CHEMICAL ENGINEERING TRANSACTIONS
VOL. 103, 2023

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Panos Seferlis, Yee Van Fan, Athanasios Papadopoulos

ISBN 979-12-81206-02-1; **ISSN** 2283-9216

DOI: 10.3303/CET23103052

Graphical Optimisation of Supplying Water and Energy in a Water-Energy Nexus System

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Water and energy are the two most essential resources for human civilisation, from day-to-day activities to overall development. These resources are interdependent on each other for their production, which constitutes a nexus between them and is called the water-energy nexus. With increasing development activities, the demand for water and energy is also growing worldwide. Sustainable water and energy resource use has become inevitable for regional energy system planning. This work proposes a graphical method for optimising the water-energy nexus system of any geographical region. The proposed method determines the minimum water and energy generation needed for the demand satisfaction of any geographical region. A mathematical optimisation formulation to verify the graphically obtained results is also presented in this work. The proposed approach can be used as a planning tool for the water-energy nexus system. A case study on Spain's water-energy nexus system is demonstrated using the developed method and determined that only 35,414 × 10^6 m^3/y of water and 273,979.9 GWh/y of energy is needed for demand satisfaction. 45.65 % of nuclear power (Open Loop) and 19.47 % of groundwater can be conserved from Spain's total available energy and water sources.

1. Introduction

Global warming has caused an increase in the earth's average temperature, which has already triggered climate change. Due to increasing climate change and global warming, the scarcity of freshwater sources has grown and is also affecting the process of energy generation. Energy and water are the two most important resources required for preserving life and socio-economic development. Energy sources require significant water for cooling power plants, extracting shale gases, producing biomass feedstock, etc. Similarly, water production requires energy for extraction, treatment, distribution, etc. It shows that water and energy are interdependent, and this interdependency is called the water-energy nexus. With increasing population and development activities, the demand for water and energy is also growing, which is to be satisfied. Any negative impact on the production of one source will affect the output of another source, making it challenging to satisfy the demand. Hence, there is a clear need to conserve the existing water and energy sources so that they can be used efficiently with minimal wastage of resources. Sustainable use of water and energy resources has become inevitable for regional energy system planning. The concepts of Pinch Analysis can be extended to the appropriate planning of the water-energy nexus system.

Pinch Analysis was developed in the 1970s and first applied for industrial energy conservation (Linnhoff et al., 1982) was further extended by conserving mass-separating agents (El-Halwagi and Manousiouthakis, 1989) and various material resources (Foo, 2012). A decomposition method was proposed by Bandyopadhyay et al. (2009) for segregated targeting problems. Pinch Analysis was applied to numerous engineering problems involving mechanical, chemical, process, energy, and environmental engineering. (Klemeš et al., 2018).

Several studies have been done on optimising the water-energy nexus system for sustainable water and energy use. For optimal water consumption in shale gas production, a mixed integer linear programming model was proposed by Yang et al. (2015). A multi-level optimization model for handling the nexus was developed by Zhang and Vesselinov (2016). Hang et al. (2016) proposed a method for optimising water energy and food by minimising the use of energy and water. Later a graph theoretic approach for minimising the redundancy between the water and energy nexus system was proposed by Tsolas et al. (2018). However, this method does

Paper Received: 03 June 2023; Revised: 06 August 2023; Accepted: 31 August 2023
Please cite this article as: Prabhakar S., Bandyopadhyay S., 2023, Graphical Optimisation of Supplying Water and Energy in a Water-Energy Nexus System, Chemical Engineering Transactions, 103, 307-312 DOI:10.3303/CET23103052

not precisely determine the minimum water and energy to be produced to satisfy demand. For optimising the nexus between water and energy for shale gas production, a mathematical model was presented by Oke et al. (2020). Idris et al. (2021) proposed a MILP model for optimal sizing of water- energy nexus system which also optimises the cost of the system. Rezaei et al. (2023) proposed a mixed integer non-linear programming model for optimising water-energy virtual power plants. In this paper, a graphical method for optimisation of the water-energy nexus system is presented. The significant contributions of this work are as follows:

- A non-iterative Pinch based graphical method for optimising the water-energy nexus system is proposed in this work.
- The method determines which energy and water source to be used for production
- The method is capable of determining the maximum demand of given water and energy that can be satisfied using the existing sources.

The remainder of the manuscript consists of a problem statement followed by mathematical optimization formulation in section 2. Section 3 consists of a graphical methodology, followed by an example in section 4, and section 5 represents the conclusion.

2. Problem statement

The general problem statement for water-energy nexus system optimisation encompassing interdependent energy and water sources can be stated as follows: A set of n energy-producing sources, each with an annual energy production capacity of E_i, is available for energy production, and w_i is the amount of water consumed by each source when it runs at full capacity. A set of m water-producing sources, each with a water production capacity of W_j, is available for producing water, and each water source consumes e_j amount of energy at full capacity. For a specific geographic region, the given annual energy demand and the given annual water demand is E_g and W_g. The aim is to determine the minimum energy and water to be produced, which satisfies the energy and water demand of the specified region. A schematic representation of the interdependent energy and energy sources is presented in Figure 1. It is assumed that a single distribution system (bus) is used to connect and distribute all the energy sources. This bus supplies the energy required for water production. Similarly, water production from different sources is connected to a single distribution system, and the water needed for energy production is provided by this bus.

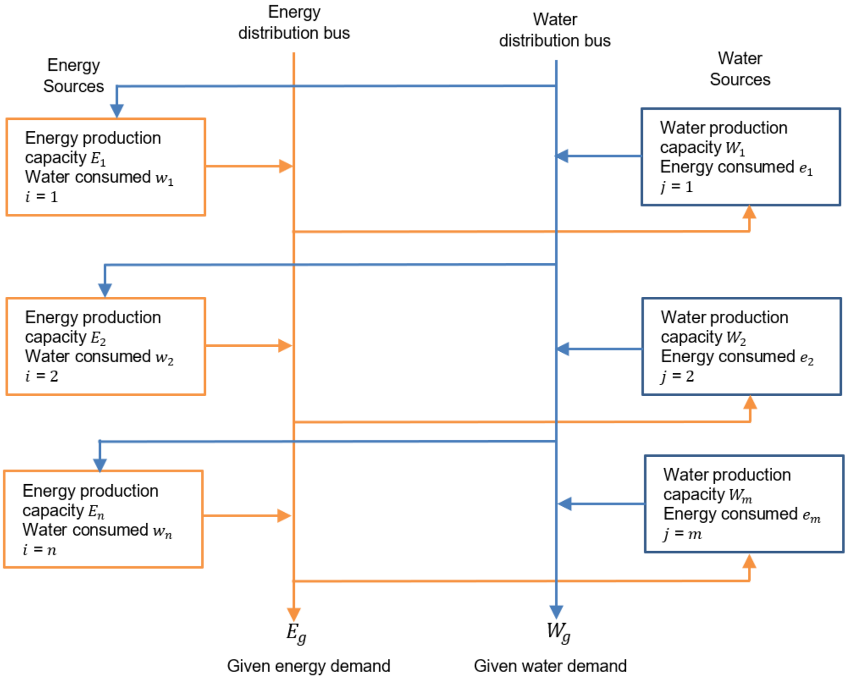

Figure 1: A schematic representation of water-energy nexus system

2.1 Mathematical formulation

Let the capacity factor be x_i for the energy source, i. The energy source i produces annual energy of x_iE_i with an annual water consumption of x_iw_i. Similarly, let the capacity factor for the water source j be y_j and it produces annual water of $y_j W_j$ while consuming $y_j e_j$ of water from the system. The objective is to determine the minimum energy generation needed to satisfy the energy demand while satisfying the water demand for the specified geographic region. The mathematical equations for the optimisation problem can be written as follows: Minimise:

$$\sum_{i=1}^{n} x_i E_i \tag{1}$$

Subjected to the following constraints:

$$\sum_{i=1}^{n} x_i E_i = E_g + \sum_{j=1}^{m} y_j e_j \tag{2}$$

$$\sum_{j=1}^{m} y_j W_j = W_g + \sum_{i=1}^{n} x_i w_i \tag{3}$$

Eq(2) implies that the total energy produced from the energy sources should satisfy the given energy demand and the energy required by water-producing sources for water production. Similarly, Eq(3) represents that the total water produced from the water sources should satisfy the given water demand and the water required by energy-producing sources for energy production specified for the region. In addition to these constraints, the capacity factors are non-negative, and their values should lie between 0 and 1.

$$0 \le x_i \le 1 \tag{4}$$

$$0 \le y_j \le 1 \tag{5}$$

The proposed work minimizes the production of both energy and water. Since water and energy form a nexus between them, minimizing the production of any of them will automatically minimize the output of another source. A graphical approach for water-energy nexus optimisation is presented in the next section.

3. Graphical solution method

The graphical method used for the optimization of interdependent water and energy systems is reported in this section. The first step is to create a piecewise linear energy composite curve drawn between energy production versus water consumption (Figure 2a). The water intensity (i.e., water consumed in producing unit energy) for each energy source is calculated, and these sources are arranged in ascending order of their water intensity. The energy composite curve is drawn in such a way that it ensures the least water-intensive energy sources are used first. The resulting curve between cumulative energy produced versus cumulative water consumed curve represents the optimal sequence for using energy sources to meet the specified energy demand while minimising water consumption.

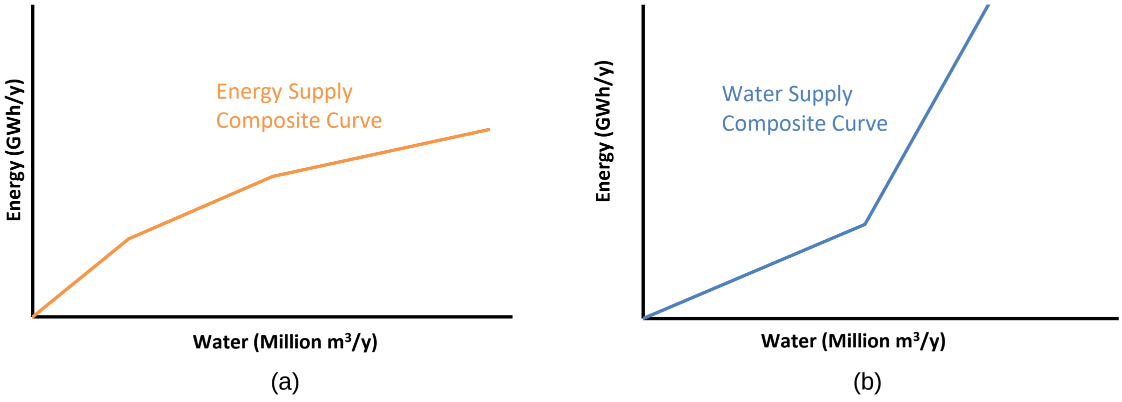

Figure 2: Composite curves for water-energy nexus: (a) Energy composite curve and (b) water composite curve

Similarly, a piecewise linear water composite curve is drawn to represent the relationship between water production and energy consumption (as shown in Figure 2b). This curve is created by calculating the energy intensity (i.e., energy consumed per unit of water produced) for each water source and arranging the sources in ascending order of their energy intensity. The resulting curve ensures that the least energy-intensive water sources are used first for water production in the region. For every point on the composite curve of water, the energy consumed by the water source is represented by the *y*-axis, and the x-axis represents the amount of water generated.

In order to fulfill constraints (2) and (3), the composite curves shown in Figure 2 are shifted vertically and horizontally. Specifically, the energy supply composite curve is shifted horizontally on the *x*-axis to indicate the water demand for the specified region. The distance of this horizontal shift represents the amount of water required by the region.

To meet the energy demand of a specific region, the water composite curve (Figure 2) is adjusted by shifting it vertically upwards. This shift is equivalent to the region's energy demand (E_g). After this adjustment, the shifted energy composite curve and the shifted water composite curve are plotted together on cumulative energy versus cumulative water graph to determine the minimum production of water and energy is essential to meet the demand. This process ensures that the region's energy needs are fulfilled while minimising the usage of water resources.

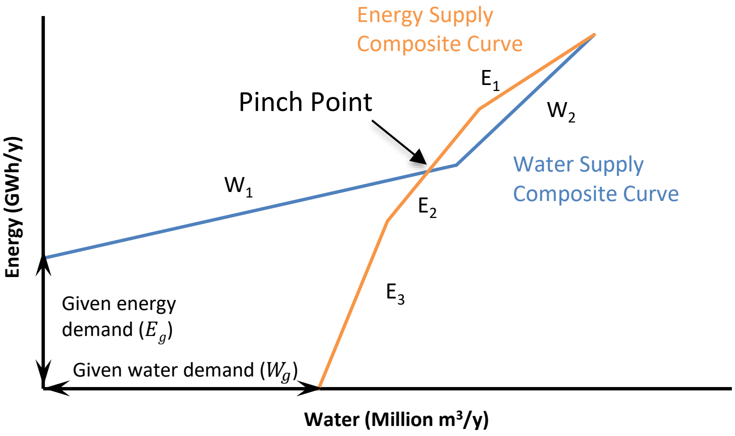

Figure 3: Graphical solution for interdependent energy and water nexus systems with shifted water and energy supply composite curves

The first point of intersection of both the shifted composite curves of water and energy represents the optimum solution to the problem (see Figure 3). This intersection point is called the Pinch point. The Pinch point ensures that the optimum water and energy required for a given water and energy demand are produced. Constraints (2) and (3) are simultaneously satisfied by the intersection of two composite curves. The horizontal projection of the composite curve represents the amount of water produced by the water sources, which must satisfy the given water demand and the water needed for energy production (as indicated by the vertical projection of the shifted water composite curve). The horizontal projections of the composite curve ensure that the water balance constraint is met. Likewise, the vertical projection of the composite curve corresponds to the energy required for the system, ensuring that the energy balance constraints are satisfied.

The point of intersection of both the composite curves is called the Pinch point as It has similar characteristics to the classical Pinch point. The Pinch point splits the system into two regions: the below-Pinch utilisation region and the unused region. The below-Pinch region contains all water and energy sources that must operate at full capacity to meet the system's demands. The energy and water sources that are not needed are included in the above-pinch region and can be shut down. The water and energy sources operate at partial capacity at Pinch point. The redundant water and energy sources above the Pinch point are discarded, representing excess water or energy production that should be conserved. Following the golden rule of Pinch Analysis, transferring water and energy across the Pinch point is not allowed.

4. Case study

The case study represents Spain's water-energy nexus optimisation, taken from Tsolas et al. (2018). The tabulated data in Table 1 represents the energy and water production capacity of various energy and water sources with their required water and energy consumption. The energy required for water production is provided by the existing sources. Similarly, the existing water sources provide the water required for energy production.

Apart from inter-industrial needs, these sources are also used to satisfy societal demands for water and energy. The overall objective of this case study is to find the minimum water and energy to be produced to meet demand.

Table 1: Energy and water production data for Spain (Tsolas et al., 2018).

Energy Sources	Energy Generated (GWh/y)	Water Required (10^6 m^3/y)	Water Sources	Water Generated (10^6 m^3/y)	Energy Required (GWh/y)
Hydropower	4,1052	2,797.18	Surface water	29,870	11,047
Photo-voltaic	8,327	7.23	Groundwater	6,884	3,273
Solar thermal	4,770	8.65	Osmosis	1,188	10,109
Wind	55,646	_	Electrolysis	108	183
Open Loop			Distillation	41	385
Coal	18,599	2,886.20	Multi-stage	14	338
Oil	6,193	947.48	Flash		
Natural Gas	25,891	3,951.17	Total	38,105	25,335
Nuclear	25,527	5,895.85			
Biomass	2,916	551.91			
Closed Loop					
Coal	22,733	704.99			
Oil	7,570	67.19			
Natural Gas	31,645	268.98			
Nuclear	31,199	776.56			
Biomass	3,564	13.90			
Total	285,632	18,877.29			

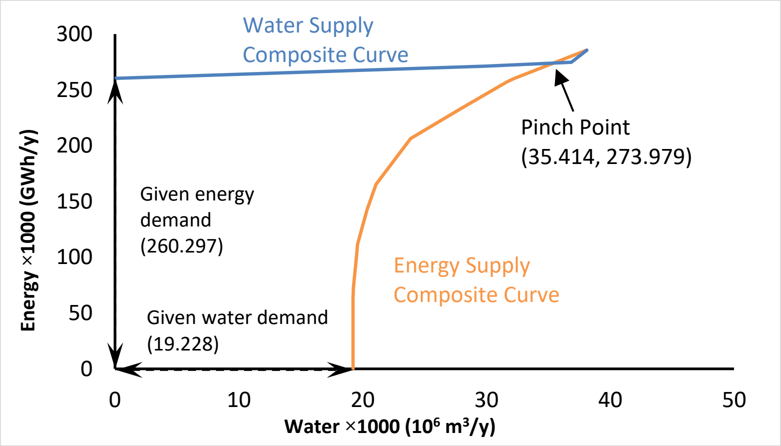

Figure 4: Graphical solution for interdependent energy and water nexus systems for Spain

Following the proposed methodology, water composite and energy composite curves are drawn for Spain in Figure 4. The first point of intersection of both the water and energy composite curves is called the Pinch point and gives the minimum generation of water and energy needed for the satisfaction of demand. The obtained solution implies that it is required to generate 35, 414 × 10^6 m^3/y of water and 273,979.9 GWh/y of energy only for demand satisfaction. The obtained results match with the results reported by Tsolas et al. (2018), where a graphical method to find the amount of redundant water and energy generation was presented. The obtained solution shows that only open-loop nuclear power plant is partially used, produces 13,874.93 GWh/y (54.35 % of rated capacity), and all other energy sources are used completely. The surface water source is used completely, the groundwater source produces only 5,544 × 10^6 m^3/y (80.53 % of rated capacity) of water for the satisfaction of demand, and all other water sources are not used.

5. Conclusions

This work proposes a novel graphical targeting technique for optimizing the water-energy nexus system. The proposed method helps determine the minimum production of resources like water and energy needed for the satisfaction of demand. The graphically obtained results can be verified using the proposed mathematical formulation to obtain the optimum water and energy production. The applicability of the proposed method is illustrated through a case study based on the water-energy nexus system of Spain. The results show that only 35,414 × 10^6 m^3 of water and 273,979.9 GWh of energy production are needed to satisfy demand.

The proposed graphical method in this work can handle the change in water and energy demand, and can give the optimal solution. The method can be used as a planning tool for the water-energy nexus system and can be applied to several other domains that constitute a nexus between them. The costs of water and energy generation are not considered in this study. Future research is directed toward determining the cost-optimal water-energy nexus optimisation.

Nomenclature

E_i – energy production capacity of ith source, GWh/y
E_g– given energy demand, GWh/y
e_j – energy consumed by jth water sources, GWh/y
m – number of water sources
n – number of energy sources
W_j - water production capacity of jth source, 106 m3/y
W_g – given water demand, 106 m3/y
w_i – water consumed by ith energy sources, 106 m3/y
x_i – capacity factor for ith energy source
y_j – capacity factor for jth water source

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