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Multi-objective Optimization of an Integrated Energy-Water-Waste Nexus for Eco-Industrial Park

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Compared to the linear economy, the circular economy promotes the minimization of fresh resources through the recovery of the applicable items. The concept of the circular economy can be implemented at the industrial level through the process systems engineering approach. A single element or multiple elements nexus can be developed in order to obtain an integrated optimal network. For a tripartite energy-water-waste nexus, focusing the wastewater as the subject of study, the optimization effort may not only be limited to the economic aspect, but it may also include the need to maximize the recovery of resource and the need to reuse and reclaim the wastewater stream. This will require the multi-objective optimization approach. In this study, a multi-objective optimization exercise to develop an integrated energy-water-waste is performed based on the fuzzy optimization constraints method. Three types of objective functions are assessed, namely to maximize profit, to maximize the amount of recovered resources, and to maximize the recovery of water. The mixed-integer non-linear programming (MINLP) model is formulated for such purposes. A case study conducted provides the solution that compromises the trade-off between the objective functions. An annual profit of 1.2 M USD/y, plus the recovery of biogas, struvite, metal hydroxides, and solid sludges, as well as the reuse and reclamation of 574 m^3/h of water can be achieved. The model offers a perspective on how the economics and the environmental considerations can be optimized simultaneously.

1. Introduction

The application of the circular economy will enable the minimization of the final waste and it also offers possibility to perform re-entry of the recovered resources into the ecosystem/supply chain. Certain resource is not actually a renewable item, for example, phosphorus (P); it is estimated that the P is production process from the phosphate rock will be ceased to be operated by the end of this century (Cooper et al., 2011). Through the application of the 6R strategies, namely reuse, recycle, redesign, remanufacture, reduce, and recover (Jawahir and Bradley, 2016), certain resources can be recovered from the process stream. Wastewater is known to possess certain type of contaminant that can be recovered via certain processes, either in the form of energy, water, and/or certain elements e.g. struvite. The idea to develop an integrated energy-water-nexus from wastewater is one of the researches to be explored. Misrol et al. (2020) explored the water-water nexus at the level of Eco-Industrial Park (EIP). Technically, the application of the process systems engineering (PSE) can be applied to achieve the circular economy goals (Avraamidou et al., 2020). The platform to perform the integration works is suggested to be at the Eco-Industrial Park (EIP) given the emphasizes to establish the industrial symbiosis among the participants, which it may not be promoted in the common industrial park. Misrol et al. (2021) explore the possible integration of domestic and industrial sources combined to recover biogas and to reuse and reclaim water for certain applications. Medeiros et al. (2021) use specifically yellow water as the main subject to form a water-energy-nutrient nexus. The application of tripartite nexus was also made by Kilkis and Kilkis (2017) in a diary facility. At residential level, the idea of the tripartite nexus was explored by Nunez Lopez et al. (2018). It was noted apart from the annual profit, there are also other items concerned, either to be maximized or to be minimized. These include the need to recover the resources as much as possible and the

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need to minimize the usage of freshwater while retaining the profitability of the works. This will require the use of multi-objective optimization in order to find the relatively best solution for the multiple objective functions. In this study, a multi-objective optimization is performed based on the fuzzy optimization concept, which the degree of satisfaction (λ) is sought to be maximized. This paper is a continuation of the paper by Misrol et al. (2021b) which it explores the multi-objective optimization for the energy-water-waste nexus. In general, the multi-objective optimization is relatively common but, in this context, pertaining to the energy-water-waste nexus mentioned earlier, it is a novel concept/insight to look at. The method of the study is described in the Section 2 following.

2. Method

The superstructure of this study is based on Misrol et al. (2021b), as shown in Section 2.1. Wastewater is the main subject of the study. It is desired to reclaim the water stream for reuse to the demand and to recover resources from the wastewater, which the optimization works can form an integrated energy-water-nexus for the EIP. The objectives in study are (i) to maximize the profit, (ii) to maximize the recovery of resources, and (iii) to minimize the consumption of freshwater. The mathematical formulations used in the model are written in Section 2.2.

2.1 Superstructure

Figure 1 shows the superstructure of the study. There are 14 sets representing the applicable process sections and the contaminants, namely the water source (h), segregation (which the section segregates the streams based on the applicable treatment process and the potential of resources to be recovered) (i), water demand (j), food waste (k), regeneration (m), biogas (n), struvite recovery (o), ammonia recovery (p), metal recovery (q), aerobic digestion (r), microalgae (s), freshwater (w), outsourced water (os), and the contaminant contents (c). The possible resources to be recovered include biogas (for renewable electricity), solid digestate, struvite, ammonium sulphate, precipitated metal, and solid sludge. Other recoverable items are the reclaimed water and the waste heat from the gas engine.

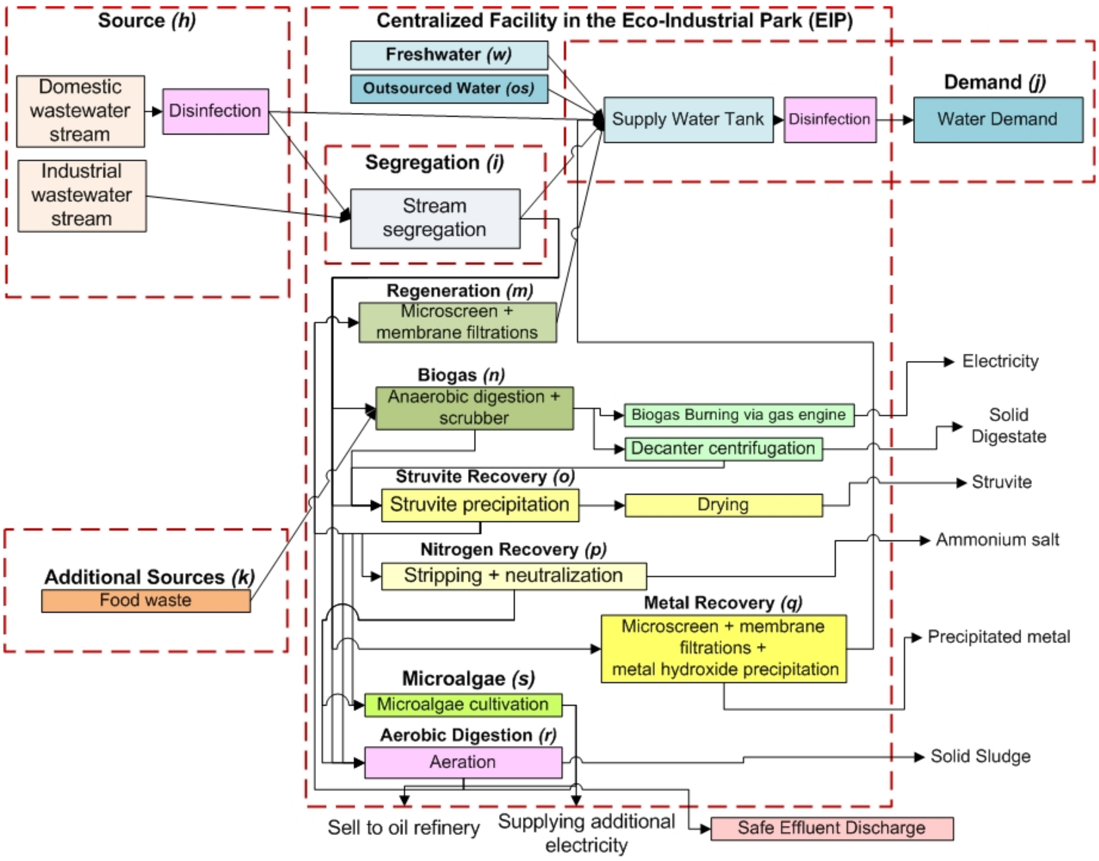

Figure 1: The superstructure of the study

There are four types of water demands, namely (i) boiler feed water (ii) process water, (iii) cooling water, and (iv) toilet flushing grade water. Each demand has different contaminant limits. The transportation of the involving streams is also considered (Misrol et al., 2021b). The main sources of revenue come from the supplying the water to the demand, selling the recovered resources, and processing fee the involving stream(s).

2.2 Mathematical formulation

In this paper, the variables are written in italic and the parameters are in non-italic format. The background of the whole equations is referred from Misrol et al. (2021b). There are three objective functions of the study, namely (i) to maximize the annual profit generated from the integration works (Pr), (ii) to maximize the annual recovery of resources from the wastewater (RR), and (iii) to maximize the volume of reused, reclaimed, and outsourced water (WR). Each objective function is written each in the following Eqs(1-3). Rev is the annual revenue (USD/y) and TAC is the total annualized cost (TAC) of the whole systems installed (USD/y), Bg is amount of biogas produced (t/h) and SD is the amount of solid digestate recovered from the anaerobic digestion's effluent (t/h). Stv is amount of struvite precipitated (t/h) and AS is the ammonium sulphate produced (t/h). MP is the amount of metal hydroxides precipitated (t/h) and SS is the amount of solid sludge generated from the aerobic digestion process (t/h). $F_{h,j}^{sd}$ is the directly reused water to the demand flow rate. $F_{i,j}^{sgd}$ is the flow rate of segregated greywater stream to the demand and $F_{m,j}^{rdd}$ is the regenerated water stream to the demand flow rate. $F_{q,j}^{ptd}$ is the flow rate of permeate generated from the metal recovery section to the demand and $F_{os,j}^{osd}$ is the outsourced water flow rate to the demand.

$$Pr = Rev - TAC \tag{1}$$

$$RR = Bg + SD + Stv + AS + MP + SS \tag{2}$$

$$WR = \sum_{h,j} F_{h,j}^{sd} + \sum_{i,j} F_{i,j}^{sgd} + \sum_{m,j} F_{m,j}^{rdd} + \sum_{q,j} F_{q,j}^{ptd} + \sum_{os,j} F_{os,j}^{osd} \tag{3}$$

The equation for each type of recoverable resources is shown in Eqs(4-9). For the Bg formulation in Eq(4), F_n^{bg} is the flow rate of the wastewater stream into the biogas digester (m^3/h) and $C_{n,c}^{bg}$ is the contaminant content of the stream (g/m^3). $\mathrm{COD^{eff}}$ is the percentage of chemical oxygen demand (COD) removal efficiency (%) and $\mathrm{COD^{yld}}$ is the conversion yield factor of biogas per kg of COD removed (m^3/kg). $\mathrm{CH4^{ct}}$ is the percentage content of methane in the raw biogas (%) and $\mathrm{CH4^{d}}$ is the density of methane (kg/m^3). $\mathrm{CF^{gkg}}$ is the conversion factor from g to kg (1,000 g/kg). $F_r^{ar}$is the flow rate of aerobic digestion process (m^3/h) and $C_{r,c}^{ar}$ is the stream's contaminant content (g/m^3). $C_{r,c}^{er}$ is the process' effluent contaminant content (g/m^3). $\mathrm{RR_r^{ss}}$ is the percentage of sludge recyclability for each aerobic digestion process option (%) and $\mathrm{Ar^{TS}}$ is the percentage conversion of COD to Total Suspended Solids (TSS) (%). $\mathrm{TS^{VSS}}$ is the percentage of Volatile Suspended Solids (VSS) relative to TSS (%) and $\mathrm{VSS^{Bg}}$ is the biogas yield per kg of VSS (m^3/kg). $\mathrm{VSS^{rmv}}$ is the percentage of VSS removal during the aerobic digestion process (%). In Eq(5), F_n^{sdg}, in m^3/h unit, is the solid digestate flow rate and $C_{n,c}^{sd}$ is the contaminant content of it. Specifically, the SD obtained is based on the total suspended solids (TSS) recovered from the F_n^{sdg} stream. $\mathrm{CF^{gMT}}$ is conversion factor from g to t (10^6 g/t). Stv recovery is as Eq(6); P^{mol} is the molarity of P in the stream and $\mathrm{MW^{Stv}}$ is the molar weight of struvite (g/mol). Formulation to recover AS is in Eq(7). $H2SO4^{mol}$ is the molarity of sulfuric acid (H_2SO_4) used to neutralize the ammonium ion and $\mathrm{MW^{AS}}$ is the molar weight of ammonium sulphate (g/mol). The recovery of metal hydroxides, specifically chromium (Cr), nickel (Ni), and Zinc (Zn) is formulated in Eq(8). Cr^{mol}, Ni^{mol}, and Zn^{mol} are the molarity of Cr, and Ni, and Zn each. The molecular weight of each metal is written as $\mathrm{MW^{Cr}}$, $\mathrm{MW^{Ni}}$, and $\mathrm{MW^{Zn}}$ each (g/mol). In Eq(9), F_r^{ar} is the influent flow rate of the aerobic digestion process (m^3/h). $C_{r,COD}^{ar}$ and $C_{r,COD}^{er}$ is the contaminant content of the influent and the effluent each (g/m^3). $\mathrm{RR_r^{ss}}$ is the constant regarding the recycling sludge into the aerobic process. $\mathrm{Ar^{TS}}$ is the COD conversion to TSS constant (TSS kg/COD kg) and $\mathrm{TSS^{rmv}}$ is the percentage of TSS removal from the process (%).

$$Bg = \frac{\sum_n\left(F_n^{bg}\times C_{n,COD}^{bg}\times \mathrm{COD^{eff}}\times \mathrm{COD^{yld}}\right)}{\mathrm{CF^{gkg}}\times \mathrm{CH4^{ct}}\times \mathrm{CH4^{d}}} + \frac{\left(F_r^{ar}\times\left(C_{r,COD}^{ar}-C_{r,COD}^{er}\right)\times\left(1-\mathrm{RR_r^{ss}}\right)\times \mathrm{Ar^{TS}}\times \mathrm{TS^{VSS}}\times \mathrm{VSS^{Bg}}\times \mathrm{VSS^{rmv}}\right)}{\mathrm{CF^{gkg}}} + \frac{\left(F_r^{ar}\times\left(C_{r,TSS}^{ar}-C_{r,TSS}^{er}\right)\times \mathrm{TSS^{rmv}}\times \mathrm{TS^{VSS}}\times \mathrm{VSS^{Bg}}\times \mathrm{VSS^{rmv}}\right)}{\mathrm{CF^{gkg}}} \quad ; c=COD \text{ or } TSS \tag{4}$$

$$SD = \frac{\sum_n\left(F_n^{sdg}\times C_{n,c}^{sd}\right)}{\mathrm{CF^{gMT}}} \quad ; c=TSS \tag{5}$$

$$Stv = \frac{P^{mol} \times \mathrm{MW}^{\mathrm{Stv}}}{\mathrm{CF}^{\mathrm{gMT}}} \tag{6}$$

$$AS^{amt} = \frac{H2SO4^{mol} \times \mathrm{MW}^{\mathrm{AS}}}{\mathrm{CF}^{\mathrm{gMT}}} \tag{7}$$

$$MP = \frac{\sum_q \left(Cr^{mol} \times \mathrm{MW}^{\mathrm{Cr}} \times \mathrm{CP}^{\mathrm{eff}}\right) + \sum_q \left(Ni^{mol} \times \mathrm{MW}^{\mathrm{Ni}} \times \mathrm{CP}^{\mathrm{eff}}\right) + \sum_q \left(Zn^{mol} \times \mathrm{MW}^{\mathrm{Zn}} \times \mathrm{CP}^{\mathrm{eff}}\right)}{\mathrm{CF}^{\mathrm{gMT}}} \tag{8}$$

$$SS = \frac{\left(F_{\mathrm{r}}^{ar} \times \left(C_{r,COD}^{ar} - C_{r,COD}^{er}\right) \times 1 - \mathrm{RR}_{\mathrm{r}}^{\mathrm{ss}}\right) \times \mathrm{Ar}^{\mathrm{TS}}\right)}{\mathrm{CF}^{\mathrm{gkg}}} + \frac{\left(F_{\mathrm{r}}^{ar} \times \left(C_{r,TSS}^{ar} - C_{r,TSS}^{er}\right) \times \mathrm{TSS}^{\mathrm{rmv}}\right)}{\mathrm{CF}^{\mathrm{gkg}}} \tag{9}$$

Eq(10) is regarding the annual revenue. Rev is the combination of the annual revenue from selling (i) the supply water (Rev^{SW}), (ii) the electricity generated from the biogas (Rev^{Bg}), (iii) the solid digestate (Rev^{SD}), (iv) the struvite (Rev^{Stv}), (v) the ammonium sulphate (Rev^{AS}), (vi) the precipitated metal hydroxides (Rev^{PM}), and (vii) the solid sludge (Rev^{SS}). Total TAC is obtained through the summation of individual TAC work section of (i) the supply water (TAC^{SW}), (ii) biogas (TAC^{Bg}), (iii) struvite (TAC^{Stv}), (iv) ammonia (TAC^{Am}), (v) metal recovery (TAC^{mr}), (vi) aerobic digestion (TAC^{Ar}), (vii) pipeline (TAC^{pl}), (viii) water tank (TAC^{wt}), and (ix) disinfection (TAC^{DUV}) as per Eq(11).

$$Rev = Rev^{SW} + Rev^{Bg} + Rev^{SD} + Rev^{Stv} + Rev^{AS} + Rev^{PM} + Rev^{SS} \tag{10}$$

$$TAC = TAC^{SW} + TAC^{Bg} + TAC^{Stv} + TAV^{Am} + TAC^{mr} + TAC^{Ar} + TAC^{pl} + TAC^{wt} + TAC^{DUV} \tag{11}$$

In this study, the multi-objective optimization method is based on the concept of fuzzy constraints optimization. The degree of satisfaction, namely lambda (λ), is the value that is intended to be maximized. The concept of λ regarding the multi-objective optimization is described by Tan et al. (2020). λ is incorporated in the fuzzy optimization constraints as per Eqs(12) – (15). Pr^l and Pr^u is the lower bound and upper bound of Pr each. The same concept applies for the lower bound and upper bound of RR and WR.

$$\frac{Pr - Pr^l}{Pr^u - Pr^l} \geq \lambda \tag{12}$$

$$\frac{RR - RR^l}{RR^u - RR^l} \geq \lambda \tag{13}$$

$$\frac{WR - WR^l}{WR^u - WR^l} \geq \lambda \tag{14}$$

$$Maximise\ \lambda;\ 0 \leq \lambda \leq 1 \tag{15}$$

3. Case study

A case study is conducted with based on the list of demands streams as in Table 1 and the water source and food waste streams as in the Table 2. The maximum flow rate of the demand is 800 m^3/h each. Certain type of water source is imposed with certain amount of processing fee. Each type of water demand has different value of selling price. Other applicable parameters are referred from Misrol et al. (2021b). Each objective function was computed in separate run each. After that, the value of Pr, RR, and WR were tabulated as it was then used to compute the maximum $\boldsymbol{\lambda}$ value.

Table 1: Properties of the demands

Streams	Flow Rate (m^3/h)	Selling Price (USD/m^3) Upper Bound
Water demand – Boiler feed water	Upper bound: 800 m^3/h	1.42
Water demand – Process water	Upper bound: 800 m^3/h	1.35
Water demand – Cooling water	Upper bound: 800 m^3/h	0.71
Water demand – Toilet flushing grade water	Upper bound: 800 m^3/h	0.68

Table 2: Properties of the sources

Streams	Flow Rate (m^3/h)	Processing Fee (USD/m^3)
Water source – Ablution greywater	1	N/A
Water source – Households greywater	125	N/A
Water source – Blackwater	12.5	0.3
Water source – Total industrial boiler blowdown	81	N/A
Water source – Total industrial cooling water blowdown	61	N/A
Water source – Oil palm refinery effluents	2.6	1.2
Water source – Pharmaceutical plant effluents	120	1.2
Water source – Semiconductor industry greywater effluents	44.1	N/A
Water source – Confectionary industry effluents	10	1.2
Water source – Chicken processing industry effluents	307	1.2
Water source – Milk industry effluents	17	1.2
Food waste	0.8	70

4. Results and discussion

A computer with processor capacity of IntelCore i3-8130U 2.2 GHz was used to find the optimal solution and BARON is used as the solver. The maximum computation time was set at 1,000 s. The lower bound and upper bound value of Pr each is 0.1 USD/y and 2.12 M USD/y. The lower bound and upper bound value of RR each is 0.49 t/h and 0.82 t/h. The lower bound of WR is 473 t/h and its upper bound value is 651 t/h. The optimal network selected is shown in Figure 2.

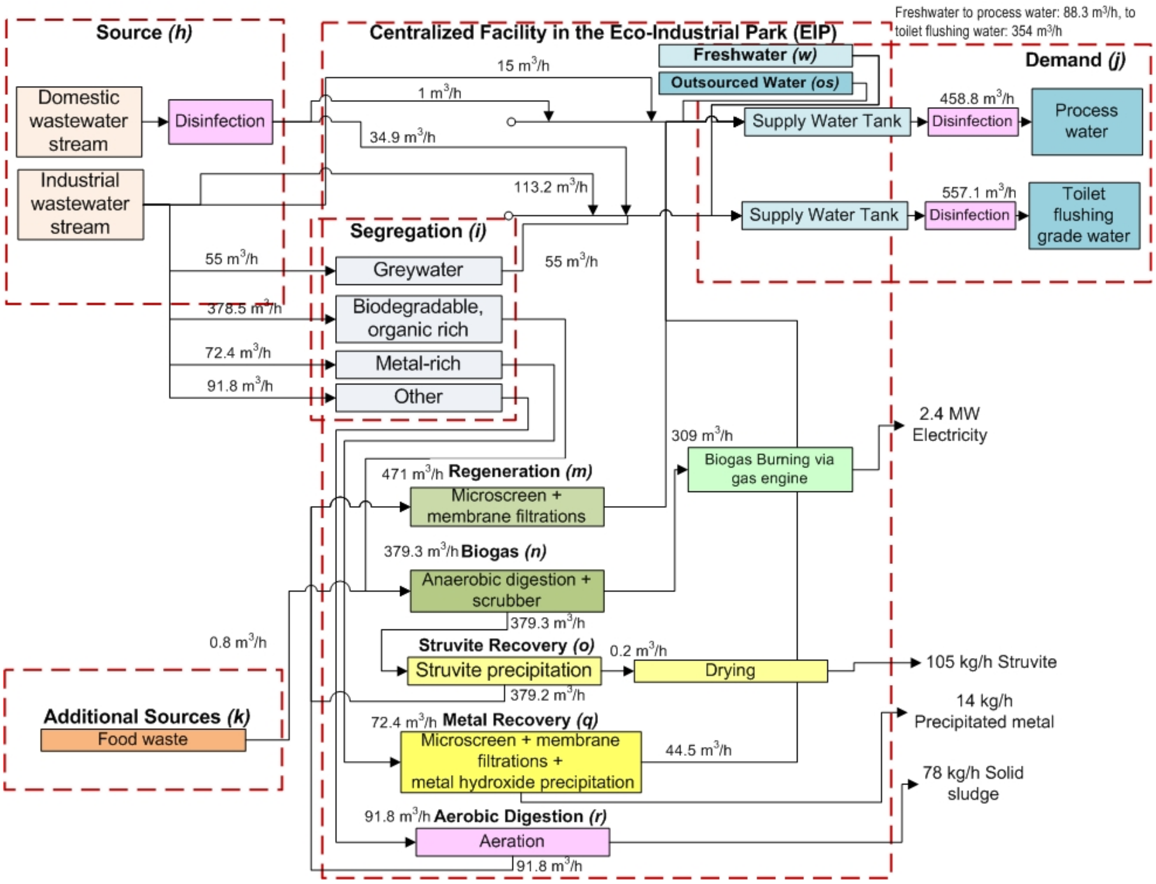

Figure 2: The proposed optimization solution

The directly reused water for process water and toilet flushing grade water is 15 m^3/h and 113.2 m^3/h each. The greywater is segregated for reuse at amount of 55 m^3/h. 2.4 MW of electricity is generated based on the anaerobic digestion of 379.3 m^3/h stream. Struvite is then precipitated from the biogas effluent at amount of 105 kg/h. The struvite recovery effluent is further sent to the regeneration (379.2 m3/h). The metal recovery stream is sourced from the industrial sources with flow rate of 72.4 m^3/h. The metal recovery process generates 44.5 m^3/h of permeate that is reused for process water application and it also precipitates 14 kg/h of metal hydroxides. A total of 442.4 m^3/h of freshwater and 1 m^3/h of outsourced water are used for mixing purpose in order to supply process water and toilet flushing grade water to the demand. Total supply for each type of demand is 458.8 m^3/h and 557.1 m^3/h each. The annual profit obtained is 1.2 M USD/y and total amount of recovered resources is 0.68 t/h, which includes the biogas, struvite, metal hydroxides, and solid sludges. The volume of reused, reclaimed, and outsourced water streams combined is 573.5 m^3/h. This corresponds to the $\boldsymbol{\lambda}$ value of 0.56. Table 3 provides the summary of the objective functions and the λ values obtained from the optimization exercise. Though the annual profit is relatively lower, the cumulative amount of recovered resources increases, and the amount reused, and reclaimed water remains substantial. The multi-objective optimization exercise based on the fuzzy optimization constraints approach compromises the needs to obtain the relatively best solution based different type of objective functions, which each may affect other adversely e.g., if profit is to be maximized, the amount of recovered resources may not be the maximum. The fuzzy optimization constraints method is relatively simpler although other method e.g. ε-method combined with the Pareto Optimal Front provides a range of optimal solutions for the multi-objectives optimization. It is intended to apply the latter approach into the next study

4. Conclusion

In this study, a multi-objective optimization to develop an integrated energy-water-waste nexus is performed. The integrated network is able to reuse and reclaim the wastewater streams, which means the amount of freshwater can be minimized. The recovery of 2.4 MW of renewable energy, 105 dry kg/h of struvite, 14 dry t/h of metal hydroxides, 78 kg/h of solid sludge, and the freshwater reduction by 56 % can be achieved through the approach. The multi-objective optimization through the fuzzy optimization constraints method offers a trade-off between the individual objective functions. This study offers a perspective on how the intended goals can be optimized collectively so that the economic and the environmental benefits can be obtained simultaneously.

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