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Synthesis of Water-Energy Network Considering Seasonality

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With the increase in water and energy demands to satisfy industrial processes requirements and convert raw materials into value-added products, natural resources are experiencing depletion stress. One of the effective solutions to decrease freshwater and energy consumption and production in industrial cities is to employ water-energy integration. Due to increasingly strict environmental regulations, integration networks became essential. Water and carbon footprints are reduced significantly via water and energy integration networks. The performance of the integration networks is affected by seasonal changes. Previous work ignored seasonal fluctuations in water/energy supply and demand or mainly utilized multi-period planning to consider seasonal variations while designing integrations networks. It is important to consider seasonal variations to reflect the real performance of the network and avoid operation disturbances. One of the drawbacks of multiperiod planning is the resulting complicated integration model. Multiperiod planning may result in implementation difficulties due to constraints on the piping layout that hinder its applicability. This paper investigates and assesses seasonal changes' impacts on different segments of the water-energy network using several tools. Based on seasonality assessment, a novel approach is proposed to design optimal water-energy integration network. The approach depends on designing the network units and utility system based on the maximum required capacity (i.e., peak conditions) to ensure that water/energy demands will be satisfied over the year. The water-energy network connectivity is determined based on average demand/supply while any water source-to-sink pipeline is designed based on maximum potential flowrate. The water network is designed based on the worst-case scenario of removal ratios to ensure the required water quality for each sink is satisfied for all connections over different seasons. A MINLP mathematical model was expanded to include the proposed approach. The objective function is to minimize the total annual cost (TAC) of the design. Finally, the framework was demonstrated by applying it to a case study which was solved using a stochastic programming tool to illustrate the applicability of the developed model. The results indicate that the optimal design of the water-energy network that considers seasonal changes in water/energy demands, and supplies can be achieved with the proposed method with a TAC of 78 MUSD/y without the need for multiperiod planning. The optimal treatment units selected in this case were one-stage and two-stage nanofiltration.

1. Introduction

The development of different sectors depends on utilizing water and energy. This includes using water and energy for residential, industrial, and auxiliary purposes. The extreme consumption of water and energy natural resources and the rapid increase in the global population lead to depletion danger. One of the main consumers is industrial activities. To mitigate this issue, various integration networks are designed and utilized. Seasonal variations need to be considered while designing water-energy integration networks to ensure continuous operation during different seasonal conditions over the year. Seasonal variability originating from different weather conditions has a direct impact on integration networks' components such as cooling systems, treatment units, desalination units, and utility systems. It is required to cover this gap by analyzing and assessing the significance of the water-energy network seasonal variations and developing a systematic approach for finding the optimal design that can handle seasonal variations. Several studies focused on developing flexible integration networks that are feasible, and energy efficient over different time periods. Earlier work focused on water-energy networks without considering seasonality while other work addressed seasonality issues by considering multi-period planning. Multiperiod planning was used for synthesizing heat exchanger networks. An

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early work considered a MILP model that aims to find minimum utility requirements with the fewest number of units in each period (Floudas and Grossmann, 1986).

Another study provided a MINLP model to design or retrofit heat exchanger network (HEN) that operates flexibly at different conditions (Papalexandri and Pistikopoulos, 1993). Kim and Han (2001) utilized heuristics and dynamic programming (DP) to develop a three-step approach for utility system short-term (days/weeks) multi-period planning. Another work focused on using total site analysis of industrial cluster after dividing the year into n-periods and identify the minimum and maximum energy supplies and demands (Bungener et al., 2015). Isafiade (2017) proposed a MINLP model to integrate renewables into the synthesis of HEN over different seasons of the operational year considering economic and environmental aspects. Hot utilities involved three levels of steam namely, HP, MP, and LP while cold utilities involved cold air and cooling water. A method for total site (TS) energy targeting considering daily (short-term), and seasonal (long-term) variations in energy supplies and demands was developed (Liew et al., 2018). The method utilized the total site energy targeting approach and the total site heat cascade to determine the short-term and long-term utility requirements.

Multiperiod planning was utilized for designing water networks. Burgara-Montero et al. (2013) designed distributed treatment systems for industrial discharges into watersheds using a multi-objective MINLP model. The model considers minimizing treatment unit TAC and pollutants' concentrations in the final destination. Bishnu et al. (2014) considered long-term planning for direct water reuse by two optimization models. The models provide the lowest cost design of the water network by minimizing the TAC and freshwater consumption. Arredondo-Ramírez et al. (2015) highlighted the optimal multi-period planning of agricultural water systems via multi-objective MINLP model that considers water collections, reuse, and distribution strategies. Another MINLP model considers the direct reuse of water and the regeneration of wastewater (Bishnu et al., 2017). The objective of the model is to minimize the TAC by long-term multi-period planning of water network considering the entire planning horizon. Another study explored water-energy nexus seasonality considering flowrates of water streams and electricity prices (Gaudard et al., 2018). Al-Mohannadi et al. (2020) proposed a MILP to evaluate CO_2 reduction policies using a two-step multiperiod planning approach.

Taheri (2021) developed a MINLP model. The model considers multiperiod planning of the water network in Eco-Industrial Park (EIP) targeting minimizing TAC. The model was applied for a three-period problem considering fluctuations in flowrate due to new plant construction within the EIP. The author stated that the obtained solution by GAMS might not be globally optimal due to model complexity and reformulation-linearization approach was used to alleviate the problem complexity. A recent study by Zhou et al. (2021) proposed MINLP model to design water network considering seasonal changes in water demands and supplies from multiple water resources. The model aims to minimize the TAC. The fluctuations in water flowrates over different periods were considered using multiperiod planning. Two technologies were considered for desalination which are ion exchange (IX) and reverse osmosis (RO). The results indicate that desalination technology selection depends on water price.

So far, most studies either ignored seasonal variations of water/energy supply and demand within industrial park networks or tackled seasonality issues by multiperiod planning. This gap needs to be addressed. It is essential to consider seasonal fluctuations in water and energy supply and demand which will reflect the real water-energy system and help maintain continuous operation. Multi-period planning may lead to complicated models which might be difficult to be solved and obtain globally optimal solutions. Implementation difficulties may hinder the applicability of the proposed models via muti-period planning due to constraints on the piping system affected by the geographical region. Figure 1 demonstrates the design of this study which focuses on three main elements. First, the study explored seasonality impacts on different components of the water-energy integration networks considering the water-energy nexus. Second, the significance of the observed variations was assessed. Third, based on performed assessment, a novel approach capable of handling seasonal fluctuations in water and energy demands within water-energy integration networks was proposed.

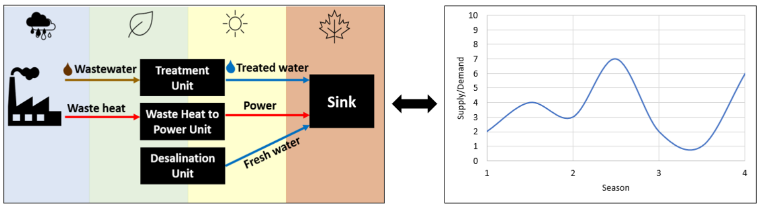

Figure 1: Illustration of study design

2. Mathematical Model

A mathematical optimization model is formulated based on minimizing the total annual cost (TAC) of the water-energy network considering seasonality. A mixed-integer nonlinear programming model (MINLP) was developed earlier by Alnouri et al. (2015) to design optimal water integration networks. The author illustrated a representation of an industrial city and used direct and indirect integration to integrate water sources and sinks while minimizing the total annual cost as the objective function. The proposed method indicates effective freshwater savings and wastewater minimization. The model was expanded by Fouladi et al. (2017) to consider the water-energy nexus. The model was extended and modified for the purpose of this study. The focus of this work is to find the optimal design of the water-energy network considering seasonal changes. The proposed approach depends on designing the water-energy connectivity based on average supplies and demands over the year, while considering minimum removal ratios of treatment units and maximum units' capacities. The network involves treatment units, cooling systems, and the waste-heat to power unit. The objective function is to minimize capital and operating cost including the cost of treatment, desalination, cooling, piping, wastewater discharges, and waste heat to power cost as indicated by Eq(1).

$$\begin{aligned} Total\ annual\ cost = {} & Treatment\ cost + Desalination\ cost + Cooling\ cost + Piping\ cost \\ & + wastewater\ discharges\ cost + waste\ heat\ to\ power\ cost \end{aligned} \tag{1}$$

The objective function subject to equality and inequality constraints including water balances of sources and sinks as indicated by Eq(2) and Eq(3) respectively.

$$\sum_{p\in P}\sum_{j\in SN_p} M_{ip,jp}^{avg} + \sum_{p\in P}\sum_{r\in R} T_{ip,rp}^{avg} + \sum_{s\in S}\sum_{t\in T} T_{ip,st}^{avg} + D_{ip}^{avg} = W_{ip}^{avg} \tag{2}$$

$$\begin{aligned} \sum_{p\in P}\sum_{i\in SU_p} M_{ip,jp}^{avg} + \sum_{p\in P}\sum_{r\in R} T_{rp,jp}^{avg} + \sum_{s\in S}\sum_{t\in T} T_{st.jp}^{avg} + \sum_{p\in P}\sum_{m\in R} T_{mp,jp}^{Des,avg} + \sum_{n\in N}\sum_{k\in K} T_{nk.jp}^{Des,avg} + \sum_{l\in L} F_{l,jp}^{avg} \\ = G_{jp}^{avg} \end{aligned} \tag{3}$$

The minimum removal ratios of treatment units were considered as shown via Eq(4).

$$x_{c,rp}^{T,max} = x_{c,rp}^{in,max}\left(1 - RR_{c,rp}^{min}\right) \tag{4}$$

Energy sources such as the waste heat to power unit and energy sinks including cooling systems, treatment units, are subject to inequality constraints as indicated in Eq(5) and Eq(6) respectively. Eq(7) indicates the total cost of central and decentral treatment units.

$$\begin{aligned} \sum_{p\in P}\sum_{r\in R} PW_{i'p,rp}^{T,avg} + \sum_{s\in S}\sum_{t\in T} PW_{i'p,st}^{T,avg} + \sum_{p\in P}\sum_{m\in M} PW_{i'p,mp}^{Des,avg} + \sum_{n\in N}\sum_{k\in K} PW_{i'p,nk}^{Des,avg} + \sum_{p\in P}\sum_{j'\in SN'_p} PW_{i'p,j'p}^{CT,avg} \\ + \sum_{p\in P}\sum_{j'\in SN'_p} PW_{i'p,j'p}^{OCSW,avg} + \sum_{p\in P}\sum_{j'\in SN'_p} PW_{i'p,j'p}^{AC,avg} \le \sum_{p\in P}\sum_{i'\in SU'_p} PW_{i'p}^{avg} \end{aligned} \tag{5}$$

$$\sum_{p\in P}\sum_{r\in R} PW_{i'p,rp}^{T,avg} \le \sum_{p\in P}\sum_{r\in R} PW_{rp}^{T,avg} \tag{6}$$

$$C^T = K_F\ (\sum_{p\in P}\sum_{r\in R}\left(T_{rp}^{max}\right)^{\alpha} C_{rp}^{CC} + \sum_{s\in S}\sum_{t\in T}(T_{st}^{max})^{\alpha} C_{st}^{CC}\ ) + H_y\ (\sum_{p\in P}\sum_{r\in R} T_{rp}^{avg}\ C_{rp}^{OC} + \sum_{s\in S}\sum_{t\in T} T_{st}^{avg}\ C_{st}^{OC}\ ) \tag{7}$$

3. Case Study

Three processes are involved in the case study which are ammonia, methanol, and Gas-to-Liquid (GTL). Process-related data including basic power load and minimum cooling requirement are shown in Table 1. Process water demands and supplies are represented in Table 2. In total, the case study involves nine water sources including freshwater, and nine water sinks including discharge with different flowrates and qualities. Three cooling systems are considered which are air-coolers, once-through cooling seawater (OCSW), and cooling towers. It is assumed that desalination units use Reverse Osmosis (RO) technology to produce freshwater. This scenario demonstrates the case of designing the water-energy network connections based on annual average values, minimum removal ratios of the treatment units, and maximum units' capacities to consider seasonal variations of water/energy elements. It is worth mentioning that the symbols P1, P2, and P3 stand for ammonia, methanol, and GTL plants respectively. The symbols "S1, S2, S3", "D", "I", and FW represent numbered water sources, water sinks, irrigation demand and, freshwater respectively. The symbols 1S and 2S stand for one-stage and two-stage treatment unit respectively while TR refers to the treatment unit. Different water sources and sinks vary in both flowrates and quality and the network is designed accordingly as shown in Table 3 and Table 4. The minimum cooling requirement Q^{min} represents the heat that should be removed by any selected cooling system. Case study data were obtained from an earlier work by Fouladi et al. (2017).

Table 1: Process data

Plant	Basic Power load (MW)	Q^{min} cooling (MW)
Ammonia	111	750
Methanol	162	409
GTL	287	1,961

Table 2: Process water supply and demand

Plant	Process Supply (m^3/d)	Process demand (m^3/d)
Ammonia	599	2,571
Methanol	896	1,912
GTL	16,795	7,115

4. Results and Discussion

The formulated case study was solved using a stochastic optimization tool. The obtained results for source-to-sink water allocation are presented in Table 3. The allocation is based on average supply and demand of different sources/sinks and sink permissible pollutant concentrations. Freshwater connections from desalination plant is used to satisfy the demands of some sinks in the three processes as these sinks require freshwater. Some water from GTL process is directly discharged. Wastewater from industrial park sources can be either directly allocated into sinks or discharged based on source and sink water quality and requirements or it can be allocated into treatment units and then utilized into sinks or discharged. In Table 3 and Table 4, 0 t/d indicates that a connection between the source on the same raw and the sink of the same column does not exist. Table 4 shows wastewater allocation from different sources into treatment units. Results indicate that 14,171 t/d of wastewater from source 1 in process 3 are treated in a two-stage nanofiltration unit. Table 5 represents treated water allocation from treatment units into different sinks or discharges. Decentral one-stage and two-stage nano-filtration membrane units are selected for wastewater treatment as required. Results show that treatment of wastewater from some sources is required in some cases prior to wastewater discharge to abide by environmental regulations.

Table 3: Source-Sink water allocation

Sink Source	P1D1 (t/d)	P1D2 (t/d)	P2D1 (t/d)	P2D2 (t/d)	P3D2 (t/d)	P1I1 (t/d)	P2I1 (t/d)	P3I1 (t/d)	Discharge (t/d)
P1S1	0	0	0	0	0	40	0	0	5
P1S2	0	0	0	0	0	0	0	0	0
P1S3	0	0	0	0	0	0	0	0	0
P2S1	0	0	0	0	0	0	139	0	0
P2S2	0	0	0	0	0	0	0	0	0
P2S3	0	0	0	0	0	0	0	0	0
P3S1	0	0	0	0	0	0	0	0	2,477
P3S2	0	0	0	0	0	0	0	0	0
FW	0	840	0	500	0	163	0	0	0

Treatment units and cooling system selection were made based on minimizing the total annual cost (TAC) which is the objective function of the formulated problem. The obtained results show that the optimal water network design utilizes air coolers as the cheapest cooling option compared to cooling towers and once-through cooling seawater (OCSW). Waste heat is converted into power via the WHP unit while the remaining waste heat will be rejected through air coolers. Table 6 represents power allocation in (MW) into different considered processes. The TAC for the optimal design of the water-energy network considering seasonal fluctuations in water and energy supply and demand using the proposed method and without the need for multiperiod planning is (78 MUSD/y). One-stage and two-stage nanofiltration units were selected as the optimal treatment options.

Table 4: Source-Treatment unit wastewater allocation

Sink Source	1S-TR-P1 (t/d)	2S-TR-P1 (t/d)	1S-TR-P2 (t/d)	2S-TR-P2 (t/d)	1S-TR-P3 (t/d)	2S-TR-P3 (t/d)
P1S1	0	0	0	0	0	40
P1S2	154	0	0	0	0	0
P1S3	0	400	0	0	0	0
P2S1	0	0	142	0	0	0
P2S2	0	0	115	0	0	0
P2S3	0	0	0	500	0	0
P3S1	0	0	0	0	0	14,171
P3S2	0	0	0	0	0	147

Table 5: Treatment unit-Sink water allocation

Sink Source	P1D1 (t/d)	P1D2 (t/d)	P2D1 (t/d)	P2D2 (t/d)	P3D2 (t/d)	P1I1 (t/d)	P2I1 (t/d)	P3I1 (t/d)	Discharge (t/d)
1S-TR-P1	0	0	0	0	0	0	0	0	139
2S-TR-P1	0	0	0	0	0	0	0	0	324
1S-TR-P2	0	0	0	0	0	0	0	74	158
2S-TR-P2	0	0	0	0	0	0	0	0	405
1S-TR-P3	0	0	0	0	0	0	0	0	0
2S-TR-P3	2,571	0	1,912	0	7,115	0	0	0	0

Table 6: Allocation of generated power (MW)

Process	Ammonia	Methanol	GTL
Ammonia	34.55	0	7.08
Methanol	12.46	3.46	7.07
GTL	24.65	31.46	36.59

5. Conclusions

This work provides a method for designing optimal water-energy networks considering seasonality to cover this gap in the literature as previous work either ignored seasonal changes or employed multiperiod planning which results in complex models that make finding the globally optimal solution difficult. It started by collecting data, analyzing seasonal changes of the network elements, and assessing the significance of the seasonal fluctuations. According to the assessment results, a novel approach was proposed to design a water-energy network that can handle seasonal variations efficiently. A MINLP model was proposed to optimize the design of the water-energy network considering seasonality. A case study consists of three processes; ammonia, methanol and GTL was considered to demonstrate the proposed approach and model. Three different options were considered for cooling purposes which are air coolers, cooling towers and once-through cooling seawater. The obtained results indicate the applicability of the proposed model which enable designing the water-energy network considering seasonality. Air coolers were selected for cooling purposes while one-stage and two-stage nanofiltration were utilized for wastewater treatment. The results show direct allocation of wastewater and indirect allocation of treated water. The power generated utilizing waste heat was allocated into power sinks. The TAC of the network is 78 MUSD/y considering seasonality without the need for multi-period planning.

Nomenclature

C^{T} – Total central and decentral treatment cost, \$/y
C_{rp}^{CC} – CAPEX parameter decentral treatment, \$/kg
C_{st}^{CC} – CAPEX parameter central treatment *t*, \$/kg
C_{rp}^{OC} – OPEX parameter decentral treatment, \$/kg
C_{st}^{OC}– OPEX parameter of central treatment, \$/kg -
D_{ip}^{avg} – Average water discharge from source *i*, kg/h
$F_{l,jp}^{avg}$ – Average freshwater flowrate, kg/h

H_y – Operating hours per year, h/y
K_F – Treatment cost annualizing factor, y^{-1}
$M_{ip,jp}^{avg}$ – Average flow from source I to sink j, kg/h
$PW_{i'p,j'p}^{CT,avg}$ – Power to cooling tower, kW
$PW_{i'p,j'p}^{OCSW,avg}$ – Power to OCSW, kW
$PW_{i'p,j'p}^{AC,avg}$ – Power to air cooler, kW
$PW_{i'p,rp}^{T,avg}$– Power from source i' to decentral treatment, kW
$PW_{i'p,st}^{T,avg}$– Power from source i' to central treatment, kW
$PW_{i'p,mp}^{Des,avg}$ – Power from i' to decentral desalination, kW
$PW_{i'p,nk}^{Des,avg}$ – Power from i' to central desalination, kW
$PW_{i'p}^{avg}$ – Power from source i', kW
$RR_{c,rp}^{min}$- Minimum removal ratio, (1)
$T_{ip,rp}^{avg}$– Average flow from to treatment r, kg/h
$T_{ip,st}^{avg}$– Average flow from to treatment s, kg/h
$T_{rp,jp}^{avg}$ – Treatment unit r flow to sink j, kg/h

$T_{st.jp}^{avg}$ – Treatment unit s flow to sink j, kg/h
$T_{mp,jp}^{Des,avg}$ – Desalinated water flow to sink j, kg/h
W_{ip}^{avg}– Average water supply from source i, kg/h
$x_{c,rp}^{T,max}$– Maximum outlet concentration, ppm

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