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Energy–Water–Carbon Nexus Study for the Optimal Design of Integrated Energy–Water Systems Considering Process Losses

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Abstract: Integrated energy–water systems have been explored using different process integration techniques considering the energy–water–carbon nexus to minimize the carbon footprint, e.g., pinch analysis techniques (power cascade table, water cascade table, and energy planning pinch diagram). However, the power and water losses while considering the energy–water–carbon nexus have not been explored in detail in the previous works. This work focuses on the modifications of the existing pinch analysis methods for energy–water–carbon nexus study while considering power and water losses, for an optimized energy–water system. Power and water losses should not be neglected in the analysis as they have a significant impact on the carbon emissions and overall capacities of energy and water. The effect of losses on energy storage capacity, outsourced electricity, water supply volume and water storage capacity were evaluated on an industrial case study. Results from the case study demonstrate that, while considering power losses during power allocation can lower storage capacity, it tends to raise the needed outsourced electricity supply. As water supply volume tends to increase, the water storage capacity tends to decline when losses are considered. The results were compared to the data without losses, and it was observed that the storage capacity of energy decreases by 4% while outsourced energy increases by 6%. Water supply volume increases by 20% but water storage capacity decreases by 13.7%. The emissions from energy system remains same while from the water system the emissions rise significantly by 20%. It is expected that consumers that takes power and water losses into account will produce more realistic and reliable energy, water, and carbon reduction targets and prevent under-sizing issues in designing integrated energy–water systems.

Keywords: pinch analysis; integrated energy–water system; energy–carbon–water nexus

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1. Introduction

The world is developing rapidly and making progress in sustainable development. However, along with fast economic growth, urbanization, and population increase, there are several environmental issues, such as resource depletion, climate change, environmental pollution, carbon emissions, and water resource scarcity that need to be considered for sustainable development [1]. The increase in human activities is having a hazardous impact on the availability of natural resources. Water and energy are the most crucial elements for the survival of mankind on this planet as our global economic growth, national security, and climatic environment are highly influenced by energy and water usage. The rapid development in every part of life has resulted in excessive usage of energy and water, resulting in the scarcity of water and energy resources, along with the emissions of harmful gases in the atmosphere like carbon dioxide (CO_2).

Energy, water, and carbon are closely interlinked. Carbon emissions resulting from the usage of energy and water sources are having a strong impact on our lives and are a great threat to our future. Energy use and CO_2 emissions in water supply systems depend on factors such as water quality, water sources, and water topographical features. Water supply, distribution, end-use, and wastewater disposal consume abundant energy and emit a lot of carbon. Water is used for energy conversion in power-generating technologies in large amounts, either directly or indirectly, for cooling, hydropower operation or storage, steam generation, and desulphurization. Electricity generation also produces a lot of CO_2 which contributes to climate change. The shifting of high-carbon-emitting energy sources to renewable solar energy is being practiced to reduce the carbon emissions from water systems and provide clean water [2]. High energy use puts a strain on energy supply and security, which leads to pollution and climate change [3]. The study of energy, water and carbon interrelations is termed an energy–water–carbon nexus. The term "nexus" comes from the study of physics, and it refers to the dynamic interdependence of two or more elements or motion forms as a result of their interconnections and interactions. In general, nexus definitions in current research are classified into two groups: (a) interactions between distinct subsystems (or sectors) inside the systematic boundary, and (b) an analysis technique to measure the linkages between the nexus nodes [4].

Most of the researchers now use the second definition of nexus and consider it as a dynamic interrelated in the manufacturing and consumption of a product. The study of the nexus between energy, water and carbon will help to optimize integrated energy–water systems. In order to accomplish sustainable resource management and assure a consistent supply of both resources in the future, a thorough understanding of the water-energy-carbon nexus is required. Different methods have been used in the energy–water–carbon (EWC) nexus analysis for exploring the interconnections and critical flows of the three resources. An integrated process-based life cycle analysis (LCA) with input–output analysis for electricity generation technologies in China was proposed by Feng (2014) to calculate their total life-cycle CO_2 emissions and water consumption. They demonstrated that 79% CO_2 reduction and 50% water savings are possible with a shift in energy mix, from current technology to renewables [5]. In order to investigate whether water charge and carbon tax policies have synergistic effects, particularly in the energy sector, a dynamic computable general equilibrium (CGE) model was constructed. The CGE model was able to quantify endogenously the effects of climate and water policy on CO_2 emissions and water withdrawal in the energy sector as a result of the integration of the carbon pricing block and the water charge block. This CGE model integrated the carbon pricing block and water fee block into the CGE model and enabled the model to quantify endogenously the effects of climate and water policy on CO_2 emissions and water withdrawal in the energy sector. However, the authors did not study the relationship between the Emissions Trading System (ETS) market and renewable energy generation [6]. The aim of the Yuhuan (2022) study was to replicate the financial and environmental impacts of Chinese energy–carbon–water (ECW) policy. The primary novel contributions involved developing an ECW-CGE policy assessment model with integrated ECW policy modules and clarifying the theoretical ECW nexus mechanism at the macroeconomic level. This model was used to create separate and combined ECW policy scenarios, which will be simulated in 2050.

An environmental input–output (EIO) model was employed to calculate the sectoral embodied energy–water–carbon nexus (EWC) from 2002 to 2015 and adopted four indicators, i.e., sectoral embodied EWC, the proportion of direct EWC in embodied EWC, and their changes to explore sectoral EWC nexus characteristics of China. In order to adopt diverse EWC-related mitigation measures across sectors, it was advised that each sector's unique EWC nexus characteristics be identified as well as the synergies and co-benefits of EWC-related policies. The study provided new insights for EWC nexus analysis and offered data references for policymakers to design integrated and targeted sectoral EWC management policies [7]. In the Yangtze River Delta urban agglomeration, China, a chance-constrained fractional programming model for the energy–water–carbon nexus systems was developed by Liang, MS [8] in order to solve challenges of energy-related water resource scarcity and carbon emission reduction. The model was used in the strategic planning of the energy–water–carbon nexus system in the Yangtze River Delta metropolitan agglomeration. In this strategic planning, two different development patterns were designed. The obtained comparative results indicated that the energy–water–carbon nexus system increased imported electricity by 4.07% and system costs by 7.85% over the planning horizon; however, renewable electricity generation was originally increased by 21.71% and system efficiency by 16.29%, saving 8.95% of water resources. Moreover, carbon emission also reduced to 14.61% [8]. A multi-objective optimization technique was used by Gomez [9] to discuss the significance of thermal storage related to a combined heat and power system. The size of a combined heat and power unit and thermal storage tank that provide energy services to a residential building was determined by a nonlinear programming model. The water–energy–carbon nexus was studied using three objective functions: water usage, direct CO_2 emissions from fuel consumption, and global energy supply efficiency. The system's overall annual cost was also taken into account when evaluating its economic success. Results demonstrated the role of thermal storage in lowering emissions (by 67.5%), water use (15.5%), and system efficiency (75%) [9].

There have been very few applications of insight-based techniques for EWC nexus study. Most studies did not take into account the nexus' carbon emission component. Pinch analysis is a process integration technique used to predict a process's optimal performance before it is synthesized and designed. It is ideal to be used as a decision-making tool during the preliminary design stage. Rozali (2013) modified the power pinch analysis (PoPA) approach by taking into account the power losses that happen during the conversion, transport, and storage of the power system. The impacts of the losses on the storage capacity and the minimal targets for outsourced electricity were assessed. According to the study conducted considering power losses only, when the losses in the power system are considered, under-size issues may occur. This framework also did not cover the losses for water system. The PoPA Storage Cascade Table (SCT) was created to take energy losses into account when designing the system [10]. Xiao Y. Lim (2018) focused on three important components of the country's power sector, including carbon emissions, energy return on investment, and water footprint, to analyse the UAE's 2050 energy plan aim of 50% clean energy. Various scenarios for meeting the 2050 goal were examined while taking into consideration the availability of energy resources, the viability of new technologies, and cost projections. This approach provided a holistic assessment of the impact of each of the three aspects on the power generation sector [11,12]. A new framework applying pinch analysis was proposed by Mohammad Rozali et al., Xian Biao (2021) [13] 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). The framework was put to the test where system design changes were made to achieve a 20% reduction in CO_2 gas release. The final integrated design had minor effect on the energy system, with alterations of up to 12%, while the water system only deviated by less than 1% from the original design. The carbon emissions tracking is very necessary, as penalty fines or legal actions may be employed on the responsible authority in power plants for polluting the environment.

However, this framework does not consider the losses occurring during several processes like power conversion, power storage, power transfer and water transfer processes in the design of an integrated energy–water system. The effects of losses should not be ignored as most of the water losses have a direct relation to the emission of carbon. Losses are considered in this work to optimize the integrated energy–water system's performance and prevent the under-sized design of system. The efficiency and reliability of the system is reduced and consumers may face economic and ecological drawbacks. The water and energy sources are already limited and losses increase their consumption resulting in cost increase. The consideration of losses helps to promote industrial sustainability by reducing resource consumption and hazardous emissions, including greenhouse gases (GHGs) such as CO_2, CH_4, and NO_x.

2. Methodology

This section describes the framework for designing optimized integrated energy–water systems considering the power and water losses, using the pinch analysis approach. In order to achieve the intended design conditions, the framework addresses the nexus between the system's energy and water resources along with carbon emissions. Water and energy system design improvements were investigated after considering the power and water losses, in order to achieve more carbon emission reduction potential. As the three resources are interrelated, each pinch analysis method in this framework required information from the other pinch analysis approaches. Changes made to one resource network had a direct impact on the operations of the others.

The framework from Mohammad Rozali [10] was reconstructed considering power and water losses in the power cascade table and water cascade table, and the results were compared with the existing framework [13] without the losses. The EPPD diagram for carbon emissions was also compared with the EPPD without losses consideration. The framework's overall processes are outlined below:

Step 1: Power cascade table with losses for minimum targeting of an energy system

In this step, the construction of PCT considered all possible power losses in the system, including charging–discharging, conversion between AC and DC electricity, and self-discharge losses in the battery storage. A lead acid battery was used as power storage in this case study. The PCT was constructed by modifying the techniques from Ho et al. (2012) [14] and also from Mohammad Rozali et al. (2013) [10]. The modifications were done by including water demands for the energy system while calculating the net demand with losses. An integrated energy–water system considers the demand for water by the energy system and also demand of power for the water systems. The steps for construction of PCT were repeated with the addition of water demand. The efficiencies of the inverter, rectifier and battery are listed in Table 1. Losses occur during the conversion from AC to DC sources, charging and discharging, and during self-discharge by the storage battery. The data was taken from the illustrative case study. The consumption factors, emission factors, and efficiencies from illustrative case studies are tabulated in Table 1. PV panels of 300 m^2 area were used, and in addition to that, the demands of various appliances in the system were also fulfilled through the electricity generation from an 85 kW biomass generator.

Table 1. Various factors considered for the illustrative case study.

	Values
Water consumption factor for biomass source [15]	0.0037 m^3/kWh
Electricity consumption by 1 m^3 water [16]	0.9246 kWh
Efficiency of inverter [17]	0.95%
Efficiency of rectifier [18]	0.90%
Battery self-discharge rate [19]	0.004%/h
Carbon emission factor for natural gas [20]	0.1810
Carbon emission factor for biomass [20]	0.4032
Carbon emission factor for water [20]	0.114

Table 2 provides the hourly power demands. The average solar radiation data of an illustrative case study was used for the methodology demonstration [14].

The generated power was sent to the water system to supply and process water in addition to powering the appliances. The hourly water consumption by users, as shown in Figure 1, and the water used by the energy system to produce electricity make up the water network's demands. Water consumption in the solar PV facility for the illustrative case study was extremely low and was considered to be zero, whereas the biomass system required water, with a water consumption factor of 0.0037 m^3/kWh [15]. Additionally, it was projected that 0.9246 kWh of electricity would be utilised for every m^3 of provided water load [16].

Table 2. Power demands for the illustrative case study.

Power Demand	Power Source	Time (h) From	To	Power Demand Rating (kW)	Electricity Consumption (kWh)
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

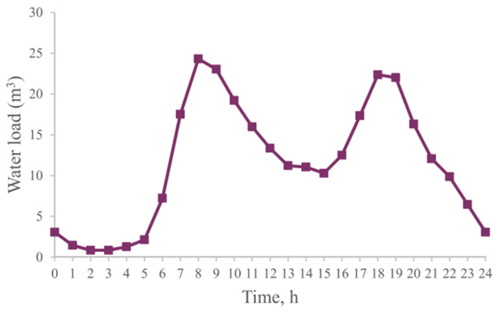


Figure 1. Hourly water load demands for the illustrative case study.

Table 3 shows the reconstructed PCT considering the losses in the power system using the procedures from Rozali (2013) [10]. That table was constructed for power pinch analysis with losses but without the consideration of power demand by the water system. The electricity source available for power supply were listed here and then further subcategorized into individual power generation sources, which were biomass and solar power.

Biomass supplied AC power and solar energy provided DC power. Column 3 of Table 3 contains the amount of electricity needed by the water and energy systems. Based on the information in Table 2, the amount needed for the energy system's power load, EDtE, was estimated, whilst the amount of electricity needed for the water system, $WD^E{}_t$, was also determined using Equation (1), [13]:

$$WD^E{}_t = [\sum(SE_{it,}{}^E \times WCF_i) + WD^W{}_t] \times ECF \quad (1)$$

where SE_{it} is the generation amount from the power sources [kWh], obtained from biomass and solar power in column 2. WCF is the respective water consumption factor for the biomass power system, which is 0.0037 [m^3/kWh] [15], and $WD^W{}_t$ is the hourly water load used by the consumers. ECF is the electricity consumed for every m^3 of water supplied, or can be called the energy consumption factor [kWh/m^3], which is 0.9246 [kWh/m^3] [16] as shown in Table 1. Other steps for columns 4 to 9 are repeated from Rozali 2013. The electricity deficit would be satisfied by converting the electricity surplus considering the power losses occurring during the conversion, which were assumed to be 5% [17]. If the battery capacity is less than the DC discharge requirement to meet the AC deficit, the battery will be discharged to its depth of discharge (DoD). The DoD of the lead–acid battery was 80% of its maximum capacity [21]. If a negative value, it means that the storage is unable to meet the power demands, and the deficit needs to be outsourced elsewhere. As with the consideration of losses, the outsourced electricity demand may increase. The results obtained from the PCT, after considering the losses in the energy system, and after considering the demand for both the water and energy systems based on column 9, shows that 495.46 kWh electricity was needed to be imported, and the calculated storage size was 156.625 kWh.

Table 3. Power Cascade table for the illustrative case study.

1	2		3			4		5		6	7	8	9
Time (h)	**Electricity Source (kWh)**		**Electricity Demand (kWh)**			**Electricity Surplus and Deficit (kWh)**		**Converted Surplus (kWh)**		**Charging and Discharging (kWh)**	**Discharge for Ac Deficit (kWh)**	**Storage Capacity (kWh)**	**Out-Sourced Electricity (kWh)**
	Bio-Mass (AC)	**Solar (DC)**	**By Power**		**By Water**			**AC-DC**	**DC-AC**				
0													
	85	0	60	1.63	22.20	24.60	0	22.20	0	22.20	24.60	19.98	0
1													
	85	0	60	1.08	22.72	25.18	0	22.72	0	22.72	25.18	40.43	0
2													
	85	0	60	1.08	22.72	25.18	0	22.72	0	22.72	25.18	60.88	0
3													
	85	0	60	1.47	22.35	24.77	0	22.35	0	22.35	24.77	81.00	0
4													
	85	0	60	2.26	21.60	23.94	0	21.60	0	21.60	23.94	100.44	0
5													
	85	0	60	6.98	17.12	18.97	0	17.12	0	17.12	18.97	115.84	0
6													
	85	0	60	16.48	8.09	8.97	0	8.09	0	8.09	8.97	123.12	0
7													
	85	6.41	60	22.77	2.44	8.76	6.41	2.12	6.09	2.44	8.76	125.31	0
8													
	85	17.1	60	21.59	-24.66	3.59	−27.9	3.24	0	−24.66	3.59	97.90	0
9													
	85	26.72	60	18.05	−11.68	7.32	−18.28	6.60	0	−11.68	7.32	84.93	0
10													
	85	34.2	60	15.07	−1.37	10.45	−10.8	9.43	0	−1.37	10.45	83.40	0
11													
	85	38.48	60	12.63	5.23	13.02	−6.52	11.75	0	5.23	13.02	88.11	0
12													
	85	42.75	60	10.66	11.37	15.09	−2.25	13.62	0	11.37	15.09	98.34	0
13													
	85	38.48	60	10.51	7.25	15.25	−6.52	13.77	0	7.25	15.25	104.86	0
14													
	85	34.2	60	9.8	3.64	16.00	−10.8	14.44	0	3.64	16.00	108.13	0
15													
	85	25.65	60	11.85	−6.86	13.84	−19.35	12.49	0	−6.86	13.84	100.51	0
16													
	85	17.1	60	16.32	−19.65	9.14	−27.9	8.25	0	−19.65	9.14	78.66	0
17													
	85	6.41	60	20.96	−34.75	4.25	−38.59	3.84	0	−34.75	4.25	40.05	0
18													
	85	0	60	20.65	−40.87	4.58	−45	4.13	0	−40.87	4.58	−5.36	5.36
19													
	85	0	60	15.38	−35.86	10.13	−45	9.14	0	−35.86	10.13	−45.21	45.21
20													
	85	0	60	11.45	−32.13	14.26	−45	12.87	0	−32.13	14.26	−80.90	80.90
21													
	85	0	60	9.41	−30.19	16.41	−45	14.81	0	−30.19	16.41	−114.44	114.44
22													
	85	0	60	6.26	−7.20	19.73	−25	17.80	0	−7.20	19.73	−122.44	122.44
23													
	85	0	60	3.12	−4.21	23.03	−25	20.79	0	−4.21	23.03	−127.11	127.11
24													

Step 2: Water Cascade table with losses for minimum targeting of the water system

The next step was to perform a cascade analysis for the water system to determine the minimum water storage and supply needs. The cascade table was constructed considering the overall losses occurring during the transfer from the water source to the demands, from source to storage, from storage to demand, leakages during transfer, and evaporation in storage. The WCT construction was comparable to the PCT structure, with minor modifications as indicated in Table 4 and as further explained:

1. Column 1: The time period for the water sources and demands were the same as for the power cascade table, i.e., one hour.
2. Column 2: The original estimate of the water supply volume was provided here; using the highest water load from Figure 1, we will use the value of 24.31 m^3.
3. Column 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 demands in Figure 1. The water demand for the energy system was calculated by using Equation

(2) [13]. Here WCF is the water consumption factor for the respective energy sources, and $ES^{E}i_{t}$ is the generation from the electricity sources indicated in Table 2, and WCF is the water consumption factor for the respective energy sources:

$$DEWt = \sum (ESEi,t \times WCFi) \quad (2)$$

4. Column 4: The net demand for water was calculated after considering the losses during the transfer of water from the source to demand. According to Interreg Central Europe [22] the amount of water loss depends on the water supply, at an estimated economically feasible level of water loss between 8% and 10% or 5% and 6% [23]. For this case it was assumed to be the maximum loss possible of 10%. After considering that 90% effective water was supplied to the demand, the net demand was calculated using Equation (3) [13]:

$$N^{W}{}_{t} = \sum S^{W}{}_{i,t} \times \eta_{L} - \sum D^{W}{}_{j,t} \quad (3)$$

where η_L is the efficiency of water after losses. The results obtained in column 4 had both positive and negative values.
5. Columns 5 and 6: In column 5, the water that can be sent to the storage tank was represented by the positive values from column 4, which were referred to as the charging quantity. On the other side, the negative values represented the discharging quantity in column 6, which represented the amount that had to be taken from the storage tank in order to satisfy the unmet water demands.
6. Column 7: The water cascade represents the total amount of water in the storage tank. It was assumed that no water is stored at t = 0 h. In column 7, the storage capacity was calculated by using Equation (4) [13]:

$$T^{W}{}_{t} = T^{W}{}_{t-1} + C^{W}{}_{t} + D^{W}{}_{t} \quad (4)$$

If there is any negative value in column 7, then iteration needs to be performed using the highest negative value as the water stored. The highest negative number from column 7 was used to represent water that had been stored at time = 0 h.

The minimum storage capacity can be reached if the total amount of water stored (TWt) at the first and last time intervals is equal in column 7. Otherwise, Equation (5) [13] should be used to estimate a new water supply volume to minimize the initial estimated volume.

$$S^{W}{}_{new} = S^{W}{}_{initial} - T^{W}{}_{t=24} - T^{W}{}_{t=0}/24 \quad (5)$$

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). The results obtained after the loss consideration in WCT showed that the supply volume was increased from 12.05 m^3 to 14.48 m^3. The storage capacity was decreased from 72.48 m^3 to 23.566 m^3.

Step 3: Constructing an EPPD for carbon dioxide emissions

This method was used to assess the amount of carbon dioxide emitted as a result of energy and water usage. Both the energy and water systems emit a considerable amount of carbon dioxide. The carbon emissions depend on the source of energy we use. As we use coal, biomass, wind etc., every source contributes to emitting carbon differently, so the calculation of carbon emissions depends on the source being used and amount of energy generated from it. According to Trubetskaya et al., the delivery of one cubic meter of water emits 0.344 kg of carbon dioxide [24]. The carbon emissions from the water system can be calculated using Equation (6) [13], where S^W is the water network capacity and CF^W is the emission factor of carbon for the water system. With the increase in water supply volume the carbon emissions also increased by 1.2%.

$$CE^{W} = S^{W} \times CF^{W} \quad (6)$$

Table 4. Water cascade table for the illustrative case study.

1	2	3		4	5	6	7
Time (h)	**Water Source (m^3)**	**Water Demand (m^3)**		**Net Demand (m^3)**	**Charging Quatity (m^3)**	**Discharging Quantity (m^3)**	**Storage Capacity (m^3)**
		DW	**DE**				
0							
	24.31	1.45	0.3145	20.1145	20.1145	0	20.1145
1							
	24.31	0.85	0.3145	20.7145	20.7145	0	40.829
2							
	24.31	0.85	0.3145	20.7145	20.7145	0	61.5435
3							
	24.31	1.28	0.3145	20.2845	20.2845	0	81.828
4							
	24.31	2.13	0.3145	19.4345	19.4345	0	101.2625
5							
	24.31	7.23	0.3145	14.3345	14.3345	0	115.597
6							
	24.31	17.51	0.3145	4.0545	4.0545	0	119.6515
7							
	24.31	24.31	0.3145	−2.7455	0	−2.7455	116.906
8							
	24.31	23.04	0.3145	−1.4755	0	−1.4755	115.4305
9							
	24.31	19.21	0.3145	2.3545	2.3545	0	117.785
10							
	24.31	15.98	0.3145	5.5845	5.5845	0	123.3695
11							
	24.31	13.35	0.3145	8.2145	8.2145	0	131.584
12							
	24.31	11.22	0.3145	10.3445	10.3445	0	141.9285
13							
	24.31	11.05	0.3145	10.5145	10.5145	0	152.443
14							
	24.31	10.29	0.3145	11.2745	11.2745	0	163.7175
15							
	24.31	12.5	0.3145	9.0645	9.0645	0	172.782
16							
	24.31	17.34	0.3145	4.2245	4.2245	0	177.0065
17							
	24.31	22.36	0.3145	−0.7955	0	−0.7955	176.211
18							
	24.31	22.02	0.3145	−0.4555	0	−0.4555	175.7555
19							
	24.31	16.32	0.3145	5.2445	5.2445	0	181
20							
	24.31	12.07	0.3145	9.4945	9.4945	0	190.4945
21							
	24.31	9.86	0.3145	11.7045	11.7045	0	202.199
22							
	24.31	6.46	0.3145	15.1045	15.1045	0	217.3035
23							
	24.31	3.06	0.3145	18.5045	18.5045	0	235.808
24							

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 in [20]. The EPPD approach, which was created using the steps outlined by [25], was used to target the quantity of carbon released from the energy network. The network's energy sources were grouped according to increasing emission factors. The carbon emission from biomass and solar energy sources were obtained on the basis of their carbon emission factors ($CF^E{}_i$) and generation capacity ($S^E{}_i$). Equation (6) can be used to perform the computation in a manner similar to that for the water network. The cumulative power generation and emission levels were used as the horizontal and vertical axes to build the source composite curve (SCC), which incorporates all energy sources. This is depicted in Figure 2. The EPPD graphic shows the 300 t CO_2 annual total emissions for the energy network's initial and final designs.

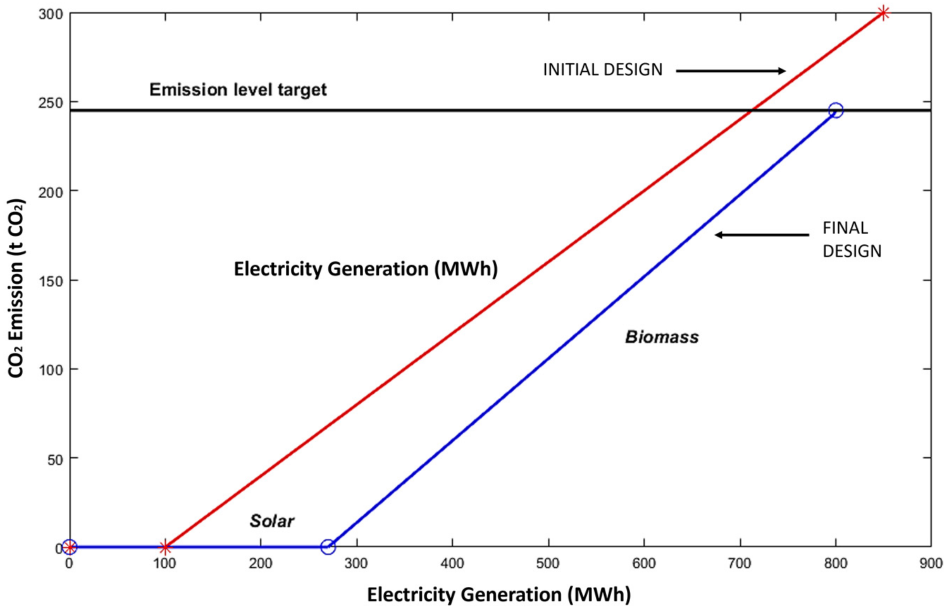


Figure 2. EPPD plot before and after design modifications for the illustrative case study.

3. Design Modification

This section discusses the changes made to the initial design. The effect of the losses is calculated by repeating the calculations, by making changes in the energy and water systems. The energy obtained from biomass sources was reduced from 85 kW to 70 kW, and area of solar panels was increased from 300 to 800 m^2. Consequently, changes made in the energy system caused changes in the energy storage capacity and outsourced energy. The calculations were performed after losses and it was seen that the energy storage capacity decreased while the outsourced electricity requirement increased. The effect on the water system showed that after losses, the water supply volume increased and water storage capacity decreased. The increase in water supply volume indicated that more carbon was released; however, the design modifications carried out on the energy system decreased the water supply volume, and hence the carbon emissions were reduced.

Table 5 summarize the overall results obtained for the integrated energy–water system with the consideration of losses and without losses in PCT, WCT and EPPD.

Table 5. Overall results for Illustrative Case study with and without losses.

	Initial		Final Iteration 1		Final Iteration 2	
	without Loss	with Loss	without Loss	with Loss	without Loss	with Loss
Biomass power	85	85	65	65	70	70
Solar panel area	300	300	750	750	800	800
Energy storage capacity	163.17	156.625	249.10	33.6175	356.53	69.42
Outsourced electricity	109.19	495.461	174.58	1035.83	43.241	818.80
Water supply volume	12.05	14.484	11.98	14.41	11.998	14.429
Water storage capacity	72.48	23.566	72.48	62.581	71.72	23.71
Carbon emissions from energy system	300	300	229	229	247	247
Carbon emissions from water system	106	127.05	105	126	105	126.5

4. Case Study

As the case study, a manufacturing facility in Peninsular Malaysia was selected [26]. Figure 3 shows statistics on the plant's hourly power and water load profiles. Biomass and natural gas generators with respective outputs of 200 kW and 100 kW power the energy system. The system also makes use of a solar system with a 1000 m^2 PV area to capture the energy that can be obtained from solar radiation. The solar PV and storage systems' efficiencies and other details were taken to be the same as in the illustrative case study. In this instance, the water requirement for the solar PV system was not taken into consideration, but the supply of water to the other two power facilities was, i.e., biomass and natural gas at 0.0037 m^3/kWh and 0.0044 m^3/kWh, respectively [15,16]. The overall results after consideration of losses have been summarized in Table 6.

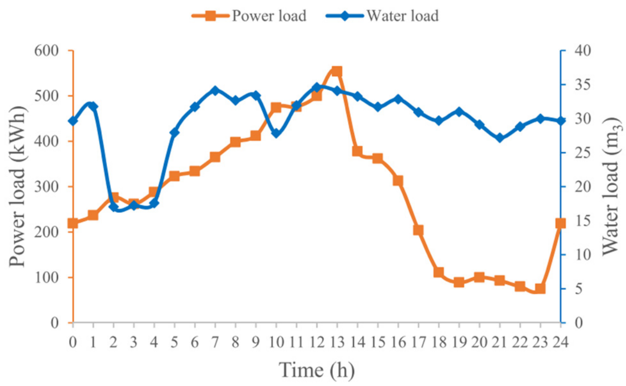


Figure 3. Hourly water load and power load for the case study [26].

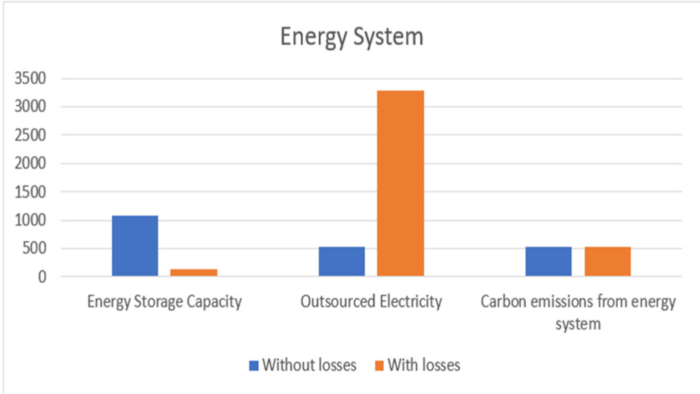
Table 6. Overall results for the case study with and without losses.

	Initial		Final	
	without Loss	with Loss	without Loss	with Loss
Generator capacity for biomass (kW)	100	100	70	70
Generator capacity for natural gas (kW)	200	200	180	180
Solar PV panel area (m^2)	1000	1000	2200	2200
Energy storage capacity (kWh)	1267	1212.51	1088	141.44
Outsourced electricity (kWh)	666	3027.27	526	3287.5
Water supply volume (m^3/h)	30.67	36.951	30.47	36.95
Water storage capacity (m^3)	37.89	32.689	37.89	32.699
Carbon emissions from energy system (t CO_2/y)	670	670	533	533
Carbon emissions from water system (tCO_2/y)	269	324.09	267	321.4

5. Result and Discussion

After considering the losses in the power cascade table (PCT) and water cascade table (WCT) for the case study, the results were compared with the initial case study. The results are shown in Table 6. The initial values of the industrial case study were compared with and without losses to find the effect on the energy storage capacity, water supply volume, water storage capacity, outsourced electricity and carbon emissions from both the energy and water systems. It was observed that the electric storage capacity was decreased from 1267 kW to 1212.51 kW, and the outsourced electricity requirement increased from 666 kW to 3027.27 kW, which indicates that after losses consideration in energy system, the amount of electricity required from outside increased more, and the capacity of storage decreased. The water supply volume was increased from 30.67 to 36.951, while the water storage capacity was decreased from 37.89 cubic meters to 32.699, which shows that if losses are considered, the water system requires more water supply volume and hence the water storage capacity decreases. After implementing the design modifications to the energy–water system by increasing the area of solar panels for more renewable energy and reducing the generation from biomass and natural gas power sources, it was observed that the electric storage capacity decreased from 1088 kW to 141.44 kW, and the outsourced energy requirement increased from 526 kW to 3287.5 kW. In the water system, the supply volume increased almost the same as before design modifications, and the water storage capacity also showed almost the same results. Figure 4 shows the comparison chart with and without losses for the case study. The carbon emissions were calculated based on the source's generation and their emission factors. For the energy system, the power sources remained the same before and after losses, but after design modifications the carbon emissions from energy were reduced from 670 (t CO_2/y) to 533 (t CO_2/y). In the water system, when the losses were considered, the supply volume increased and hence the carbon emissions also increased by 20%. It was observed that carbon emissions increased from 269 (t CO_2/y) to 324 (t CO_2/y), but after design modifications it reduced to 321.4 (t CO_2/y). The calculated results shows that losses consideration is very important for optimizing the design and modifications in the system. The losses show that the storage capacity of energy decreased by 4%, while outsourced energy increased by 6%. The energy system and water supply volume increased by 20%, and the water storage capacity decreased by 13.7%. The emissions from the energy system remained the same, while from the water system, the emissions increase by 20%.

Overall, the results obtained from the case study after comparison with the previous framework demonstrate that the losses consideration for the energy–water–carbon nexus give a clearer idea on carbon emissions from the integrated energy–water system. It is anticipated that power and water allocation that takes power and water losses into account will produce more realistic energy and water targets and prevent under-sized system designs. Under-size issues lead to outsourced electricity, which directly affects the efficiency and economy of the energy–water system, hence releasing more carbon. Moreover, the results of the losses consideration enable good technical comprehension and improved control over the solution space through visual insights on the network design. Utilizing various energy sources to generate electricity could lead to a more significant modification in the water system.



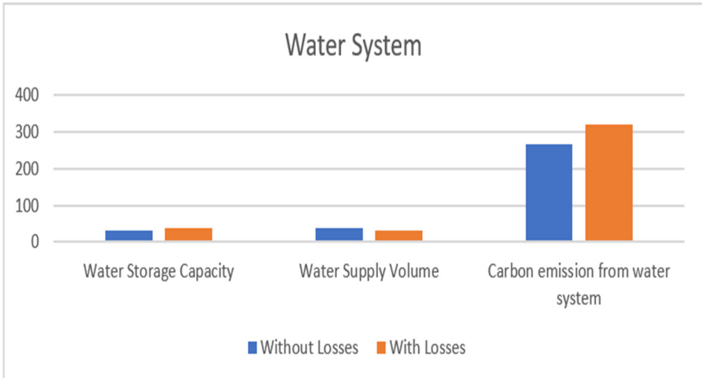


Figure 4. Overall results for the case study before and after losses.

6. Conclusions

In this study, the energy–water–carbon nexus has been studied using the pinch analysis technique, while considering the losses occurring in energy and water systems. The consideration of losses plays an important role in identifying carbon emissions and then optimizing the integrated energy–water system. The presented case study showed the effect of losses on carbon emissions in the environment. The ideal conditions (without losses) for estimation of carbon emissions are insufficient, as losses increase the usage of sources, and hence result in more carbon emissions. Losses must be taken into account for designers to efficiently manage issues and implement the required design adjustments. Design modifications are required in the power and water systems to reduce the effect of losses and optimize the systems operation, along with reducing carbon emissions. The output from this study provides knowledge on how losses effect carbon emissions. Users can consider minimizing the losses in energy and water systems to reduce carbon emissions. Future studies should consider methods to minimize the losses occurring in both energy and water systems by detailed analysis. A similar concept as EPPD can be explored for water systems too, for more accurate design modifications for the optimizing of energy–water systems. Other kinds of power storage systems and their losses can be researched in order to determine the optimal storage solutions for integrated energy–water systems.

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