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WATER SYSTEM MODIFICATIONS FOR THE OPTIMAL INTEGRATED ENERGY-WATER SYSTEMS DESIGN CONSIDERING THE ENERGY-WATER-CARBON NEXUS

Urwah Naveed[1], Nor Erniza Mohammad Rozali[*2], Shuhaimi Mahadzir[2]

[1]Department of Chemical Engineering, Universiti Teknologi PETRONAS, 32610, Bandar Seri Iskandar, Perak, Malaysia
[2]Centre for Systems Engineering (CSE), Institute of Autonomous Systems, Universiti Teknologi PETRONAS, Bandar Seri Iskandar 32610, Malaysia

*Corresponding author: erniza.rozali@utp.edu.my

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Abstract

One of the biggest challenges to global stability and economic growth is climate change. Numerous research has been carried out considering the nexus between energy and carbon emissions in an integrated energy-water system. The water sector and its resultant carbon emissions are mostly neglected even though the amount of carbon discharge from water systems contributes significantly to global warming. The carbon footprint from various water sources should also be assessed to establish optimal integrated systems with minimal environmental impact. This paper aims to study the effects of carbon emissions from the water sector on the design of integrated energy-water systems. A framework consisting of the Water Pinch Planning Diagram (WPPD) technique is proposed to calculate the carbon emission from the processing of two water sources i.e., freshwater, and treated water in an integrated energy-water system. Design modifications on the water processes are proposed to achieve the desired carbon emissions target for the integrated system. The results from the case study show that freshwater supply and use in the manufacturing process emits 86% more carbon as compared to treated water because its supply volume to fulfill the water demand is higher by 66%. Water sources supply volume was adjusted accordingly, and a 5% carbon emissions reduction has been achieved. Considering carbon emissions from the water sources and the carbon discharge from the energy system can provide more realistic targets for energy, water, and carbon emission for the optimal design of an integrated energy-water system.

Keywords: Integrated energy-water system, Water Planning Pinch Diagram, Energy Planning Pinch Diagram, Carbon Emission, Energy-Carbon-Water Nexus

1.0 INTRODUCTION

The world is advancing rapidly while moving towards sustainable development. thus, an increase in energy consumption [1]. One significant worldwide concern is how to supply sufficient water and energy services to seven billion urban residents while simultaneously maintaining a decent standard of living. This problem is far more complicated than it appears since water and energy are inextricably intertwined and should not be seen as separate systems [2]. The advancement of innovative energy technology may substantially reduce reliance on conventional fossil fuels while fostering the transformation of the energy supply [3]. Living beings are impacted by carbon emissions caused by the use of energy and water resources, and their future is significantly threatened. These three elements (energy, water, and carbon) are interrelated and have complicated relationships, such as energy being required for water production and distribution, water being required for energy generation, and energy consumption emitting CO_2 [3]. This interrelationship was referred to as the energy-water-carbon (EWC) nexus [4].

Recent research has placed great attention on the EWC nexus. Nair et al [5] examined the EWC nexus of water systems focusing on individual or multiple subsystems using the Life Cycle Analysis (LCA) method. The research indicated that energy, water, and carbon emissions are inextricably linked; nevertheless, a comprehensive, systemic, and appropriate framework for scientifically demonstrating the EWC nexus is still being developed. Along with the main methods and models employed, the paper also examined the energy intensity of decentralized water systems and diverse water end-uses. Lee et al. [6] studied the impact of the Water-Energy nexus in urban water systems in terms of environmental implications and energy intensity. Water use in the energy sectors was scrutinized. He characterized the influence of water risks on the water-energy nexus, including baseline water stress and return flow ratio. The result of this study shows that on-site energy recovery in wastewater treatment systems offered a great opportunity for reducing overall energy demand. Gu et al. [7] analyzed the wastewater treatment plant-EWC nexus. In his work, he quantified energy consumption in nine different WWTPs in South China, with different treatment processes, objects, and capacities. Due to China's massive annual wastewater discharge, considering climate change connected to wastewater treatment was suggested.

Water is utilized in almost every industry [8], with significant consumption for manufacturing, processing, chilling, transporting substances, cleanliness requirements within a facility, incorporating water into a final product, and so on. In other words, the sources of the sector's carbon emissions are the treatment and pumping of water. The water sector is responsible for a variety of carbon emissions, which use a lot of energy. The processing of carbon-containing waste from the water sector can result in several emissions that have a significant impact on the management of water systems, including power production. 4% of the world's electricity use is attributed to the water sector [9]. Louis Zib [10] evaluated the carbon footprints of the operating energy use for 76 wastewater utilities and 64 drinking water utilities across the United States. In this study, they utilized the empirical approaches of assigning carbon footprints using impact factors to convert GHG emissions to CO_2e. To comprehend how GHG emissions vary on a monthly scale, they investigated water-related greenhouse gas (GHG) emissions at a sub-annual scale through three case cities. According to estimates, the total emissions from wastewater and drinking water related to the use of electricity, natural gas, and fuel oil in the United States are 26.5 109 kg CO_2e and 16.2 109 kg CO_2e, respectively. Additionally, the average carbon footprint per volume of wastewater and drinking water emissions was 0.38 kg CO_2e/m^3 and 0.46 kg CO_2e/m^3, respectively, and represented 2.1% of all U.S. emissions. Most of this research focused on carbon footprints from individual water or energy systems. Studies on carbon emissions from the water sector in an integrated energy water system are limited and need to be explored. Figure 1 [11] illustrates the main operational phases of an industrial unit while emphasizing the carbon emissions from both the energy and water sectors. In this work, the carbon footprint assessment of water was performed on the industrial site using a product of energy emission factors with the recalculation factors. Using the emission factor (EF), the carbon footprint of the water used at this industrial location was estimated by Anna Trubetskaya et. al. [11] The number of stages shown in the figure can vary from one type of industrial site to another. This study included two simple approaches for industrial sites to calculate their carbon footprint in the water sector. The assessment of the milk powder manufacturing using both approaches indicates that the combined emission factor of the water supply and treatment is approximately 1.28 kg CO_2 m^{-3} of water.

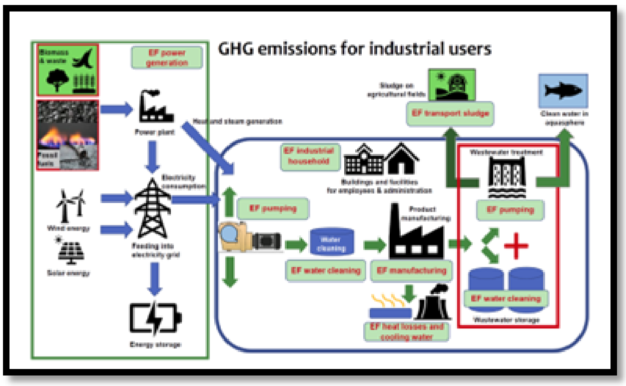


Figure 1. Greenhouse gas (GHG) emission sources in the energy-water sector [11]

A framework applying Pinch Analysis [12] was proposed by Mohammad Rozali to study the energy–water–carbon nexus for the optimal design of integrated energy–water systems. To determine the minimum targets for each resource, the framework used a variety of pinch analysis methodologies including the Power Cascade Table (PCT), Water Cascade Table (WCT), and Energy Planning Pinch Diagram (EPPD). This framework was then studied with the consideration of losses [13] in energy and water systems. Losses from energy and water systems were considered in the optimal design of the energy-water system. The effect of losses on energy storage capacity, outsourced electricity, water supply volume, and water storage capacity was evaluated.

The existing literature on the Energy-Water-Carbon (ECW) nexus studies has primarily focused on individual components of the nexus, with limited attention given to the optimization of integrated energy-water systems. considering pinch analysis. Some studies have explored the interconnection between energy and water systems, while considering the carbon emissions in energy systems, but have not delved into the impact of water systems on carbon emissions in the context of integrated designs. The study presented here narrows this research gap by providing a detailed investigation into carbon emissions from water systems within the broader ECW nexus. The neglect of carbon considerations in water systems has implications for the overall environmental footprint and economic efficiency of integrated systems [1]. It can contribute to larger carbon footprints, which may worsen environmental issues such as climate change. Moreover, from an economic perspective, it implies that failure to account for carbon emissions may lead to inefficiencies and increased operational costs, highlighting the importance of considering environmental factors for the overall economic efficiency of integrated systems. This study explicitly accounts for the carbon emissions associated with water systems, thereby providing a more holistic understanding of the nexus dynamics. By sub-categorizing water supply volumes into freshwater and treated water, the study offers an analysis that identifies the key areas for intervention. Moreover, the incorporation of design modifications based on detailed water source analyses and subsequent carbon emission calculations represents a novel contribution. This research provides valuable insights for policymakers, engineers, and researchers aiming to achieve sustainability goals through the optimal design of integrated energy-water systems within the intricate framework of the ECW nexus.

Therefore, in this paper, the framework from [13] is improved to consider the effects of different water sources on the total carbon emission from integrated energy-water systems. The WCT from [12] is revised to incorporate the multiple water sources and a new method called the Water Pinch Planning Diagram is proposed to target the carbon footprint of the water system, which then serves as the guidelines to carry out effective design modification strategies on the water sources to meet the demands at minimum environmental impacts.

2.0 METHODOLOGY

This section describes the framework for the optimal designing of an integrated energy-water system considering carbon emissions from the water system and the design modifications of the respective water processes. The framework from Mohammad Rozali [12] was revised by proposing the Water Pinch Planning Diagram method to set minimum targets for carbon emissions from specific water processes in the integrated system. The framework follows six key steps which include data extraction, construction of the Power Cascade Table (PCT), Water Cascade Table (WCT), Energy Planning Pinch Diagram (EPPD), Water Planning Pinch Diagram (WPPD), and design modifications in the energy mix and water supply volumes to meet the carbon emissions target.

2.1 Data Extraction

Table 1 enlists the data required for the framework including the water and power consumption factors, carbon emission factors, and component efficiencies. An Illustrative Case Study was used to demonstrate the application of the proposed framework. Other data required includes the hourly demand for energy and water systems as shown in Table 2 and Figure. 2, respectively. The energy system in the Illustrative Case Study uses 300 m^2 of PV panels and an 85 kW biomass generator to provide electricity to meet the needs of various appliances. The water system in the Illustrative Case Study is subcategorized into two supply volumes. Freshwater supply volume and treated water volume were considered to be two water supply volumes.

Table 1. Various factors were considered for the Illustrative Case Study.

	Values
Water consumption factor for biomass source [14]	0.0037 m^3/kWh
Water consumption factor for natural gas [14]	0.0044 m^3/kWh
Electricity consumption by 1 m^3 water [15]	0.9246 kWh
The efficiency of inverter [16]	0.95 %
Efficiency of rectifier [17]	0.90%
Battery self-discharge rate [18]	0.004%/h
Carbon emission factor for natural gas [19]	0.1810
Carbon emission factor for biomass [19]	0.4032
Carbon emission factor for treated water [20]	0.344
Carbon emission factor for freshwater [20]	0.708

Table 2. Power demands for the Illustrative Case Study

Power Demand	Power Source	Time (h)		Power Demand Rating (kW)	Electricity Consumption (kWh)
		To	From		
Appliance 1	AC	0	24	30	720
Appliance 2	DC	8	24	25	400
Appliance 3	AC	0	24	30	720
Appliance 4	DC	8	24	20	280

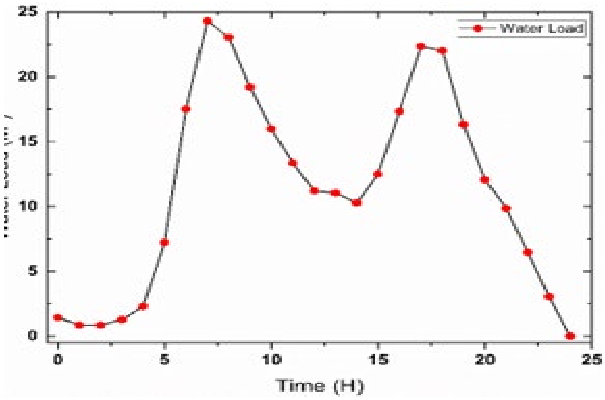


Figure 2. Hourly water load demand for Illustrative Case Study [12]

2.2 Construction of Power Cascade Table and Water Cascade Table

Firstly, PCT was constructed using the procedures described by Mohammad Rozali [12] to determine the minimum energy storage capacity and outsourced electricity. The electricity generation by biomass and solar generators was used to fulfill energy demand in the energy and water system for the Illustrative Case Study.

The next step was to construct the Water Cascade Table (WCT). The demands in the water network consist of the hourly water load by the consumers, as shown in Figure. 2 [12], as well as the water required in the energy system for production processing, cooling in thermal processes, cleaning process, etc. WCT was constructed to minimize the water supply and storage requirements. Table 3 shows the WCT for the Illustrative Case Study that considers multiple water sources, which in this case are freshwater and treated water. Freshwater does not emit any carbon itself, although the supply of freshwater for different processes such as pumping, cooling/heat losses, product manufacturing, and cleaning of supplied water/waste contribute to the carbon discharge. The main operational stages are shown in Figure 3. The freshwater is first supplied to the water demand. After fulfilling the water demand, the water was being treated and reused along with the freshwater supply. Excess water from the water supply was sent to storage to be stored and discharged to satisfy the unmet water demand just in case.

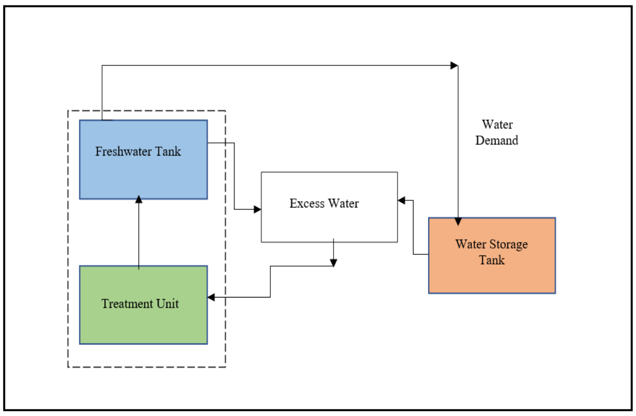


Figure 3. Water supply flow diagram

The steps for WCT construction from [12] were revised with minor modifications as follows:

1. Column 1: The time period for the water sources and demands was set to be the same as for the power cascade table, i.e., one hour.

2. Columns 2 and 3: The water demand was subcategorized for both the energy and water systems. The water demand for the water system is the hourly water load demand in Figure 2. The water demand for the energy system, DE was calculated by using Equation (1) [11]. Here WCF is the water consumption factor for the respective energy sources shown in Table 1, and SE is the generation from the electricity sources (biomass in this case) which was calculated according to the hourly electricity produced from the power generation facilities [14]. Water consumption in the solar PV facility was very low and assumed negligible for the Illustrative Case Study.

$$DE = \sum (SE \times WCF) \tag{1}$$

3. Columns 4 and 5: The water source was subcategorized to freshwater supply volume, V_S, and water treated volume, V_t. The water supply volume was estimated using the highest water load from Figure. 2. According to Dariusz [21], the average daily amount of water inflowing to the water treatment plant (WTP) is 67% of the facility design capacity. Around 24 – 25 % of the recorded inflows are then admitted back to the plant to be reused [21]. Therefore, it was assumed that 25% of the water demand inflows back to the plant in each hour. The treated water volume in column 5 was considered after fulfilling the water demand in columns 2 and 3. For the time interval of 0 to 1 hour, the treated water is considered zero because the freshwater will first fulfill the water demand and then be treated in the following hour before being reused.

4. Column 6: The net water demand was calculated after considering the losses during the transfer of water from the source to demand. It was assumed that the maximum water loss of 10%. [22] occur during the transfer. The net demand, NWt was calculated using Equation (2) [12].

$$NWt = \sum S_W \times \eta_L - \sum D_W \tag{2}$$

where NWt is the net water demand, $\sum S_W$ is the sum of freshwater supply volume and treated water volume shown in columns 4 and 5, D_W is the water demand shown in columns 2 and 3, and η_L is the efficiency of water after losses.

5. Columns 7 and 8: The positive values from column 6 represent the amount of water that can be stored and listed in column 7, which were referred to as the charging quantity. On the other hand, negative values represent the discharging quantity and are listed in column 8, which indicates the amount that needs to be taken from the storage tank to satisfy the unmet water demands.

6. Columns 9 and 10: The total amount of water in the storage tank was obtained by cascading the charging and discharging quantities in Columns 7 and 8. It was assumed that no water was stored at t = 0 h. The storage capacity in Column 9 was calculated by using Equation (3), [12] where TW_t and TW_{t-1} are the cumulative water stored in the tank at current and previous time intervals, CW_t and DW_t are the charged and discharged water amount extracted from Columns 7 and 8.

$$TW_t = TW_{t-1} + CW_t + DW_t \tag{3}$$

If there is any negative value in column 9, a new cascade needs to be performed by using the highest negative value in column 9 as the stored value at t = 0 instead of zero. For the Illustrative Case Study, the highest negative number from column 9 was between time intervals 21 and 22 h, which was 68.513 m^3. The minimum storage capacity can be reached if the total amount of water stored (TW_t) at the first time interval is equal to the storage at the last time intervals in the feasible cascade (column 10). Otherwise, Equation (4) [12] should be used to estimate a new water supply volume (SW_{new}) to minimize the initially estimated volume.

$$SW_{new} = SW_{initial} - \frac{(TW\ t{=}24 - TW\ t{=}0)}{24} \tag{4}$$

If the difference between the two volumes (new and initial assumption) is less than 0.05%, the water network's optimum supply capacity can be calculated using the new estimated volume in Equation (4). Overall results after iterations give a freshwater supply volume requirement of 10.79 m^3, while treated water varies throughout the day based on the freshwater supply volume. The storage volume was calculated to be 83.61 m^3.

Table 3. Power demands for the Illustrative Case Study

Time	Water Demand		Water Source		Net Demand	Charging Quantity	Discharging Quantity	Storage Capacity	
h	m^3	m^3	m^3	m^3	m^3	m^3	m^3	m^3	m^3
	DE	DW	V_S	V_t					
0									
	0.314	1.45	10.79	0	7.9546	7.9546	0	7.9546	76.4681
1									
	0.314	0.85	10.79	0.79546	9.2705	9.2705	0	17.225	85.7386
2									
	0.314	0.85	10.79	0.92705	9.3889	9.3894	0	26.614	95.1276
3									
	0.314	1.28	10.79	0.93889	8.9696	8.9696	0	35.586	104.097
4									
	0.314	2.13	10.79	0.89696	8.0818	8.0818	0	43.665	112.179
5									
	0.314	7.23	10.79	0.80816	2.9019	2.9019	0	46.567	115.081
6									
	0.314	17.5	10.79	0.29019	-7.8442	0	-7.8442	38.723	107.236
7									
	0.314	24.3	10.79	-0.7844	-15.611	0	-15.611	23.111	91.6255
8									
	0.314	23.0	10.79	-1.5611	-15.040	0	-15.040	8.0714	76.5850
9									
	0.314	19.2	10.79	-1.5040	-11.15	0	-11.159	-3.0875	65.4259
10									
	0.314	15.9	10.79	-1.115	-7.5797	0	-7.5797	-10.667	57.846
11									
	0.314	13.3	10.79	-0.7579	-4.6275	0	-4.6275	-15.294	53.218
12									
	0.314	11.2	10.79	-0.4627	-2.2318	0	-2.2318	-17.526	50.986
13									
	0.314	11.5	10.79	-0.2231	-1.8462	0	-1.8462	-19.373	49.140
14									
	0.314	10.2	10.79	-0.1846	-1.0516	0	-1.0515	-20.424	48.0889
15									
	0.314	12.5	10.79	-0.1051	-3.1904	0	0	-20.424	48.0889
16									
	0.314	17.3	10.79	-0.319	-8.2225	0	-8.2225	-28.647	39.866
17									
	0.314	22.3	10.79	-0.8222	-13.954	0	-13.695	-42.342	26.171
18									
	0.314	22.0	10.79	-1.3695	-13.848	0	-13.848	-56.190	12.3230
19									
	0.314	16.3	10.79	-1.3848	-8.1612	0	-8.6172	-64.352	4.1613
20									
	0.314	12.0	10.79	-0.8161	-3.3995	0	-3.3999	-67.752	0.7613
21									
	0.314	9.86	10.79	-0.34	-0.7614	0	-0.7614	-68.513	0
22									
	0.314	6.46	10.79	-0.0764	2.8760	2.8760	0	-65.637	2.8760
23									
	0.314	3.06	10.79	0.28760	6.6034	6.6034	0	-59.03	9.4795
24									

2.3 Construction of Power Cascade Table and Water Cascade Table

The energy system contributes to the carbon emissions depending on the type of fuel used. For biomass, the carbon emission factor is 0.4032 (t CO_2/MWh), as noted by the U.S. Environmental Protection Agency [19]. Emissions from solar panels were considered negligible [23]. The EPPD approach was used to target the quantity of carbon released from the energy network and was constructed using the steps outlined in [12]. The network's energy sources were grouped according to increasing emission factors. The total carbon emission from the energy sources was obtained based on their carbon emission factors (CEF) and generation capacity (SE). Equation (5) can be used to compute the carbon emission from the energy system, CEE.

$$CEE = SE \times CEF \tag{5}$$

The cumulative power generation and emission levels were used as the horizontal and vertical axes in the EPPD as depicted in Figure. 4. The EPPD for the Illustrative Case Study shows that the annual total emissions for the energy network **is** 300 t CO_2.

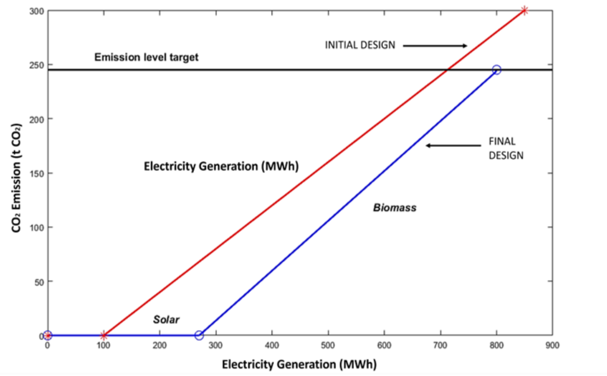


Figure 4. Energy Planning Pinch Diagram for Illustrative Case Study

2.4 Construction of Water Planning Pinch Diagram

A Water Planning Pinch Diagram (WPPD) for minimum targeting of carbon emissions was constructed based on the carbon emissions amount from the freshwater extraction and water treatment process. The WPPD construction was adapted from the EPPD construction procedures as described by Lim [24]. All water sources in the network were first arranged in ascending order of emission factors, which in this case is freshwater with lower emission factor followed by treated water. The emission levels of each water source (CE^w) were obtained based on their respective emission factors (CF^w) and supply volume capacity (S^w) accordingly. The computation was done using Equation (6).

$$CE^W = S^W \times CF^W \tag{6}$$

According to UK DBEIS (Department for Business, Energy and Industrial Strategy), the delivery of freshwater contributes to 0.344 kg of CO_2 release while the treated water emission factor is 0.708 kg CO_2 termed as CF^W. [20]. The sum of water supply volumes was taken along the x-axis and the carbon emission from the water system was plotted along the y-axis as shown in Figure. 5.

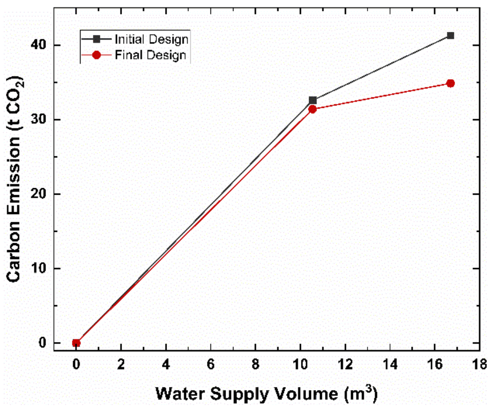


Figure 5. Water Planning Pinch Diagram for Illustrative Case Study

The carbon emissions from the freshwater supply process were calculated to be 30.688 t CO_2 while from treated water volume, it was calculated to be 8.69 t CO_2. The volumes of the freshwater and the treated water were adjusted to achieve the desired reduction in the carbon emissions target for the integrated system, as further explained in the next step.

2.5 Design Modification

Water Planning Pinch Diagram (WPPD) for minimum This section discusses the changes made to the initial design established in the previous steps to reduce the amount of carbon emissions from the integrated system. Malaysia has submitted its Intended Nationally Determined Contribution (INDC) to the United Nations. In this INDC, Malaysia has indicated that it will reduce its greenhouse gas emissions intensity of Gross Domestic Product (GDP) by 45% by 2030 [25]. A minimum target of 45% carbon emission per year was assumed to be reduced by design modifications in accordance with the carbon emission reduction target set globally. The EPPD plot gave annual total carbon emissions of 300 t CO_2 from the energy system, while the annual carbon emission from the water system obtained from the WPPD was 39.358 t CO_2. The emissions from energy systems can be reduced by increasing solar PV panel area, which has a lower carbon emission factor than biomass. The biomass generation capacity was reduced on the other hand. The new EPPD considering the new energy mix was then plotted and it was found that the carbon emission level had been reduced to 240 t CO_2 from 300 t CO_2. Since the carbon emission factor from treated water is higher as compared to freshwater, the treated water volume was reduced from 25% to 10% and consequently, the freshwater supply volume was increased to fulfill the water demand. As a result, the targeted carbon emissions from the WPPD were reduced from 39.358 to 34.864 t CO_2 which translates as an 11.4% carbon emissions reduction in the water system. Due to the proposed modifications to the water system, the water storage capacity has increased from 54.88 m^3 to 83.61 m^3. The overall results of the Illustrative Case Study are tabulated in Table 4. The emissions from freshwater usage have slightly increased because of the increase in the freshwater supply volume to fulfill the demand for both energy and water, however, the total carbon emissions from the water system were significantly reduced as desired. EPPD shown in Figure 4 and WPPD shown in Fig 5 show two curves each highlighting initial and final carbon emissions from energy and water sources after the design modifications in the energy-water system.

Table 4. Overall results for the Illustrative Case Study.

	Initial	Final
Biomass generation capacity (kW)	85	65
Solar panel area (m^2)	300	750
Energy Storage Capacity (kWh)	495.46	1028.04
Outsourced electricity (kWh)	156.625	33.612
Water treatment volume (m^3)	6.156	2.46
Water supply volume(m^3)	10.55	10.799
Water storage capacity (m^3)	54.88	83.61
Carbon emissions from freshwater (t CO_2/y)	30.688	31.474
Carbon emission from treated water (t CO_2/y)	8.69	3.474
Carbon emissions from energy system (t CO_2/y)	300	229

3.0 RESULTS AND DISCUSSION

3.1 Case Study

As the Case Study, a manufacturing facility in Malaysia's Peninsular region was chosen [26]. Fig. 6 shows the plant's hourly power and water load profiles. The energy system is powered by 200 kW and 100 kW biomass and natural gas generators, respectively. To gather the available energy from solar radiation, the system additionally uses a solar system with a 1,000 m^2 PV area. The solar PV and storage systems' efficiencies and other details were taken to be the same as in the Illustrative Case Study as shown in Table 1. The supply of water to the biomass and natural gas power facilities, is at 0.0037 m^3/kWh and 0.0044 m^3/kWh, respectively [14]. The framework was applied to the Case Study data and the overall results are tabulated in Table 5. Results from PCT showed that 670 t CO_2 was emitted initially. Iterations of WCT yield a freshwater supply of 28.29 m^3 and a treated water volume of 9.432 m^3 initially. The water storage capacity was calculated to be 41.349 m^3. The WPPD shows that the freshwater supply process emits 82.238 t CO_2 while the water treatment process releases 13.322 t CO_2.

Design modifications were done in both energy and water systems to reduce carbon emissions, as both energy and water systems are interrelated changes made to one system will have an impact on the other system too. The generation from energy sources (biomass and natural gas) emitting high carbon was reduced in the final design to 180kW and 70kW. Solar PV panels area was increased to 2200 m^2, as it emits negligible carbon. As a result, energy storage capacity was reduced from 1212.51 kWh to 141.44 kWh, while outsourced electricity was increased from 3027.27 kWh to 3287.5 kWh which indicates that in the energy system, the amount of electricity required from outside increased more, and the capacity of storage decreased. This is because the time for the highest solar radiation coincides with the period when the power load demand is at its peak. The carbon emission in the final design was calculated to be 533 t CO_2, showing about a 20%

reduction. EPPD is shown in Figure. 7(a) [12] was constructed for the energy system before and after design modifications.

For design modifications in the water system, the inflow of treated water was reduced to 1.518 m^3, and the supply volume for freshwater was increased to 30.67 m^3. As a result, the storage capacity also increased from 41.349 m^3 to 48.71 m^3 to fulfill the water demand in case of unmet water load demands. With the increase in the freshwater supply volume, the carbon emission from the freshwater supply process also increased even though the emission factor for freshwater supply is less than that for treated water. Freshwater supply emitted 89.156 t CO_2 while treated water showed a reduction to 2.144 t CO_2. The overall result shows that the total carbon emissions were reduced from 95.56 to 91.3 t CO_2 which is 4.45% emission reduction in the water system. This reduction in carbon discharge is not much but has a significant effect in optimizing the design. However, the overall carbon emission from the energy-water system was calculated to be 765.56 t CO_2 and was reduced to 605.38 t CO_2 which is a 20.9% reduction. WPPD shown in Figure 7 (b) was constructed for the water system before and after design modifications.

The study underscores the long-term economic viability of considering water supply sources and their associated carbon emissions in designing integrated energy-water systems. While the initial modifications may require investment for design, construction, equipment, etc., the long-term benefits, including reduced operational costs and improved environmental performance, contribute to the overall economic sustainability of the system. In summary, the economic implications of the proposed solution extend beyond immediate cost considerations. By addressing carbon emissions and optimizing water supply sources, the study aligns with broader trends in sustainable development, regulatory compliance, and the growing demand for environmentally responsible practices in the business and infrastructure sectors.

Table 5. Overall results for the Case Study.

	Initial	Final
Biomass generation capacity (kW)	100	70
Solar panel area (m^2)	1000	2200
Natural Gas Generation capacity (kW)	200	180
Energy Storage Capacity (kWh)	1267	1088
Outsourced electricity (kWh)	666	526
Water treatment volume (m^3)	9.432	1.518
Water supply volume(m^3)	28.29	30.67
Water storage capacity (m^3)	41.349	48.71
Carbon emissions from freshwater (t CO_2/y)	82.238	89.156
Carbon emission from treated water (t CO_2/y)	13.322	2.144
Carbon emissions from energy system (t CO_2/y)	670	514.08

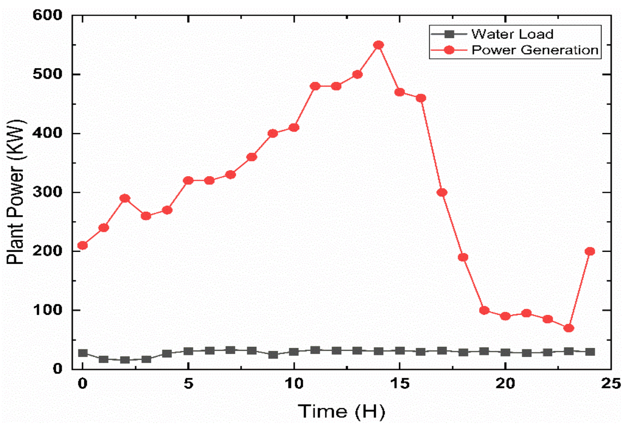
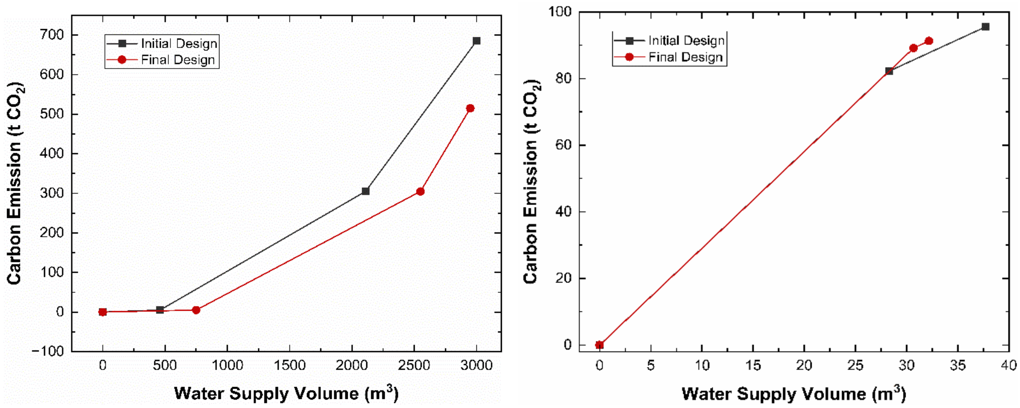


Figure 6. Hourly water and power load for the Case Study [26]



(a) (b)

Figure 7. (a) EPPD plot before and after design modifications for the Case Study [12] (b) WPPD plot before and after design modifications for the Case Study

4.0 CONCLUSION

This research significantly advances our understanding of integrated energy-water systems within the Energy-Water-Carbon nexus. By addressing the often-overlooked carbon emissions from water systems and implementing targeted design modifications, the study demonstrates tangible environmental and economic benefits. The presented Case Study showed that even though the carbon emission factor for freshwater is less as compared to treated water volume, the freshwater supply emits more carbon because of higher supply volume as compared to treated water volume. After design modifications in the water system, about 5% of carbon emissions were reduced in the water system and 20% in the energy system. Overall, about 20.9% (yearly) of carbon emissions were reduced for the integrated energy-water systems. Though the emissions reduction in the water system is lower as compared to the energy system, the carbon footprint from the water system should not be neglected. In light of the Sustainable Development Goals, this study represents a crucial step toward achieving a sustainable balance in integrated energy-water systems, aligning with Goal 7 (Affordable and Clean Energy) and Goal 13 (Climate Action). As industries strive to meet carbon reduction targets, the findings of this study offer a pragmatic model for designing and optimizing integrated systems. By showcasing the economic and environmental benefits of even minor reductions, the study advocates for a paradigm shift in approaching sustainable development. For future studies, the economic aspects of this study can be explored to reduce the carbon penalty.

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