An optimal water regeneration, reuse and resource recovery network integrating domestic and industrial sources

M A Misrol, S R Wan Alwi, J S Lim, and Z A Manan

Process Systems Engineering Centre (PROSPECT), Research Institute for Sustainable Environment (RISE), School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia.

*Corresponding author: syarifah@utm.my

Abstract. Implementation of reduce, reuse, recycle strategies are pertinent to ensure sustainability. There are studies to minimize freshwater reduction via mathematical modelling method. However, study to explore possibilities of combining both domestic and industrial wastewater regeneration, reuse, and resource recovery in a centralised facility is yet to be made. This study develops a mathematical model that could provide optimal water regeneration and reuse network that also be capable to produce biogas from the selected wastewater streams. The main objective is to maximize profit from the network established. A superstructure that consists of sources, outsource, freshwater, mixers-demands, and biogas systems is developed. A combination of the sources, regenerated sources, outsource water, and freshwater is performed in the mixers. The multi integer nonlinear programming (MINLP) model is optimized by BARON solver in General Algebraic Modelling System (GAMS) software. The case study result shows that freshwater water saving is 42% and 377 kW of electricity can be generated from the biogas produced. This offers possibilities to consider the idea of the centralised wastewater facility that considers water regeneration, reuse, and resource recovery for both domestic and industrials sources, as the Eco-Industrial Park (EIP) may serve as the suitable platform.

1. Introduction

The circular economy concept emphasizes the need to minimize usage of fresh resources via the 3R strategies namely reduce, reuse, and recycle. Usage of water in domestic and industrial activities contributes to more than 50% total consumption in Malaysia [1]. Hence, there is a need to reduce water consumption in the areas as the wastewater can be regenerated, reused, and/or treated in order to reduce the freshwater consumption. The strategies to manage water include elimination, reduction, outsource, regeneration, and recycling [2].

There are many researches that have been conducted to obtain optimal water network. Ahmad Fadzil et al. [3] has proposed the concept of one-way centralised water reuse header (CWRH) for application at Total Site. However, the usage is limited to a single contaminant only. Li et al. [4] developed a method that is based on heuristic considering multiple contaminants for usage of batch networks. Fan et al. [5] presented an iterative method which considers simultaneous reuse, regeneration reuse/recycling and treatment of the wastewater as the result is comparable with the mathematical method.

A multi-objective optimization model regarding optimal water-energy-nexus for a residential complex has been studied by Núñez-López et al. [6]. The model incorporates water network synthesis...
and it also incorporates wastewater reclamation and harvesting of the rainwater. They also exclude water regeneration and/or outsourcing. However, the model proposed also does not specify properties of the sources and demands and applicable for residential complex level only.

As the wastewater can be regenerated for subsequent reuse, a resource recovery step can also be conducted simultaneously to recover or extract any valuable elements or compounds in it. This includes cellulose, biogas, phosphorus, nitrogen, heavy metal, and bioplastics, for example [7]. The recovery work can be considered as an indirect regeneration or treatment of the wastewater as the contaminant content may be removed during such process.

O’Dwyer et al. [8] developed an optimisation framework that perform wastewater treatment/recovery in an eco-industrial park. It considers pipeline cost and the spatial aspects regarding the sources’ location. The same main author presented a mixed integer linear non-integer programming (MILP) that can generate a set of treated output streams based a combination of different treatment recovery technologies [9].

However, there is a research gap that requires attention; an optimal water network combining both domestic and industrial sources that perform simultaneous regeneration, reuse and resource recovery works is yet to be developed. Some of the wastewaters from the domestic source e.g ablution water from mosque and households’ greywater can be applicable for regeneration and reuse for industrial usage. The low strength industrial wastewater, which is defined as wastewater that has Chemical Oxygen Demand (COD) content lower than 1,000 mg/L, may not require extensive treatment as the high strength wastewater (COD content is higher than 7,000 mg/L), while the latter may have certain valuable contents that can be recovered. The regenerated water, in reality, must meet the demands’ properties, given certain demand may require different contaminant content e.g. process water may require a relatively ‘cleaner’ water compared to cooling water.

In this study, a mathematical model that could provide optimal water regeneration and reuse network that also be capable to produce biogas from the selected wastewater streams is developed. The main objective is to maximize profit from the network established. A superstructure that consists of sources, outsource, freshwater, mixers-demands, and biogas systems is developed in this study. A combination of the sources, regenerated sources, outsource water, and freshwater is performed in the mixers, subject to the demands’ contaminant properties, namely Chemical Oxygen Demand (COD) and Total Suspended Solid content (TSS). Section 2 will provide description of the model further.

2. Superstructure and model development

2.1. Superstructure

Superstructure of the study is shown in Figure 1. The superstructure consists of sources, demands, outsource, and biogas sets. There are four type of sources, namely ablution water from mosque, greywater from households, low strength industrial wastewater, and high strength industrial wastewater. The detailed properties of each stream are provided in the Section 3 – Case Study. All the sources’ flow will have options, either to be directly sent to the mixer, or to be regenerated prior to the mixer, to be used as feedstock for biogas production, or to be sent to the conventional wastewater treatment plant. However, there is exception regarding the regeneration unit for the high strength industrial wastewater as it requires relatively extensive regeneration steps i.e primary, secondary, and tertiary treatment [10], hence providing a regeneration unit option is not suggested.
Figure 1. Superstructure of the study

At the mixer, the streams from outsource, freshwater, the regenerated streams, and the treated streams via ultrafiltration (UF) and reverse osmosis (RO) will be combined, subject to the demands’ flow rate and minimum contaminant content properties. The list of the demands’ properties will be provided in the Section 3. The regeneration units and the combined UF and RO systems (later written as UF+RO) have fixed contaminant removal percentage respectively.

The sources that are sent to the biogas digester will be used to produce biogas for subsequent electricity generation. There is a certain minimal COD content level that the stream needs to have, which in this case is 7,000 mg/L. The purified biogas will used in the gas engine to generate renewable electricity, which it acts a source of revenue. The remaining stream, namely digestate in the digester will be sent to the decanter centrifuge for a solid-liquid separation process. The solid portion of the digestate will be used as an additional fuel for the boilers, while the digestate’s liquid portion will be sent to the UF and RO systems. The recovery of struvite or nitrogen from the liquid digestate is not considered in this study. The purified water from the UF+RO will be sent to the mixers, thus the amount of freshwater can be minimized. The UF+RO will be disposed accordingly; however, it is not in the study’s scope. The model is developed on the centralized facility service provider’s point of view, which it obtains revenue from processing fee of industrial wastewaters and selling of treated water, based on type of the demand and its respective contaminant content. The detailed mathematical equations used in this study are provided in section 2.2.
2.2. Mathematical formulation

Main objective of the model is to obtain maximum profit \((Pr)\) from selling of the renewable electricity, selling of regenerated water to the demand(s), processing fee of industrial wastewaters, and selling the solid digestate as the solid fuel. The list of equations for the model are listed as follows:

Objective function:

\[
Pr = Rev - TIC - TOC \tag{1}
\]

where \(Rev\) is revenue generated as per described above. \(TIC\) stands for total annualized capital cost of the whole systems combined. \(TOC\) is the associated total operation and maintenance cost.

Constraints:

Source-to-demand flow rate constraint:

\(F^s_h\) is the flow rate of the sources. \(F^{srg}_{h,r}, F^{bg}_{h,k}, F^{sd}_{h,i}, \) and \(F^{ow}_{h}\) are the flow rate from the sources to the regeneration units, mixers, biogas digester, and the conventional wastewater treatment plant respectively. \(C^s_{h,p}\) is the contaminant content of the sources. \(B_{h,r}\) is a binary parameter to assign the sources \(h\) to the regeneration units, where \(K\) is a large integer value to limit the flow rate from the sources of the \(r, F^r_{rg}\) is the flowrate at the regeneration unit. \(C^r_{r,p}\) is the respective contaminant content. \(A^r_{r,egen}\) is filtration yield of the regeneration units as \(F^r_{r,rgnd}\) is the flow rate of the regenerated water. \(A^r_{r,contremoval}\) is contaminant removal yield of the regeneration unit and the resulting reduced contaminant content of the regenerated stream is \(C^r_{r,rgnd}\), \(F^r_{r,i}\) is the flow rate of the regenerated water to the mixers. \(F^d_i\) is the flow rate of the demand and \(C^c_{i,p}\) is the contaminant limit of it. \(Y^d_i\) is a binary variable regarding existence of connection regarding water supply to the demand. \(F^{fw}_{i}, F^{owd}_{i}\), and \(F^{pmtd}_{k,l}\) are the flow rate of freshwater, outsourced water, and the treated water (via UF+RO) from the biogas set, respectively. \(C^{fw}_{i}\) is contaminant content of the freshwater. \(C^{pmt}_{k,p}\) is the contaminant content of the permeate. \(C^{ow}_{p}\) is the contaminant content of the outsourced water.

\[
F^s_h = \sum_r F^{srg}_{h,r} + \sum_k F^{bg}_{h,k} + \sum_i F^{sd}_{h,i} + F^{ow}_{h} \quad \forall h \tag{2}
\]

\[
F^s_h \times C^s_{h,p} = (F^{srg}_{h,r} \times C^{s}_{h,p}) + \sum_k (F^{bg}_{h,k} \times C^{s}_{h,p}) + \sum_i (F^{sd}_{h,i} \times C^{s}_{h,p}) + (F^{ow}_{h} \times C^{s}_{h,p}) \quad \forall h,r,p \tag{3}
\]

\[
K \times B_{h,r} = F^{srg}_{h,r} \quad \forall h,r \tag{4}
\]

\[
F^r_{rg} = \sum_h F^{srg}_{h,r} \quad \forall r \tag{5}
\]

\[
F^r_{rg} \times C^r_{r,p} = \sum_h (F^{srg}_{h,r} \times C^{s}_{h,p}) \quad \forall r,p \tag{6}
\]

\[
F^r_{rg} \times A^r_{r,egen} = F^r_{r,rgnd} \quad \forall r \tag{7}
\]

\[
C^r_{r,p} \times A^r_{r,contremoval} = C^r_{r,rgnd} \quad \forall r,p \tag{8}
\]

\[
F^r_{r,rgnd} = \sum_i F^r_{r,i,rgnd} \quad \forall r \tag{9}
\]

\[
F^d_i = Y^d_i \times (\sum_r F^r_{r,i,rgnd} + \sum_h F^{sd}_{h,i} + F^{fw}_{i} + F^{owd}_{i} + \sum_k F^{pmtd}_{k,l}) \quad \forall i \tag{10}
\]
\[
F_i^d \leq K \times Y_i^d \quad V i
\]

\[
F_i^d \times C_{ip} = \sum_r(F_{r,i}^{gnd} \times C_{r,p}^{gnd}) + \sum_h(F_{h,i}^{sl} \times C_{h,p}^{sl}) + (F_{i}^{fw} \times C_{p}^{fw}) + \sum_{os}(F_{os,i}^{owd} \times C_{p}^{ow}) + \sum_{k}(F_{k,i}^{pmtd} \times C_{k,p}^{pmt}) \quad V i, p
\]

Outlet constraints:

Maximum flow rate of outsource supply is a multiplication product of roof area \(AR\), average monthly rainfall \(AMF\), and flow rate factor \(ff\). \(F_{os,i}^{owd}\) is the flow rate of outsource to the mixers. Determination of \(F_{os}^{ow}\) is based on formulation written by the Department of Irrigation and Drainage, Ministry of Environment and Water of Malaysia (MEWA) [11]. Details of the parameters used regarding the outsource investment cost is given in the results and discussion section.

\[
F_{os}^{ow} = AR \times AMF \times ff \quad V os
\]

\[
F_{os}^{ow} = \sum_i F_{os,i}^{owd} \quad V os
\]

Source-to-biogas flow rate constraint:

Flow rate of the biogas digester \(F_{k,bg}^{bg}\) is a summation of flowrate of the sources to the biogas digester \(F_{h,k}^{bg}\). \(C_{k,p}^{bg}\) is the contaminant content of the stream prior to the anaerobic digestion process. A multiplication of \(r_k^{bg}\) and \(c_{k,p}^{bg}\) \((p = \text{COD})\) will result in the total COD available for the biogas production process \(TCOD\). \(B_g\) is the amount of raw biogas produced. The equation to produce biogas is based on the study by Misrol et al. [12]. \(Bg^{eff}\) and \(COD^{eff}\) is the COD removal and the COD conversion to methane constant respectively. \(CH4^{cvt}\) is the percentage of methane content in the raw biogas and \(CH4^{dsty}\) is the density of the methane gas. \(CH4^{cv}\) is the calorific value of the methane and \(GE^{eff}\) is the efficiency of the gas engine to generate electricity. \(Bp\) is the electricity power generated from the biogas burning. \(AD_p\) is the contaminant reduction factor during the anaerobic digestion process. \(TRS\) is the remaining solid content in the stream after the anaerobic digestion step. Solid digestate recovered \(SD\) is obtained via multiplication of \(TRS\) with solid fraction factor during the centrifugation process \(SP^{dc}\). The centrifugation step will generate two streams i.e the solid digestate \(SD\) and the liquid digestate \(L_i^{dc}\). \(L_i^{dc}\) is obtained via multiplication of \(F_k^{bg}\) with liquid fraction factor during the separation process \(LF^{dc}\). \(C_{k,p}^{bg}\) is the contaminant content of the liquid digestate. \(UF^{eff}\) and \(RO^{eff}\) is the filtration efficiency of the UF and the RO respectively. \(F_{k}^{pmtd}\) is the permeate generated after the UF+RO. \(AUF_p\) and \(ARO_p\) are the contaminant removal constant of the UF and the RO respectively. \(C_{k,p}^{pmt}\) is the resulting contaminant content of the permeate after the UF+RO. \(F_{k,i}^{pmtd}\) is the flow rate of the permeate to the demand.

\[
F_{k,bg}^{bg} = \sum_h F_{h,k}^{bg} \quad \forall k
\]

\[
F_{k,bg}^{bg} \times C_{k,p}^{bg} = \sum_h(F_{h,k}^{bg} \times C_{h,p}^{sl}) \quad \forall k,p
\]

\[
F_{k,bg}^{bg} \times C_{k,p}^{bg} = TotalCOD \quad \text{; } p = \text{COD}
\]

\[
\frac{TCOD \times Bg^{eff} \times COD^{eff}}{1.000 \times CH4^{cvt} \times CH4^{dsty}} = B_g
\]
\[
\frac{B_g \times CHA^{cw} \times GE^{eff} \times CHA^{ctt}}{3,600} = BgP
\]  

(19)

\[
F_k^{bg} \times AD_p = TRS
\]  

; \( k = \text{K1, p = TSS} \)  

(20)

\[
SD \times (1e^{-6}) = TRS \times SF^{dc}
\]  

(21)

\[
F_k^{bg} \times LF^{dc} = F_k^{ld}
\]  

(22)

\[
F_k^{bg} \times C_{k,p}^{bg} \times AD_p \times LF^{dc} = F_k^{ld} \times C_{k,p}^{ld}
\]  

(23)

\[
F_k^{pmt} = F_k^{ld} \times UFeff \times RO^{eff}
\]  

(24)

\[
F_k^{pmt} \times C_{k,p}^{pmt} = F_k^{ld} \times C_{k,p}^{ld} \times AUF_p \times ARO_p
\]  

(25)

\[
F_k^{pmt} = \sum_i F_{k,i}^{pmt}
\]  

(26)

\[
F_k^{pmt} \times C_{k,p}^{pmt} = \sum_i(F_{k,i}^{pmtd} \times C_{k,p}^{pmt})
\]  

(27)

Revenue generation:

There are four sources of revenue in the model i.e via selling electricity from burning the biogas \( BgR \), usage of the solid digestate as the solid fuel \( SDR \), selling of treated water to the applicable industries or consumers \( STW \) and annual processing fee of industrial wastewaters \( WWF \). \( BgP \) is amount of electricity power generated from the biogas engine and \( AWH \) is the annual working hour. \( p^{ect} \) is the selling price of the electricity. \( P^{SD} \) is the price of the digestate as solid fuel. \( STW \) and \( P^{fw} \) is the revenue from selling the treated water and selling price of the treated water respectively. Selling price for boiler feed water is different from cooling water, for example. \( P^{fw} \) is the cost of freshwater. \( FF \) is processing fee of treating wastewater that the sources need to pay to the centralized facility. \( FF \) is amount of processing fee based in USD/m³

\[
Rev = BGR + SDR + STW + WWF
\]  

(28)

\[
BgP \times 1000 \times AWH \times P^{ect} = BgR
\]  

(29)

\[
SDR = SD \times P^{SD} \times AWH
\]  

(30)

\[
STW = \sum_i(F_i^{ld} \times P^{tw} \times AWH) - \sum_i(F_i^{fw} \times P_i^{fw} \times AWH)
\]  

(31)

\[
WWF = \sum_h[(F_h^{g} - F_h^{ww}) \times FF_h^{g}] \times AWH
\]  

(32)

Investment, Operating and Maintenance (O&M) Cost estimations:

The annualized total investment cost \( TIC \) is summation of investment cost of the digester \( ICD \), scrubber \( ICS \), gas engine \( IGE \), decanter \( IDC \), and piping connection \( ICP \), and outsourcing \( ICO \). Investment cost of the NF, UF and UF+RO are covered in the O&M equations later. ICP consists of piping elements (i) from the sources to the centralized facility, and (ii) from the centralized facility to the demands combined. \( Af \) is the annualization factor. Cost equations for \( ICD \) and \( ICS \) are based from
the six-tenth formula as by Misrol et al. [12]. ICGE is derived from IEA [13] ICDC is based from cost estimation formula by Seider et al. [14].

\[
TIC = (ICD + ICS + ICGE + ICDC + ICP + ICO) \times Af
\] (33)

\[
ICD = 168,000 \times \left( \frac{Bg}{500} \right)^{0.6}
\] (34)

\[
ICS = 1,380,000 \times \left( \frac{Bg}{500} \right)^{0.6}
\] (35)

\[
ICGE = 1,050,000 \times BgP
\] (36)

\[
ICDC = 68,040 \times SD^{0.5}
\] (37)

ICP is a combination of connection cost to connect streams (i) from the source to the centralized facility ICPS, and (ii) from the centralized facility to the demands ICPS. The ICS consists of the pipeline cost of the sources ICPS, pump cost of the sources ICPS, and motor cost of the sources ICMS. The ICDC consists of the pipeline cost of the demand(s) ICPS, pump cost of the demand(s) ICPS, and motor cost of the demand(s) ICMD. The pipeline cost of the sources PC^S_h and the demand(s) PC^D_i are mainly based from Marchionni et al. [18]. Incorporation of binary variable specifically for the demand is required in order to ensure that only the applicable demand is considered, thus avoiding costing consideration of non-existing supply to the demand. Yrafted is a binary variable regarding existence of connection regarding supply to the demand. Dh is the distance of the sources to the centralized facility in km, and D_i^d is distance between the centralized facility to the demands. power_h^S and power_i^D is the power required to 'bring' the sources to the centralized facility and from it to the demand(s) respectively.

\[
ICP = ICS + ICDC
\] (38)

\[
ICPS = ICP + ICPS + ICMS
\] (39)

\[
ICPS = ICP + ICPS + ICMD
\] (40)

\[
ICPS = \sum_h (PC^S_h \times D_h^d)
\] (41)

\[
ICPS = \sum_h \left[ 6900 + (206) \left( \frac{PC^S_h \times 1000}{3600} \right)^{0.9} \right]
\] (42)

\[
ICPS = \sum_i \left[ (-950) + (1,770) \left( \text{power}_h^S \right)^{0.6} \right]
\] (43)

\[
ICPS = \sum_i (PC^D_i \times D_i^d \times Y_i^d)
\] (44)

\[
ICPS = \sum_i \left[ \left( 6900 + (206) \left( \frac{PC^D_i \times 1000}{3600} \right)^{0.9} \right) \times Y_i^d \right]
\] (45)

\[
ICPS = \sum_i \left[ (-950) + (1,770) \left( \text{power}_i^D \right)^{0.6} \right] \times Y_i^d
\] (46)

Costing regarding the ICO is based from Towler and Sinnott [15] and the water tank volume required is referred from MEWA [11]. tankvf is the volume factor of the water tank.
\[ ICO = (5,000) + (1,400) \left( \frac{AR \times AMR \times f_{ff}}{tank^{rf}} \right)^{(0.7)} \] (47)

Total operation and maintenance cost \( TOC \) is a summation of operation and maintenance cost of the biogas digester \( OMD \), scrubber \( OMS \), gas engine \( OMGE \), the decanter \( OMDc \), and the regeneration units, which is as the NF systems \( OMNF \) or UF systems \( OMUF \), the UF+RO filtration \( OMUFRO \), the connection item \( OMP \), and the outsource \( OMO \). The formulations for \( OMD \) and \( OMS \) are based from Misrol et al. [12]. \( OnM^GE \) is a constant regarding the O&M cost of the gas engine. \( OnM^{base} \) is the percentage of typical maintenance cost (usually 5%). \( TC^{UF} \), \( TC^{RO} \), and \( TC^{NF} \) is the treatment unit cost (USD/m³) of the UF, RO, and NF respectively as per referred from Tran et al. [16]. \( C^{ect} \) is the cost of electricity.

\[ TOC = OMD + OMS + OMGE + OMDc + OMNF + OMUF + OMUFRO + OMP + OMO \] (48)

\[ OMGE = OnM^GE \times BgP \] (49)

\[ OMDc = ICDc \times OnM^{base} \] (50)

\[ OMUFRO = (TC^{UF} \times F_k^{ld}) + (TC^{RO} \times UF^{eff} \times F_k^{ld}) \] \; k = 1 (51)

\[ OMNF = TC^{NF} \times F_r^{rg} \] \; r = 1 (52)

\[ OMUF = TC^{UF} \times F_r^{rg} \] \; r = 2 (53)

\[ OMP = (ICP \times OnM^{base}) + \sum_{h}(power_h^s \times C^{ec} \times AWH) + \sum_{i}(power_i^d \times C^{ec} \times AWH \times Y_i^d) \] (54)

\[ OMO = ICO \times OnM^{base} \] (55)

Since the model involves the binary variables and the usage of non-linear equations, it is formulated as the mixed-integer non-linear program (MINLP).

3. Case study

A case study is based on parameters and information tabulated in Tables 1, 2, and 3. The distance of the ablution water from mosque and household’s greywater from the centralized facility is set at 15 km. The low and high strength wastewaters are located 1 km from the centralized facility. Properties of the sources, freshwater, outsourced water, and demands are shown in Table 1. There is not fixed value regarding of the demands’ flow rate as the upper bound is set at 1,000 m³/h. In this study, density of the wastewaters is assumed at 1 metric ton/m³:

| Sources | Hourly Flow Rate (m³/h) | COD (mg/L)* | TSS (mg/L) | Distance from the Centralized Facility (km) | Processing Fee from the Centralized Facility (USD/m³) | Reference |
|---------|-------------------------|-------------|------------|------------------------------------------|-------------------------------------------------|-----------|
| Ablution water from mosque | 1 | 31 | 31 | 15 | N/A | [17] |
| Greywater from households | 94 | 250 | 200 | 15 | N/A | [18] |
Sources | Hourly Flow Rate (m$^3$/h) | COD (mg/L)* | TSS (mg/L) | Distance from the Centralized Facility (km) | Processing Fee from the Centralized Facility (USD/m$^3$) | Reference
---|---|---|---|---|---|---
Low strength industrial wastewater | 15 | 900 | 200 | 1 | 0.80 | [19]
High strength industrial wastewater | 15 | 19,000 | 1,000 | 1 | 0.80 | [20]
Freshwater | 1.1 | 25 | 10 | N/A | N/A | [21]
Outsourced water | 1,000** | 14 | 15 | N/A | N/A | [22]
Process water | 1,000** | 60 | 5 | 1 | 1.35 | [23],[24]
Boiler feed water | 1,000** | 60 | 10 | 1 | 1.35 | [23],[24]
Cooling water | 1,000** | 75 | 100 | 1 | 0.68 | [24]
Irrigation | 1,000** | 100 | 300 | 1 | 0.68 | [21]

*The value is same if the unit is converted to kg/m$^3$ as per used in the model.
**Upper boundary

The filtration yield and the contaminant removal yield of the UF, NF, and RO is provided as per Table 2.

Table 2. The UF, NF, and RO removal yield

| Filtration unit | Filtration yield (%) | COD removal yield (%) | TSS removal yield (%) | Reference |
|---|---|---|---|---|
| UF | 90 | 85 | 98 | [10] |
| NF | 80 | 95 | 99 | [10] |
| RO | 75 | 97 | 99 | [10] |

Other parameters used in the model is shown via Table 3.

Table 3. Other parameters used in the mathematical model

| Parameters | Value |
|---|---|
| Annual operating hours, $AWH$ | 8,000 hours |
| Operating years of the system | 20 years i.e $Af = 0.05$ |
| Electricity cost, $C_{cst}$ | 0.08425 USD/kWh |
| Renewable electricity selling price, $P_{cst}$ | 0.089 USD/kWh |
| Selling price of solid digestate | USD 3/dry metric ton (MT) |
| Piping cost from the sources to the centralized facility, $ICostpipeline^h$ | Mosque: USD 2,500 per km [25] |
| | Households: USD 49,550 per km [26] |
| | Industry 1 USD 32,810 per km [26] |
| | Industry 2: USD 32,810 per km [26] |
| Pumping power required from the sources to the centralized facility, $power^h$ | Mosque: 4.55 kW |
| | Households: 43.2 kW |
| | Industry 1 1.15 kW |
| | Industry 2: 1.15 kW |
| | [27] |
| Piping cost from the centralized facility to the demand, $ICostpipeline^i$ | USD 50,440 per km [26] |
| Pumping power required from the centralized facility to the demand, $power^i$ | 2.97 kW [27] |
| Base percentage of the O&M cost, $OM_{base}$ | 5% |
### Parameters and Values

| Parameter                                      | Value                                      |
|------------------------------------------------|--------------------------------------------|
| Gas engine O&M cost, $O_nM^{\text{GE}}$       | USD 222/kW                                 |
| Outsource water tank volume factor, $tank^{\text{eff}}$ | 65%                                       |
| Roof area for rain harvesting, $AR$            | 5000 m²                                    |
| Average monthly rainfall, $AMR$               | 2.875 m/month                              |
| Flow rate factor, $ff$                        | 90%                                        |
| COD removal efficiency, $Bg^{\text{eff}}$     | 70%                                        |
| COD conversion to methane constant, $COD^{\text{eff}}$ | 0.25 m³ methane per kg of COD            |
| Percentage of methane content in the raw biogas, $CH_4^{\text{cte}}$ | 65%                                       |
| Density of the methane gas, $CH_4^{\text{dysty}}$ | 0.716 kg/m³                                |
| Calorific value of the methane, $CH_4^{\text{cv}}$ | 39.8 MJ/m³                                 |
| Efficiency of the gas engine to generate electricity | 49%                                        |
| Contaminant reduction factor during the anaerobic digestion process, $AD_p$ | COD = 0.30, TSS = 0.80                     |
| Solid fraction factor during the centrifugation process, $SF^{dc}$ | 48%                                        |
| Liquid fraction factor during the separation process, $LF^{dc}$ | 90%                                        |

*1 USD = 4 MYR as current exchange rate

### 4. Result and discussion

The mixed-integer non-linear program (MINLP) model is run via GAMS version 24.7.4 in a computer with processor capacity of IntelCore i3-8130U 2.2GHz. It was solved using BARON solver. Execution time takes less than 1 second. The optimal network selected is shown in Figure 2. The result’s validity is done via cross checking and calculation of the same result input in MS Excel. In order to ease understanding, the optimal network is translated into table form as per Table 4.

![Figure 2. The optimized superstructure.](image-url)
Table 4. The specific individual flow rate to the demands.

| Source(s)                        | Demand(s) (m$^3$/hour) |
|----------------------------------|------------------------|
|                                  | Process water | Boiler feed water | Cooling water | Irrigation |
| Ablution water from mosque       | N/A           | N/A              | N/A           | 1.00       |
| Households greywater             | N/A           | N/A              | N/A           | 90.4       |
| Low strength industrial wastewater | N/A           | N/A              | N/A           | N/A        |
| High strength industrial wastewater | N/A           | N/A              | N/A           | N/A        |
| Regen Unit 1                     | N/A           | 2.8              | N/A           | N/A        |
| Regen Unit 2                     | N/A           | 13.5             | N/A           | N/A        |
| Outsource                        | N/A           | 1.1              | N/A           | N/A        |
| Freshwater                       | N/A           | 12.6             | N/A           | 150        |
| UF+RO permeate                   | N/A           | 9.1              | N/A           | N/A        |
| Total cumulative flow rate for each demand (m$^3$/hour) | 0             | 39.1             | 0             | 241.4      |

The optimization result suggests that all the sources are used either as direct reuse, regeneration, or for biogas production. All of ablation water from mosque and most of the households’ greywater are sent for subsequent reuse for irrigation applications. 3.6 m$^3$/h of household greywater is sent to the UF regeneration, generating 2.8 m$^3$/h of UF permeate. All of the dairy industry wastewater is sent to the UF regeneration; 13.5 m$^3$/h of the UF permeate is generated as both permeates are used for the boiler feed water supply. All of the outsourced water, 12.6 m$^3$/h of freshwater and 9.1 m$^3$/h of the UF+RO permeate are also used for the same purpose; this corresponds to total amount of 39.1 m$^3$/h of water is able to be supplied for the boiler feed water usage. Total water supply for the irrigation application is 241.4 m$^3$/h as most of the supply is from the freshwater with amount of 150 m$^3$/h.

By default, the freshwater and the outsourced water properties cannot meet both demands’ properties as the formers require additional treatment e.g NF or RO in order meet the specifications. This is applicable in real world situation which the tap water requires ‘softening’ step prior to be used as boiler feed water, for example. Overall, the proposed solution is able to minimize freshwater usage by 42% (based on direct usage of the freshwater. If the incurred water loss from the filtration of freshwater, which may be in range of 10% – 30% of the input is considered, the value of freshwater minimization is even relatively higher).

All the high strength wastewater is used for biogas production. An estimated amount of 107.2 nm$^3$/hour raw biogas will be produced which will generate 377 kW of electricity. After the solid-liquid separation via the screw press, 5.8 dry kg/hour of digestate is generated. 13.5 m$^3$/hour of liquid digestate will be treated via the UF+RO systems prior to reuse.

The selling price of the supplied water is set at 10% lower from the typical cost. The processing fee of the industrial wastewater is also set at 50% lower [15]. The pricing mechanism may be pertinent as it provides the economic benefits to the involving parties i.e the sources providers and the demands, while at the same time the centralized wastewater utility service provider could also obtain profit. Total annualized capital cost for the whole proposed systems is calculated at USD 114,189 while the annual O&M cost is estimated at USD 641,173. Revenue generated is calculated at USD 1,210,856 per year while profit obtained is USD 455,494. Revenue of supplying water provides more than half of the revenue. Translated into local currency, it is equal to MYR 1,821,976 of yearly profit. The proposed systems may remove the conventional wastewater treatment necessities as a closed water circulation system can be achieved. That said, the filtrate from the UF and RO membrane still needs to be disposed as per procedure. In future, more extensive resource recovery options e.g phosphorus, nitrogen, and/or heavy metal recovery is foreseen to be considered for the next study.

5. Conclusion
In this study, a mathematical model to provide optimal water network while performing resource recovery works that is applicable for domestic and industrial sources is proposed. Optimization of the
input streams considering the COD and TSS has been performed together with consideration of the regeneration unit(s). Piping elements are also included based on certain distance between the sources and the centralized facility. The case study conducted shows that most of the regenerated or treated water can be reused except the membrane retentate. The possible water integration and the resource recovery works can be symbiotically applied while at the same time providing beneficial economic outcomes that are applicable for all the parties involved. In this case, the sources providers can minimize their cost of wastewater treatment, while the demands are able to minimize their supply water purchase cost. The centralized wastewater utility service provider can also obtain profit from the buying and selling service. The freshwater amount can be reduced by 42% and 377 kW of renewable electricity can be generated. For implementation in real world application, a further study is suggested, which may focus on the basic and detailed engineering aspects.

Acknowledgement
The authors thank Universiti Teknologi Malaysia (UTM) for funding the research presented in this paper via grant Q.J130000.3509.05G96, Q.J130000.2409.08G86 and Q.J130000.21A2.04E44.

Nomenclature

Sets

\( h \) Sources
\( i \) Demands
\( k \) Biogas
\( os \) Outsource
\( r \) Regeneration
\( p \) Contaminant content

Parameters

\( K \) Integer value to limit the flow rate from \( h \) to regen unit \( r \)
\( B_{h,r} \) Binary parameter to assign the sources \( h \) to regen unit \( r \)
\( F_{h}^{s} \) Flow rate of source \( h \) (\( m^3/h \))
\( C_{h,p}^{s} \) Contaminant content of source \( h \) (mg/L)
\( A_{r}^{regen} \) Percentage recovery factor at \( r \)
\( A_{r}^{contremoval} \) Contaminant removal factor at \( r \)
\( C_{p}^{fw} \) Contaminant content of freshwater (mg/L)
\( C_{p}^{ow} \) Contaminant content of outsourced water (mg/L)
\( AR \) Area of roof (m\(^2\))
\( AMR \) Average monthly rainfall (m/month)
\( ff \) Flow rate factor
\( tank_{vf} \) Outsource water tank volume factor (%)
\( Bg_{eff} \) COD removal efficiency (%)
\( COD_{eff} \) COD conversion to methane constant (\( m^3 \) methane per kg of COD)
\( CH_{4}^{ctt} \) Percentage of methane content in the raw biogas (%)
\( CH_{4}^{dsty} \) Density of the methane gas (kg/m\(^3\))
\( CH_{4}^{cv} \) Calorific value of the methane gas (MJ/m\(^3\))
\( GE_{eff} \) Efficiency of the gas engine to generate electricity (%)
\( AD_{p} \) Contaminant reduction factor during the anaerobic digestion process
\( SF_{dc} \) Solid fraction factor during the centrifugation process (%)
\( LF_{dc} \) Liquid fraction factor during the separation process (%)
\( UF_{eff} \) Percentage water recovery of UF (%)
**Variables**

- $RO_{eff}$: Percentage water recovery of RO (%)
- $AWH$: Annual working hour (hour)
- $C_{ect}$: Electricity cost (MYR/kWh)
- $p_{ect}$: Renewable electricity selling price (MYR/kWh)
- $AU_{F_p}$: Contaminant removal constant of the UF
- $AR_{O_p}$: Contaminant removal constant of the RO
- $PSD$: Selling price of solid digestate (USD/dry MT)
- $p_{tw}$: Selling price of the supplied water (USD/m$^3$)
- $Fee_h^s$: Processing fee of the industrial wastewater (USD/m$^3$)
- $PC_h^s$: Piping cost from the sources to the centralized facility (USD/km)
- $PC_i^d$: Piping cost from the centralized facility to the demand (USD/km)
- $D_h$: Distance of the sources to the centralized facility (km)
- $D_i$: Distance of the centralized facility to the demand(s) (km)
- $power_h^s$: Pumping power required from the sources to the centralized facility (kW)
- $power_i^d$: Pumping power required from the centralized facility to the demand (kW)
- $TC_{UF}$: Treatment unit cost of the UF (USD/m$^3$)
- $TC_{NF}$: Treatment unit cost of the NF (USD/m$^3$)
- $TC_{RO}$: Treatment unit cost of the RO (USD/m$^3$)
- $Af$: Annualization factor
- $p_{fw}$: Cost of freshwater (USD/m$^3$)
- $OnM_{GE}$: O&M cost of gas engine (USD/kW)
- $OnM_{base}$: Base percentage of the O&M cost (%)

- $F_h^s$: Flow rate from source h to regen unit r (m$^3$/hour)
- $F_r^d$: Flow rate at regen unit r (m$^3$/hour)
- $F_{k,r}^s$: Flow rate from source h to regeneration r (m$^3$/hour)
- $F_h^{sbg}$: Flow rate from source h to biogas k (m$^3$/hour)
- $F_k$: Flow rate at biogas k (m$^3$/hour)
- $F_h^{ww}$: Flow rate from source h to the wastewater treatment facility (m$^3$/hour)
- $F_h^{sd}$: Flow rate from source h to mixer at i (m$^3$/hour)
- $F_i^{d}$: Flow rate from mixer at i (m$^3$/hour)
- $C_r$: Contaminant content at regen unit r (mg/L)
- $F_{r}^{r,d}$: Flow rate of regenerated water (m$^3$/hour)
- $C_{r,p}$: Contaminant content of the regenerated water (mg/L)
- $F_{r,i}^{r,d}$: Flow rate from regen unit to mixer at i (m$^3$/hour)
- $F_i^{fw}$: Flow rate of freshwater (m$^3$/hour)
- $F_{i,os}^{fw}$: Flow rate of outsource (m$^3$/hour)
- $F_{i,osd}$: Flow rate from outsource to mixer at i (m$^3$/hour)
- $F_{k,i}^{pmnt}$: Flow rate from permeate (m$^3$/hour)
- $C_{k,p}$: Contaminant content of the permeate (mg/L)
- $F_{k,i}^{pmnt}$: Flow rate from permeate to mixer at i (m$^3$/hour)
- $TCOD$: Total COD mass load (mg)
- $Bg$: Amount of raw biogas produced (nm$^3$)
- $BgP$: Power generated from the biogas (MW)
**Total solid content in the biogas digester effluent stream (m³)**

**Solid content of the digestate after centrifugation (MT/hour)**

**Flow rate of the liquid digestate (m³/hour)**

**Contaminant content of the liquid digestate (mg/L)**

**Annual revenue generated (USD)**

**Annual revenue generated from selling of the solid digestate (USD)**

**Annual revenue of supplying treated water to the applicable industries or consumers (USD)**

**Annual processing fee of industrial wastewaters (USD)**

**Annual revenue generated from selling electricity (USD)**

**Power generated from biogas (MW)**

**Total annualized investment cost (USD)**

**Investment cost of biogas digester (USD)**

**Investment cost of biogas scrubber (USD)**

**Investment cost of gas engine (USD)**

**Investment cost of decanter centrifuge (USD)**

**Investment cost of piping facilitation (USD)**

**Connection cost of the sources (USD)**

**Connection cost of the demand(s) (USD)**

**Pipeline cost of the source(s) (USD)**

**Pipeline cost of the demand(s) (USD)**

**Pump cost of the source(s) (USD)**

**Pump cost of the demand(s) (USD)**

**Motor cost of the source(s) (USD)**

**Motor cost of the demand(s) (USD)**

**Investment cost of outsource (USD)**

**Total O&M cost (USD)**

**O&M cost of biogas digester (USD)**

**O&M cost of biogas scrubber (USD)**

**O&M cost of gas engine (USD)**

**O&M cost of decanter centrifuge (USD)**

**Annual treatment cost of the UF+RO (USD)**

**Annual treatment cost of the UF (USD)**

**Annual treatment cost of the NF (USD)**

**O&M cost of piping facilitation (USD)**

**O&M cost of outsource (USD)**

**Existence of connection between the centralized facility to the demand i**

**References**

[1] FAO 2016 Country Fact sheet 2016.

[2] Alwi S R W and Manan Z A 2013 10 - Water Pinch Analysis for Water Management and Minimisation: An Introduction Handbook of Process Integration (PI) Woodhead Publishing Series in Energy ed J J Klemeš (Woodhead Publishing) pp 353–82

[3] Fadzil A F A, Wan Alwi S R, Manan Z and Klemeš J J 2018 J. Clean. Prod. 200 174–87

[4] Li A, Liu C and Liu Z 2019 Chinese J. Chem. Eng. 27 1103–12

[5] Fan X-Y, Klemeš J J, Jia X and Liu Z-Y 2019 J. Clean. Prod. 240 118098

[6] Núñez-López J M, Rubio-Castro E, El-Halwagi M M and Ponce-Ortega J M 2018 Clean Technol.
Environ. Policy 20 1061–85

[7] van der Hoek J P, de Fooij H and Struiker A 2016 Resour. Conserv. Recycl. 113 53–64

[8] O'Dwyer E, Chen K, Wang H, Wang A, Shah N and Guo M 2020 Chem. Eng. J. 381 122643

[9] O'Dwyer E, Wang H, Wang A, Shah N and Guo M 2018 Optimisation of Wastewater Treatment and Recovery Solutions in Industrial Parks 28th European Symposium on Computer Aided Process Engineering Computer Aided Chemical Engineering vol 43, ed A Friedl, J J Klemes, S Radl, P S Varbanov and T Wallek (Elsevier) pp 1407–12

[10] Tchobanoglous G, Stensel H D, Tsuchihashi R and Burton F 2013 Metcalf and Eddy, AECOM - Wastewater Engineering: Treatment and Resource 2048

[11] MEWA 2017 Rainwater Harvesting Guidebook

[12] Misrol M A, Wan Alwi S R, Lim J S and Manan Z A 2019 IOP Conf. Ser. Mater. Sci. Eng. 702

[13] IEA 2010 Energy Technology system analysis programme: Combined Heat and Power 1–6

[14] Seider W D, Lewin D R, Seader J D, Widagdo S, Gani R, and Ng K M 2016 Product and process design principles : synthesis, analysis, and evaluation (New York : Wiley)

[15] Towler G and Sinnott R 2013 Chapter 7 - Capital Cost Estimating ed G Towler and R B T-C E D (Second E Sinnott (Boston: Butterworth-Heinemann) pp 307–54

[16] Tran Q K, Schwabe K A and Jassby D 2016 Environ. Sci. Technol. 50 9390–9

[17] Al Mamun A, Muyibi S A and Abdul Razak N A B 2014 Adv. Environ. Biol. 8 558–64

[18] Mohamed R M, Al-Gheethi A A, Aznin S S, Hasila A H, Wurochekke A A and Kassim A H 2017 Int. J. Energy Environ. Eng. 8 259–72

[19] Driessen W and Yspeert P 1999 Water Sci. Technol. 40 221–8

[20] Ismail Z, Mahmood N A N, Ghafar U S A, Umor N A and Muhammad S A F 2017 IOP Conf. Ser. Mater. Sci. Eng. 206 6–13

[21] INWQS 2014 National Water Quality Standards For Malaysia Parameter Source : EQR2006 National Water Quality Standards For Malaysia 1–5

[22] Asrah Bin Muhamad M and Abidin M Z 2016 Water Quality Assessment of Rainwater Collected from Rooftop at UTM

[23] Metcalf & Eddy I an A C, Asano T, Burton F and Leverenz H 2007 Water Reuse: Issues, Technologies, and Applications (New York: McGraw-Hill Education)

[24] Rodrigues S and and Liu Xujun 2009 China Reclaimed Water Reuse Regulations 1–11

[25] ATKÇ Hardware Trading Sdn Bhd 2020 High Density Polyethylene HDPE Pipe 63MM x 100M PN12.5 PE80 (SIRIM)

[26] Valentina M, Marta C, Conceição A and Didia C 2016 J. Water Resour. Plan. Manag. 142 4016003

[27] Matthew Milnes The Mathematics of Pumping Water AECOM Design Build Civil, Mechanical Engineering R. Acad. Eng.