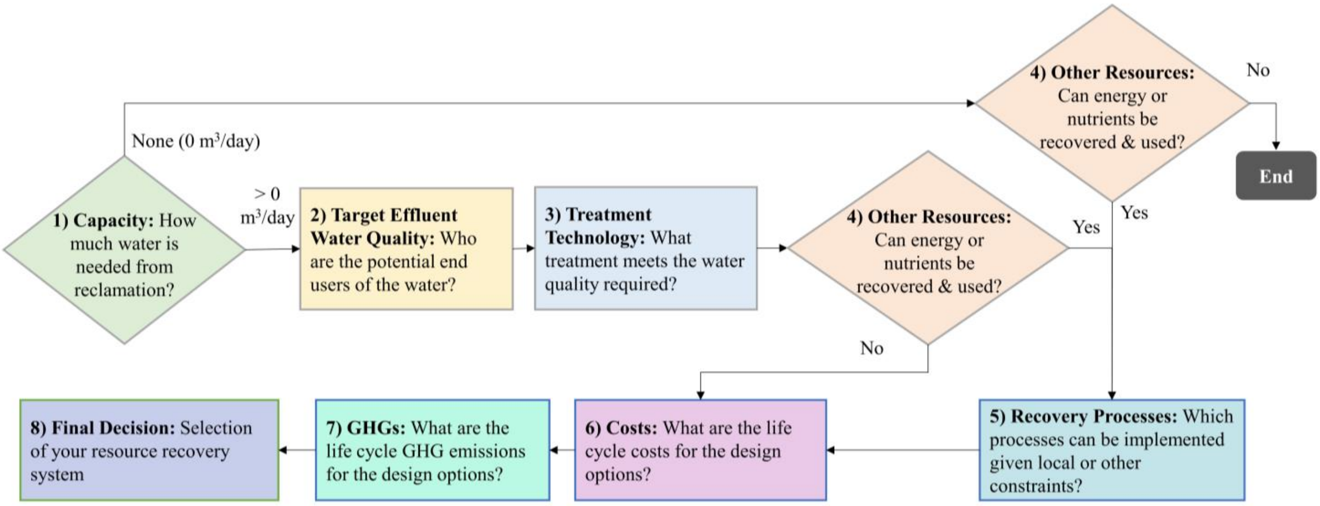

Figure 4. The decision framework for wastewater-based resource recovery. It is recommended to reference Section 3.1 for Steps 2 and 3, Figure 5 for Step 4, Section 4.1 for Step 6, and Section 4.2 for Step 7. Abbreviations—GHG: Greenhouse Gas.

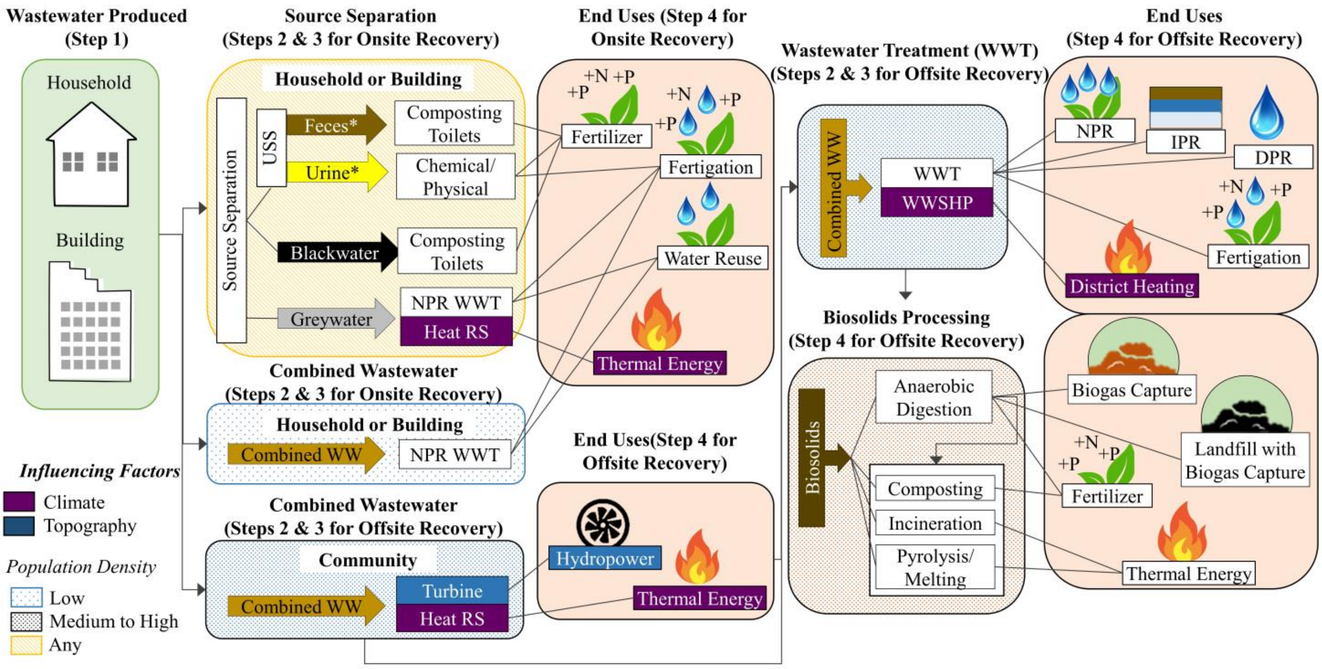

Figure 5. The potential options for resource recovery for onsite and offsite (more centralized) applications. The resources denoted with an asterisk (*) can be diluted. Abbreviations—DPR: Direct Potable Reuse; Heat RS: Heat Recovery System; IPR: Indirect Potable Reuse; NPR: Non-Potable Reuse; USS: urine source separation; WW: Wastewater; WWSHP: wastewater source heat pump; WWT: Wastewater Treatment.

Step 1: Determine the quantity of reclaimed water that is needed or will be needed according to the projected population for the time span of interest. Source separation is feasible for household or building level recovery (see Figure 5). Existing sub-urban and urban communities typically have sewer connections already in place for treatment at a WWTP, so water reclamation can occur during the conveyance or treatment stages. Since the efficiency of resource recovery varies with scale [10], the wastewater flow rate should be estimated; for reference, about 0.42 m^3/capita-day of wastewater is generated in the United States [43]. If water will not be reclaimed, continue to Step 4.

Step 2: Identify the target effluent water quality as determined by the potential end use/end users of the reclaimed water. At a WWTP, three forms of water reclamation are feasible: NPR, IPR, and DPR. Guidelines and local regulations for target effluent water quality for each type are available [10,25].

Step 3: Determine the set of wastewater treatment technologies that are feasible considering the target effluent water quality, treatment scale, and local ordinances. Section 3.1 introduced water reclamation technologies in the context of the effluent water quality achieved in prior life cycle studies. Additional local considerations, such as land availability and proximity to the residential areas, can also be accounted for.

Step 4: Determine if energy and/or nutrients can be recovered for the scope under consideration, e.g., onsite or a WWTP (see Figure 5). End uses for onsite recovery will likely be driven by the need for a particular resource and/or major end users (e.g., local farms or green space for fertilizer). For offsite treatment of combined wastewater flows, energy and/or nutrients can be recovered from conveyance, wastewater treatment, and/or biosolids processing. While biosolids are produced at a rate of ~24.3 kg dry solids/PE-year [44], co-digestion (e.g., with yard or food waste) can be considered when only small quantities are available.

Step 5: Identify local considerations or other constraints that would restrict the recovery of energy and/or nutrients, e.g., local restrictions on the quality and quantity of biosolids for land application during agricultural off-seasons, space constraints, or restrictions on WWTP GHG emissions. Determine the feasible processes for energy and/or nutrient recovery considering these constraints.

Step 6: Determine the life cycle costs of the resource recovery systems as options are prioritized. Costs are influenced by several factors including flow rate, local rates (e.g., for energy, construction, material, and labor), climate, distance to the end users, etc. Readers can refer to Section 4.1 where the LCC of alternative systems were presented.

Step 7: Determine the environmental impact of the resource recovery system. Life cycle GHG emissions are emphasized as they are reported most often in LCAs [10]. Section 4.2 can be referenced for developing these estimates. Considering the prominence of the energy mix in the environmental impacts of wastewater treatment systems, low-emission energy sources should be utilized when feasible.

Step 8: Determine the final configuration of the resource recovery system.

6. Application of the Framework to An Existing Case Study

A step-by-step assessment was conducted through a case study to demonstrate the applicability of the developed framework in finding sustainable solutions for implementation of wastewater-based resource recovery schemes. Accordingly, Ryaverket Wastewater Treatment Facility located at Norra Fågelrovägen 3 in Göteborg (Sweden) was selected, and the results were compared to the findings from the Lundin et al. [33] study that evaluated alternatives for sludge handling at the WWTP. The treatment facility has a design capacity of 91 MGD, providing service for 617,781 habitants in the water service area [33]. The service area, which is approximately 172.9 mi^2, has a population density of 3573 capita/mi^2 and a population growth rate of 1.19% as of 2021 [45]. The current treatment facility consists of pre-precipitation with Ferrous Sulphate followed by Activated Sludge (2^{nd} Bio) and Nitrogen removal. The produced biosolids are sent to digestors for sludge handling and energy recovery via biogas production. The digestate is used for soil improvement and land reclamation. Currently, the effluent from the treatment plant is being released to the North Sea (environmental reuse).

Lundin et al. [33] evaluated four alternatives for sludge handling at the treatment facility. The alternatives consisted of agricultural use, co-incineration with waste, incineration combined with phosphorus recovery (Bio-Con), and fractionation with phosphorus recovery (Cambi-KREPRO). According to their study, there are also some limitations that need to be considered and addressed while designing for a wastewater-based resource recovery system in the service area. The major limitations consist of: (1) limitation on land application of dewatered digestate due to emerging legislation; (2) concerns regarding the presence of pathogen and harmful chemicals in the produced biosolids; (3) limitation on the capacity of the current incineration system in the city; (4) low phosphorus recovery in the current system; and (5) low demand for dewatered digestate from the farmers. Anaerobic digestion of biosolids followed by incineration combined with phosphorus recovery (Bio-Con), land application, and increasing the capacity of incinerators was the proposed solution in Lundin et al. study [33].

6.1. Framework Application

The developed framework was applied to a design for a resource recovery scheme in the selected treatment facility and its corresponding service area. The assessments associated with each step in the developed framework are presented in this section, and the outcomes from the application study have been summarized in Figure 6.

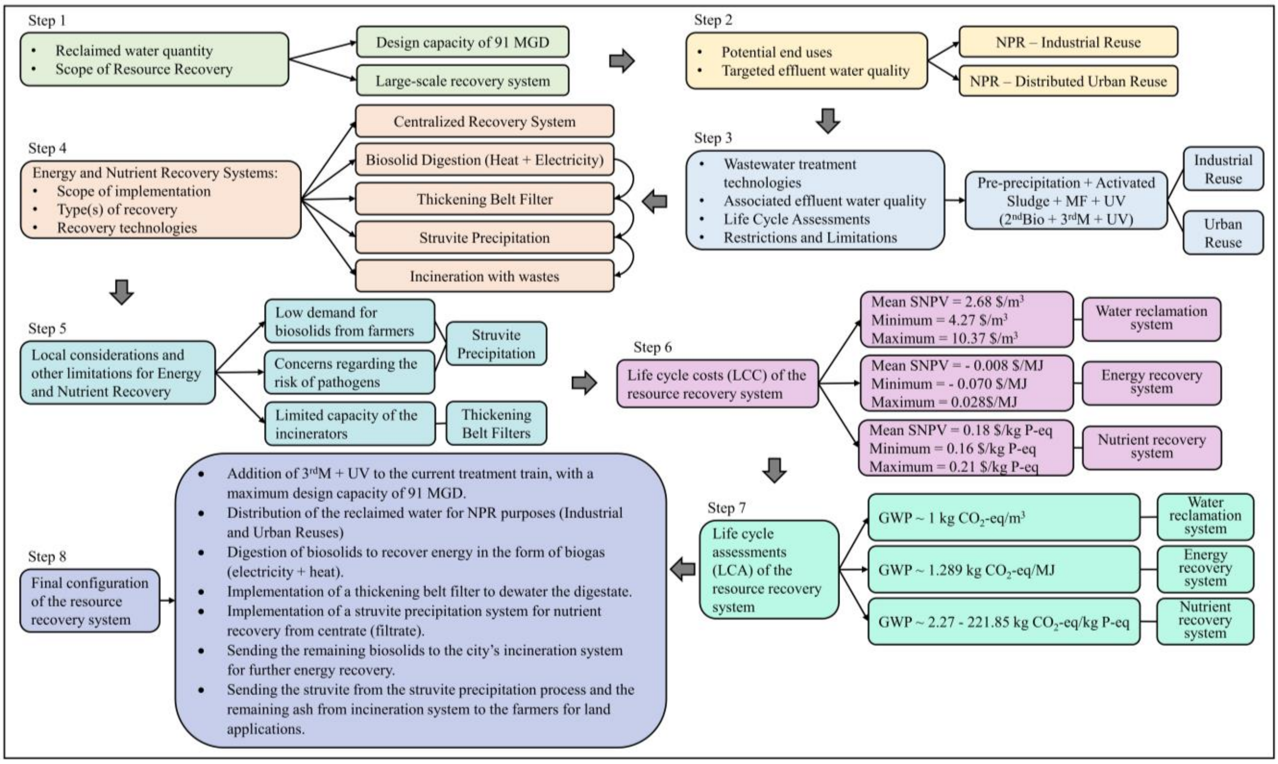

Figure 6. Summary of the case study assessment for validation/applicability evaluation of the developed framework. Abbreviations—AD: anaerobic digestion; Bio: biological; GWP: global warming potential; LCA: life cycle assessment; LCC: life cycle costs; LR: land reclamation; M: membrane; MF: microfiltration; MGD: million gallons per day; NPR: non-potable reuse; P: phosphorous; PC: physical chemical SNPV: specific net present value; UV: ultraviolet.

Step 1: The sewer collection system is currently implemented in the water service area. The service area has a population of 579,281 as of 2019, with an estimated growth rate of 1.19% as of 2021. The current treatment system has a design capacity of 91 MGD, which can provide service for 780,000 habitants in the service area. Since the collection and treatment system is currently implemented and the design capacity of the system can provide service for the residents until 2044 (with a 1.19% population growth rate), larger scale resource recovery systems would be more feasible options for this case. The current system recovers energy in the form of electricity and heat, and no water reclamation scenario (i.e., NPR, IPR, and DPR) has been implemented in the service area.

Step 2: Since the current treatment system consists of pre-precipitation with Ferrous Sulphate followed by an Activated Sludge system and Nitrogen removal, using the reclaimed water for NPR purposes seems to be the more feasible scenario due to the effluent water quality from the current plant. The treatment system is located within the residential area of the city of Gothenburg, Sweden, which makes the distance between the generation of reclaimed water and the residents relatively short. Moreover, the plant is located near an industrial site (within 1 mile of the WWTP). Consideration of these local conditions associated with the treatment facility make Industrial Reuse and Distributed Urban Reuse suitable scenarios for the water service area.

Step 3: To meet the water quality requirements for industrial reuse, the current treatment train (2ndBio) can be extended by implementation of a micro-filtration (MF), followed by UV disinfection (i.e., 2ndBio + 3rdM + UV). The design capacity for this expansion depends on the demand for the reclaimed water, with a maximum of the current system's design capacity (91 MGD). These modifications also make the effluent water quality suitable for urban reuse scenarios. Hence, the excess reclaimed water (e.g., during the low-demand industrial seasons) can be sent to the residential areas for urban reuse purposes. For industrial reuse, the current system can also be enhanced by implementation of hardness removal, if it is necessary for specific types of industrial reuse options (e.g., for boilers or cooling water that require lower water hardness) at the industrial site (i.e., 2ndBio + 3rdM + 3rd PC). Considering the topography of the current WWTP, expansion of the current facility seems to be a feasible option. If the current treatment system was not in place for this water service area, due to the proximity of the plant's location to the residential areas and the limitations regarding land application of biosolids in the service area, a membrane bioreactor (MBR) followed by biological nutrient removal and UV disinfection (2ndBio or 3rdBio) would have made a good treatment train for this case. This not only reduces the land requirements for implementation of the treatment facility, but also reduces the volume of the produced sludge and eliminates the higher costs, energy requirements, and GHG emissions associated with more aggressive filtration processes.

Step 4: Since the current treatment system is operating at a large-scale capacity and the collection system is currently in place, according to the correlation analysis in this study, centralized resource recovery would be an economic alternative with lower environmental impacts for this water service area. Recovering energy (in the form of electricity and heat) through digestion of biosolids, which is currently implemented at the WWTP, makes a good solution to reduce the costs and the environmental impacts of the wastewater treatment system. The recovered energy (electricity + heat) can be used onsite for the operation of the treatment facility. To recover the desired amount of nutrients (especially for phosphorus recovery), due to the concerns for pathogen contents of the biosolid, struvite precipitation would be a feasible solution to recover N and P and increase the demand for the land application of the material from farmers in the area. Moreover, the volume of the remaining biosolids can be further reduced by implementation of a centrifuge system to make it more feasible to send the final biosolids to the city's incinerators. Alternatively, a thickening belt system can be implemented as a more economical solution with lower GHG emissions if lower levels of volume reduction are desired. The final product can be sent to the city's incinerators for further energy recovery. As the study by Lundin et al. [33] also confirms, co-incineration of biosolids with waste in the incinerators produces the highest amount of energy for the biosolid handling system in the city (approximately 2300 KWh per dry ton of produced sludge). The alternatives would be Incineration combined with phosphorus recovery (Bio-Con) and Fractionation with phosphorus recovery (Cambi-KREPRO). As it was also mentioned by Lundin et al. [33], increasing the operation capacity of the incineration system is also a good solution that decreases the overall environmental impacts of the wastewater system in the area.

Step 5: One local consideration in this service area is the lower demand for biosolids from the farmers in the area. New legislation is also restricting the use of produced biosolids for land applications. Hence, the land application and agricultural use do not seem feasible scenarios for recovering nutrients from the biosolid. Alternatively, struvite precipitation not only increases the demand for the product from the farmers, but also decreases the risk of pathogens, one of the concerns associated with the use of produced biosolids in the area. Moreover, limited capacity of the incinerators makes it challenging to send a higher volume of the sludge to the incineration facility. Further dewatering of the remaining biosolid (along with increasing the capacity of incinerators) makes it more feasible for this type of energy recovery. Since the collection system is currently in place and the city is not located in a very cold region, according to this study, implementation of a thermal energy recovery system does not seem economically and environmentally sustainable. The relatively flat topography of the service area also makes energy recovery through hydropower infeasible.

Step 6: According to the correlation analysis in this study, centralized recovery technologies are more economically feasible for this service area. As the study conducted by Lundin et al. [33] also shows, co-incineration of biosolids with waste has the highest implementation and operation costs; however, it produces the highest amount of energy, which further reduces the overall environmental impacts of the design.

Step 7: According to the correlation analysis in this study, centralized recovery technologies are more environmentally friendly alternatives for this service area. Moreover, co-incineration of biosolids with waste decreases the GHG emissions associated with the system.

Step 8: The final suggested resource recovery scheme for the selected treatment facility is as below.

a. Implementation of additional treatment technologies (3^{rd}M and UV) to the current treatment train at the WWTP (with a capacity that depends on the demand, with a maximum of the current system's design capacity);
b. Sending the reclaimed water to the industrial site located next to the plant for industrial purposes (NPR), and the excess reclaimed water to the residential areas for urban reuse purposes during the lower-demand industrial seasons;
c. Digestion of the produced sludge to recover energy in the form of biogas (electricity + heat);
d. Implementation of a thickening belt system to further dewater the remaining biosolids at the plant;
e. Implementation of a struvite precipitation system for nutrient recovery from the centrate (filtrate);
f. Sending the remaining dewatered biosolids to the city's incineration system for further energy recovery;
g. Sending the struvite from the struvite precipitation process and the remaining ash from the incineration system to farmers for land application.

6.2. Case Study Validation

As the outcomes of the assessment show, the developed framework can be successfully applied to propose sustainable solutions for resource recovery from wastewater in the studied area, given its local conditions and operational limitations. The detailed results of the case study assessment are provided in Table A3 of the Appendix A. The proposed treatment train for water reclamation and industrial reuse consists of pre-precipitation followed by activated sludge, microfiltration, and UV disinfection (i.e., 2^{nd}Bio + 3^{rd}M), which has a mean SNPV of 2.68 USD/m^3 (with a minimum of 0.08 USD/m^3 and a maximum of 10.37 USD/m^3). For sludge handling, the proposed scenario consists of anaerobic digestion of biosolids for energy recovery followed by a thickening belt filter to dewater the digestate. The centrate from the dewatering system is sent to struvite precipitation for nutrient recovery, and the thickened digestate is sent to the incinerators for additional energy recovery. The remaining ash from incineration system can also be land applied as a fertilizer.

The proposed alternatives for energy recovery (i.e., AD + Incineration) has a mean SNPV of −0.008 USD/MJ (with a minimum of −0.070 USD/MJ and a maximum of 0.028 USD/MJ), and the proposed scenario for nutrient recovery, excluding the struvite precipitation, (i.e., AD + Incineration + LR) has a mean SNPV of 0.18 USD/kg P-eq (with a minimum of 0.16 USD/kg P-eq and a maximum of 0.21 USD/kg P-eq). A study conducted by Ishii and Boyer [29] also shows that the revenue from struvite precipitation exceeds the costs associated with its operation (e.g., MgO inputs, Na_3PO_4 inputs, and energy requirements), if USD 0.57/kg dry weight is considered as the price of the produced struvite.

The global warming potential (GWP) for the proposed water reclamation system would be ~1 kg CO_2-eq/m^3, and for the proposed energy recovery system would be ~1.289 kg CO_2-eq/MJ. The GHG emissions for the proposed nutrient recovery system would be between ~2.27 kg CO_2-eq/kg P [46] (struvite precipitation) and ~221.85 kg CO_2-eq/kg P-eq (AD + Incineration + LR). Moreover, a study conducted by Linderholm et al. [46] reviews the LCA associated with the operation of a struvite precipitation system in Sweden. Results of the assessment show that operation of a struvite precipitation system in Sweden has a GWP of ~2.27 kg CO_2-eq/kg P, which is significantly lower than recovering P from minerals or from ash [46]. The GWP for the scenario proposed in Lundin et al. [33] study (i.e., AD + Incineration + LR) would be approximately 221.85 kg CO_2-eq/kg P-eq for a large-scale system. Considering the significant decrease in the digestate volume, the overall GWP of the proposed scenario in this study would be significantly lower than the GWP (~221.85 kg CO_2-eq/kg P-eq) associated with the scenario proposed by Lundin et al. [33]. Additionally, the proposed solution in this study addresses all the limitations in the study area (e.g., emerging legislations that limit land application of biosolids, concerns regarding the presence of pathogens in the produced biosolids, limited incinerator capacity, low phosphorus recovery in the current system, and low demand for digestate), while capable of recovering notably more valuable resources from the produced wastewater in the service area. These considerations further improve the sustainability of the proposed solution, when compared to the scenarios that are introduced in the previous studies.

7. Conclusions

A framework for integrated wastewater management has been presented in conjunction with a case study application. The design of sustainable resource recovery systems was found to be largely driven by the scale of implementation, the location (e.g., as it pertains to the energy mix and water quality restrictions), and the scope of the system considered. Specific costs and GHG emissions were both negatively correlated to scale, which suggests that large scale systems tend to cost less and produce less GHG emissions on a per unit basis—thus, benefiting from economies of scale. Some data sets of the impact assessments had large variations, but nonetheless highlighted resource recovery systems that could achieve comparable or lower impacts. For example, most energy recovery technologies provided a higher revenue than water and nutrient recovery technologies, which highlights an opportunity for a sustained investment in a technology. Future research is recommended to incorporate social impacts to the framework and to embed multi-objective optimization in the decision-making process for the simultaneous recovery of multiple resources across scales.

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Appendix A

Appendix A.1. Case studies Included in the Correlation Analysis

Table A1. The journal articles which include a life cycle assessment of water, energy, and nutrient recovery are included in this review [19,27,29–35,46–100]. A cost analysis is conducted in the articles with an asterisk (*), and (ˆ) shows articles that appear in multiple columns (multiple types of resources were recovered). In addition, references [26,28,100–105] focused on cost analysis discussion.

	References
Water	[19,47–53,58,59,61–63,66], [54–56,60,64,65] *, [57] *ˆ
Energy	[48,62,70–72,74,76–78,80,82,83], [27,33,49,55,68,69,73,75,79,81,84] *, [50,53,67] ˆ
Nutrient	[32,35,46,72,73,80,85–89,91–99], [29–31,34,90] *, [67,70] ˆ, [33,57] *ˆ
Cost analysis	[26,28,100–105]

Appendix A.2. Correlation Analysis Table

Table A2. The table shows the screened result of paired correlation analysis with *p*-value larger than 0.05, and coefficient higher than 0.5 or lower than −0.5. Abbreviations—2nd Bio: secondary biological treatment; 3rd PC: tertiary physical and/or chemical treatment; 3rd Bio: tertiary biological treatment; AD: anaerobic digestion; BOD: biological oxygen demand; Chem: chemical treatment; COD: chemical oxygen demand; eff: effluent; GHG: greenhouse gasses; in: influent; LR: land reclamation; M: membrane filtration; N: number of data points used in the analysis; *r*: correlation coefficient; RR: removal rate; STW: sludge treatment wetland; TD: thermal drying; TN: total nitrogen; TP: total phosphorus; TSS: total suspended solid; USS: urine source separation; V: volume reduction treatment.

Sample 1	Sample 2	N	*r*	*p*-Value
	Water			
TSS in	TP eff	7	−0.999	0
TP eff	TP RR	13	−0.994	0
COD eff	TP RR	12	−0.984	0
COD in	BOD in	13	0.979	0
COD eff	TSS RR	6	0.969	0.001
TP RR	COD RR	12	0.966	0
TP eff	TSS RR	7	−0.965	0
TN in	TSS RR	7	−0.958	0.001
BOD in	TSS RR	7	0.958	0.001
TSS in	TSS RR	7	0.958	0.001
COD eff	COD RR	20	−0.957	0
TP eff	COD RR	12	−0.948	0
TN eff	TN RR	20	−0.948	0
TP in	BOD in	13	0.863	0
TN in	TP eff	14	0.857	0
TP in	BOD RR	12	0.855	0
BOD eff	BOD RR	12	−0.834	0.001
BOD in	COD eff	13	0.784	0.002
BOD in	TP RR	13	−0.751	0.003

Table A2. *Cont.*

Sample 1	Sample 2	N	*r*	*p*-Value
BOD RR	2^{nd} Bio + 3^{rd} PC	12	−0.742	0.006
TP eff	Centralized	14	−0.722	0.004
TP eff	Decentralized	14	0.722	0.004
COD in	TP eff	13	0.719	0.006
BOD in	BOD RR	12	0.711	0.01
COD RR	cost (USD2019/m^3)	13	−0.694	0.008
COD eff	cost (USD2019/m^3)	13	0.689	0.009
BOD eff	2^{nd} Bio + 3^{rd} PC	20	0.674	0.001
TN in	COD in	21	0.659	0.001
COD in	TP RR	13	−0.655	0.015
TP in	COD in	21	0.643	0.002
BOD in	COD RR	12	−0.64	0.025
COD in	BOD RR	12	0.634	0.027
COD in	2^{nd} Bio + 3^{rd} Bio	21	0.628	0.002
cost (USD2019/m^3)	2^{nd} Bio + 3^{rd} Bio	14	−0.625	0.017
TN RR	COD RR	19	0.607	0.006
cost (USD2019/m^3)	GHG (kg CO2-eq/m^3)	14	0.592	0.026
cost (USD2019/m^3)	Decentralized	14	0.586	0.028
TP eff	BOD RR	12	0.586	0.045
cost (USD2019/m3)	Centralized	14	−0.586	0.028
TN RR	Decentralized	20	−0.581	0.007
TN RR	Centralized	20	0.581	0.007
TP in	TN in	21	0.575	0.006
TN in	COD RR	20	0.557	0.011
COD RR	2^{nd} Bio + 3^{rd} Bio	20	0.556	0.011
TN eff	2^{nd} Bio + 3^{rd} Bio	21	−0.551	0.01
BOD eff	scale (m^3/day)	20	0.547	0.013
cost (USD2019/m^3)	scale (m^3/day)	14	−0.535	0.049
COD eff	TN RR	19	−0.531	0.019
TN RR	2^{nd} Bio + 3^{rd} Bio	20	0.518	0.019
TN eff	2^{nd} Bio + 3^{rd} PC	21	0.484	0.026
TN in	Decentralized	22	0.476	0.025
TN in	Centralized	22	−0.476	0.025
TN eff	COD RR	20	−0.472	0.036
BOD eff	GHG (kg CO_2-eq/m^3)	20	−0.46	0.041
GHG (kg CO_2-eq/m^3)	scale (m^3/day)	22	−0.453	0.034
COD in	2^{nd} Bio + 3^{rd} M	21	−0.441	0.045
COD in	TN eff	21	−0.434	0.049
	Energy			
m^3/day	sludge (tons/day)	8	0.951	0

Table A2. *Cont.*

Sample 1	Sample 2	N	*r*	*p*-Value
cost (USD2019/MJ)	sludge (tons/day)	14	−0.839	0
wastewater	heat exchanger	174	0.701	0
wastewater	sludge	174	−0.657	0
wastewater + sludge	AD + landfilling	174	0.489	0
wastewater	hydropower	174	0.505	0
wastewater	AD + composting	174	−0.461	0
sludge	heat exchanger	174	−0.46	0
wastewater	wastewater + sludge	174	−0.424	0
sludge	wastewater + sludge	174	−0.404	0
hydropower	scale (m^3/day)	116	0.396	0
sludge	AD + incineration	174	0.374	0
wastewater + sludge	AD + composting	174	0.352	0
sludge	hydropower	174	−0.332	0
cost (USD2019/MJ)	AD + landfilling	112	−0.331	0
heat exchanger	AD + composting	174	−0.323	0
wastewater	AD + landfilling	174	−0.316	0
wastewater + sludge	heat exchanger	174	−0.297	0
sludge	V + incineration	174	0.28	0
cost (USD2019/MJ)	wastewater + sludge	112	−0.274	0.003
GHG (kg CO_2-eq/MJ)	V + incineration	127	0.274	0.002
wastewater	AD + incineration	174	−0.246	0.001
heat exchanger	hydropower	174	−0.244	0.001
sludge	TD + AD + pyrolysis	174	0.239	0.002
hydropower	AD + composting	174	−0.233	0.002
heat exchanger	AD + landfilling	174	−0.221	0.003
wastewater	V + incineration	174	−0.216	0.004
GHG (kg CO_2-eq/MJ)	AD + landfilling	127	−0.215	0.015
wastewater + sludge	hydropower	174	−0.214	0.005
AD + landfilling	AD + composting	174	−0.211	0.005
sludge	AD + pyrolysis	174	0.194	0.01
sludge	TD + pyrolysis	174	0.194	0.01
heat exchanger	scale (m^3/day)	116	−0.184	0.049
heat exchanger	AD + incineration	174	−0.172	0.023
sludge	AD + composting	174	0.173	0.023
AD + incineration	AD + composting	174	−0.164	0.03
hydropower	AD + landfilling	174	−0.159	0.036
wastewater	TD + AD + pyrolysis	174	−0.157	0.039
wastewater + sludge	AD + incineration	174	−0.151	0.047
heat exchanger	V + incineration	174	−0.151	0.047
	Nutrient			
urine	USS + Chem + fertilizer	135	0.896	0

Table A2. *Cont.*

Sample 1	Sample 2	N	*r*	*p*-Value
sludge	urine	135	−0.727	0
sludge	USS + Chem + fertilizer	135	−0.652	0
urine	AD + fertilizer	135	−0.609	0
sludge	AD + fertilizer	135	0.568	0
USS + fertigation + AD + fertilizer	scale (m^3/day)	131	0.539	0
urine + faeces + greywater	scale (m^3/day)	131	0.539	0
AD + fertilizer	USS + Chem + fertilizer	135	−0.545	0
wastewater + sludge	drying + fertilizer	135	0.341	0
sludge	wastewater + sludge	135	−0.312	0
AD + incineration + LR	sludge(tons/day)	57	0.343	0.009
GHG (kg CO_2-eq/kg P-eq)	wastewater + sludge	135	0.28	0.001
sludge(tons/day)	scale (m^3/day)	57	0.275	0.038
urine	USS + M + fertigation	135	0.265	0.002
wastewater + sludge	AD + fertilizer	135	0.25	0.003
GHG (kg CO_2-eq/kg P-eq)	USS + Chem + fertilizer	135	−0.216	0.012
AD + fertilizer	scale (m^3/day)	131	−0.211	0.016
drying + incineration + LR	AD + fertilizer	135	−0.199	0.021
STW + dewatering + fertilizer	AD + fertilizer	135	−0.199	0.021
GHG (kg CO_2-eq/kg P-eq)	urine	135	−0.194	0.024
sludge	urine + faeces + greywater	135	−0.192	0.025
sludge	USS + fertigation + AD + fertilizer	135	−0.192	0.025
sludge	USS + M + fertigation	135	−0.192	0.025
wastewater + sludge	urine	135	−0.187	0.03
urine	USS + drying + fertilizer	135	0.186	0.031
AD + incineration + LR	AD + fertilizer	135	−0.181	0.036
sludge	AD + incineration + LR	135	0.178	0.039
sludge	scale (m^3/day)	131	−0.172	0.049

Appendix A.3. Application of the Framework to Existing Studies

The Ryaverket Wastewater Treatment Facility located at Norra Fågelrovägen 3 in Göteborg, Sweden, was selected to evaluate the applicability of the developed framework in the sustainable design of recovery systems. The treatment facility has a design capacity of 91 MGD, providing service for 617,781 habitants in the water service area [70]. The service area, which is approximately 172.9 mi^2, has a population density of 3573 capita/mi^2 and a population growth rate of 1.19% as of 2021 [45].

The current treatment facility consists of pre-precipitation with Ferrous Sulphate followed by Activated Sludge (2^{nd} Bio) and Nitrogen removal. The produced biosolids are sent to digestors for sludge handling and energy recovery via biogas production. The digestate is used for soil improvement and land reclamation. Currently, the effluent from the treatment plant is being released to the North Sea (environmental reuse).

Lundin et al. [74] evaluated four alternatives for sludge handling at the treatment facility. The alternatives consisted of agricultural use, co-incineration with waste, incineration combined with phosphorus recovery (Bio-Con), and fractionation with phosphorus recovery (Cambi-KREPRO). According to Lundin et al.'s [74] study, there are also some limitations that need to be considered and addressed while designing for a wastewater-based resource recovery system in the service area. The major limitations consist of:

- Limitation on land application of dewatered digestate due to emerging legislation;
- Concerns regarding the presence of pathogen and harmful chemicals in the produced biosolids;
- Limitation on the capacity of the current incineration system in the city;
- Low P recovery in the current system;
- Low demand for dewatered digestate from the farmers.

Table A3. Results of the case study assessment for to apply and validate the developed framework. Abbreviations—MGD: million gallons per day; WWTP: wastewater treatment plant; NPR: non-potable reuse; IPR: indirect potable reuse; DPR: direct potable reuse; Bio: biological; M: membrane; UV: ultraviolet; MF: microfiltration; PC: physical chemical; CAS: conventional activated sludge; GHG: greenhouse gas; KWh: kilowatt hour; LCC: life cycle cost; LCA: life cycle assessment.

Step	Assessment
Step 1: Determine the quantity of reclaimed water that is needed or will be needed according to the projected population in the considered time span for the design. What is the scope of resource recovery, i.e., onsite recovery (household or building level) or larger scales such as a wastewater treatment plant? If planning is occurring at the household or building level, source separation would be feasible to separate wastewater streams (see Figure 3b). Sub-urban and urban communities typically have sewer connections already in place for treatment at a wastewater treatment facility, so resource recovery can occur during conveyance, wastewater treatment, or biosolids processing. Opportunities for resource recovery vary by scale[8], so the wastewater flow rate should be estimated. For reference, about 0.42 m^3/capita-day of wastewater is generated in the United States [19]. If water will not be reclaimed, continue to Step 4.	The sewer collection system is currently implemented in the water service area. The service area has a population of 579,281 as of 2019, with an estimated growth rate of 1.19% as of 2021. The current treatment system has a design capacity of 91 MGD, which can provide service for 780,000 habitants in the service area. Since the collection and treatment system is currently implemented and the design capacity of the system can provide service for the residents until 2044 (with 1.19% population growth rate), larger scale resource recovery systems would be more feasible options for this case. The current system recovers energy in the form of electricity and heat, and no water reclamation scenario (i.e., NPR, IPR, and DPR) has been implemented in the service area.
Step 2: Identify the target effluent water quality as determined by the potential end use/end users of the reclaimed water. At a WWTP, three forms of water reclamation are feasible: non-potable reuse, indirect potable reuse (IPR), and direct potable reuse (DPR). Guidelines and local regulations for target effluent water quality for each type are available [8,20].	Since the current treatment system consists of pre-precipitation with Ferrous Sulphate followed by an Activated Sludge system and Nitrogen removal, using the reclaimed water for NPR purposes seem to be more feasible scenarios due to the effluent water quality from the current plant. The treatment system is located within the residential area in the city of Gothenburg, Sweden, which makes the distance between generation of reclaimed water and the residents relatively short. Moreover, the plant is located near an industrial site (within 1 mile of the WWTP). Consideration of these local conditions associated with the treatment facility make Industrial Reuse and Distributed Urban Reuse suitable scenarios for the water service area.
Step 3: With consideration of the target effluent water quality, the scale of treatment, and local ordinances, determine the set of wastewater treatment technologies that can feasibly be applied. Readers can refer back to Section 3.1, which discussed the technologies that have been implemented for water reclamation in prior life cycle studies and the effluent water quality achieved for the technologies used in the studies. Other considerations may also be taken into account in this step, such as restrictions on implementation of specific treatment technologies. For instance, some treatment technologies such as CAS require larger area for implementation. For urban areas with limitations on land availability, this treatment technology may not be a feasible option. Moreover, other restrictions such as proximity to the residential areas may also limit selection and implementation of treatment technologies with higher level of odor issues (e.g., anaerobic treatment techniques).	To meet the water quality requirements for industrial reuse, the current treatment train (2^{nd}Bio) can be extended by implementation of a micro-filtration (MF), followed by UV disinfection (i.e., 2^{nd}Bio + 3^{rd}M + UV). The design capacity for this expansion depends on the demand for the reclaim water, with the maximum of current system's design capacity (91 MGD). These modifications also make the effluent water quality suitable for urban reuse scenarios. Hence, the excess reclaimed water (e.g., during the low-demand industrial seasons) can be sent to the residential areas for urban reuse purposes. For industrial reuse, the current system can also be enhanced by implementation of hardness removal, if it is necessary for specific type of industrial reuse options (e.g., using for boilers or cooling water that require lower hardness in the water) in the industrial site (i.e., 2^{nd}Bio + 3^{rd}M + 3^{rd} PC). Considering the topography of the current WWTP, expansion of the current facility seems to be a feasible option.If the current treatment system was not in place for this water service area, due to the proximity of the plant's location to the residential areas and the limitations regarding land application of biosolids in the service area, membrane bioreactor (MBR) followed by biological nutrients removal and UV disinfection (2^{nd}Bio or 3^{rd}Bio) would have made a good treatment train for this case. This not only reduces the land requirements for implementation of the treatment facility, but also reduced the volume of the produced sludge and eliminates the higher costs, energy requirements, and GHG emissions associated with more aggressive filtration processes.

Table A3. *Cont.*

Step	Assessment
Step 4: Determine if energy and/or nutrients can be recovered for the scope under consideration (i.e., onsite vs. a WWTP). Figure 3b presents options for the recovery of energy and nutrients as well (adapted from Diaz-Elsayed et al. [8]).For onsite recovery, consider the potential end use applications of energy and nutrients: fertilizer, fertigation, and thermal energy recovery. Fertilizer can also be transported offsite for local use if there is not an immediate need onsite. The end use of the recovered resource will likely be driven by the need for a particular resource and/or the major end users available to consume the recovered resource (e.g., local farms or green space for fertilizer).For combined wastewater flows that are treated offsite (e.g., in a sub-urban or urban community), several stages can be considered for energy and nutrient recovery: • Conveyance: Hydropower can be generated during conveyance and used directly for pumping stations. Additionally, thermal energy can be recovered before or after arriving at the WWTP and used as a heat source for the community; • Wastewater Treatment: If nutrients remain in the reclaimed water, then fertigation is feasible. Additionally, thermal energy can be recovered for district heating (if it was not done so prior to treatment). Biosolids Processing: During this stage, energy and/or nutrients can be recovered via anaerobic digestion, composting, or combustion processes (see Figure 3b). The rate of biosolids production for a community can be approximated at 24.3 kg dry solids/PE-year if data are not readily available [21]. When the rate of biosolids generation is relatively small, co-digestion with other waste (e.g., yard or food waste) can be considered.	Since the current treatment system is operating on a large-scale capacity and the collection system is currently in place, according to the correlation analysis in this study, centralized resource recovery would be an economic alternative with lower environmental impacts for this water service area. Recovering energy (in form of electricity and heat) through digestion of biosolids, which is currently implemented at the WWTP, makes a good solution to reduce the costs and the environmental impacts of the wastewater treatment system. The recovered energy (electricity + heat) can be used onsite for the operation treatment facility. To recover the desired amount of nutrients (especially for phosphorus recovery), due to the concerns on pathogen contents of the biosolid, struvite precipitation would be a feasible solution to recover N and P and increase the demand for the land application of the material from the farmers in the area. Moreover, volume of the remaining biosolids can be further reduced by implementation of a centrifuge system to make it more feasible to send the final biosolids to the city's incinerators. Alternatively, a thickening belt system can be implemented as a more economical solution with lower GHG emissions if lower levels of volume reduction are desired. The final product can be sent to the city's incinerators for further energy recovery. As the study by Lundin et al. (2004) also confirms, co-incineration of biosolids with waste in the incinerators produces the highest among of energy recovery for the biosolid handling system in the city (approximately 2300 KWh per dry ton of produced sludge). The alternatives would be Incineration combined with phosphorus recovery (Bio-Con) and Fractionation with phosphorus recovery (Cambi-KREPRO). As it was also mentioned by Lundin et al. (2004), increasing the operation capacity of incineration system is also a good solution that decreases the overall environmental impacts of the wastewater system in the area.
Step 5: Are there local considerations or other constraints to account for that would restrict the recovery of energy and/or nutrients? For example, are there restrictions on the quality and quantity (especially during agricultural off-seasons) of biosolids to be reused for land application or restrictions on emissions from the incineration process. If so, what are the set of feasible options for resource recovery?	One local consideration in this service area is the lower demand for biosolids from the farmers in the area. New legislations are also restricting the use of produced biosolids for land applications. Hence, the land application and agricultural use do not seem feasible scenarios for recovering nutrients from the biosolid. Alternatively, struvite precipitation not only increases the demand for the product from the farmers, but also decreases the risk of pathogens, one of the concerns associated with the use of produced biosolids in the area. Moreover, limited capacity of the incinerators makes it challenging to send a higher volume of the sludge to the incineration facility. Further dewatering of the remaining biosolid (along with increasing the capacity of incinerators) makes it more feasible for this type of energy recovery. Since the collection system is currently in place and the city is not located in a very cold region, according to this study, implementation of a thermal energy recovery system does not seem economically and environmentally sustainable. The relatively flat topography of the service area also makes energy recovery through hydropower infeasible.
Step 6: Determine the life cycle costs (LCC) of the resource recovery systems as options are prioritized. The LCC can be influenced by a variety of factors including the flow rate, local costs (e.g., energy, construction, material, and labor), climate, the distance to the end users, etc. Readers can refer back to Section 4.1 where the LCC of alternative resource recovery systems were presented.	According to the correlation analysis in this study, centralized recovery technologies are more economically feasible for this service area. As the study conducted by Lundin et al. (2004) also shows, co-incineration of biosolids with waste has the highest implementation and operation costs; however, it produces the highest amount of energy, which also further reduces the overall environmental impacts of the design.
Step 7: Determine the environmental impact of the resource recovery system. Life cycle GHG emissions are reported most often in LCAs [8]; a comparison of the GHG emissions for resource recovery systems were presented in Section 4.2 for reference.	According to the correlation analysis in this study, centralized recovery technologies are more environmentally friendly alternatives for this service area. Moreover, co-incineration of biosolids with waste decreases the GHG emissions associated with the system.

Table A3. *Cont.*

Step	Assessment
Step 8: Determine the final configuration of the resource recovery system.	• Implementation of additional treatment technologies to add (3rdM and UV) to the current treatment train at the WWTP (with a capacity that depends on the demand, with a maximum of the current system's design capacity). • Sending the reclaimed water to the industrial site located next to the plant for industrial purposes (NPR), and the excess reclaimed water to the residential areas for urban reuse purposes during the lower-demand industrial seasons. • Digestion of the produced sludge to recover energy in the form of biogas (electricity + heat). • Implementation of a thickening belt system to further dewater the remaining biosolids at the plant. • Implementation of a struvite precipitation system for nutrient recovery from the centrate (filtrate). • Sending the remaining dewatered biosolids to the city's incineration system for further energy recovery. • Sending the struvite from the struvite precipitation process and the remaining ash from incineration system to the farmers for land applications.

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