The Energy-Water-Food Nexus Architecture for the Optimal Resource Allocation

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***Abstract*—For sustainable development, potable water, green energy, and fresh food are essential resources that are required by any society. Much devotion is given to energy and water infrastructures due to an interlinked networked system of global concerns under the energy-water-food (EWF) nexus paradigm. Generally, these infrastructure systems deliver power and water through separate and uncoupled systems. However, these are coupled infrastructures serving in their respective domains. Considering these interdependent networked systems, the power, water, and food infrastructures required joint optimization. In this regard, a joint optimization program has been developed to optimally allocate the energy and water that includes power, water, and co-generation facilities. Therefore, a mathematical optimization program for simultaneous co-dispatch of power and water from power generation, water production, and co-generation facilities is first developed. This optimization model runs considering production, demand, transmission, and process limits. Furthermore, the inclusion of a co-generation facility helps in alleviating the binding constraints and leads to flat power generation and water production with reduced cost. Moreover, the proposed model is designed to follow a systematic approach in achieving the optimal results without violating the limits based on which the plants can easily achieve optimal control. For simulation, we use IEEE standard bus, Hanoi water distribution, and food systems and used a nonlinear optimization with a CPLEX solver. Results show that the optimal resource allocation with fair cost reduction is achieved.**

***Index Terms*—Nonlinear optimization, energy-water-food nexus, water distribution network, power flow, water flow.**

I. Background and Motivation

Green energy, potable water, and fresh food are essential resources that any developed society needs to be delivered for sustainable development, e.g., to meet the social, environmental, and economic goals [1–6]. Considering green energy, extensive use of conventional energy sources such as coal, oil, and natural gas has raised serious concerns regarding climate change, global warming, and carbon dioxide emissions [7]. Consequently, many authors have started research in finding renewable energy sources and energy-efficient methods [8–11]. Similarly, potable water is another vital source of sustainable development and survival [5], [6]. Its extensive use has remarkably increased in the recent decade due to the growing population and industrial use. As a result, the natural water reservoirs are depleted very quickly in many other regions [12], [13]. Therefore, it is inevitable to develop some methods to optimally utilize the use of power and fresh water resources for long-term sustainability and economic growth. Because the excessive use of power and water could raise sustainability issues including carbon dioxide emission and food security [2]. Furthermore, power and water growth are strongly associated with population growth. Economic growth along with individual lifestyle implies intensification in per capita energy and water demands. In addition, the hot climate in other developing countries can also have the coupling of power and water network systems. Because, due to the poor planning of these resources, power and water deficits may create aggravated scarcity. So, the nations should take early steps in their infrastructure development to possibly reduce the power and water deficits.

TABLE I
Supply and demand sides couplings of EWF nexus [5], [6].

	Power supply	Power demand
Water supply	Co-generation Thermal desalination – Hydroelectric	Supplied water – Water distribution Wastewater management
Water demand	Thermal power generation food processing industry agriculture industry	Residential & commercial cooling of water Industrial use of water and power for heating

A. Contribution

This proposed work considers the supply-side couplings of energy and water for optimal resource allocation in the presence of line limits and process constraints [5], [14]. The first part was the optimal power and water flow which further developed here. Firstly, the extended architecture presented by Abdullah & Farid [6] is considered and further developed here for the agriculture and/or food industry. Here, it is also found that in the presence of process constraints and line limits, we can efficiently utilize the available resources. Here, we further develop a joint optimization program to optimally utilize power and water resources. Unlike previous work, this work has considered power, water, and co-generation facilities while demand includes agriculture and food processing networks. For this purpose, we have introduced the water distribution network (32 nodes system) [14] to supply water and power to both the food and agriculture sectors (12 nodes system, proposed). However, this paper does not address the integration

TABLE II
WATER DEMAND IN FOOD PROCESSING INDUSTRY.

Sr. No.	Product	Min. water usage (m^3)	Max. water usage (m^3)
1	Beer	9.08	14.53
2	Milk products	9.08	18.16
3	Meat packing	13.62	18.16
4	Bread	1.81	3.64
5	Whisky	54.50	72.67
6	Green beans	45.42	64.35
7	Peaches and pears	13.62	18.16
8	Fruits and vegetables	3.64	31.79

of renewable energy resources. Finally, this work utilized the proposed optimization program to analyze a hypothetical test case taken from the Hanoi water distribution network in the UK [14] with water storage facility, standard IEEE 30 bus system, while the water demand for food processing is taken from Ellis et al. [15] and the units are shown (see Fig. 1), & table II. The topological description of the Trimetrica smart EWF nexus of the proposed layered architecture Fig. 2.

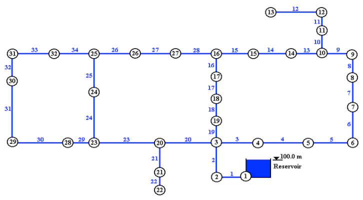


Fig. 1. Hanoi water distribution network [14].

II. METHODOLOGY

This section briefly discusses the proposed modeling methodology for the program of network flow dealing with the optimal resource allocation of both power water and food networks. Section II-A discusses the underlying model of EWF nexus. While, the remaining subsections recount the basic optimization models, whose objective is to provide set points for both, power and water and co-generation facilities used for target optimization. Considering the underlying objectives of an interlinked EWF nexus market, the proposed optimization model can maintain the symmetry between control variables to maintain a minimum level of complexity.

A. System Model

Fig. 2 represents the conceptual diagram of the proposed optimization model. It consists of power, water, and co-generation facilities that are used, simultaneously to fulfill the required power and water demand. The power, water, and food networks are modeled as independent but interlinked nodal networks. Based on the demand, the utility dispatches the electrical power, potable water, energy storage, and water storage capacities. Unlike the traditional independent systems, the co-generation facilities can be considered either independent or vertically integrated. Where, the power and water plants require a fuel source to produce the electricity and potable

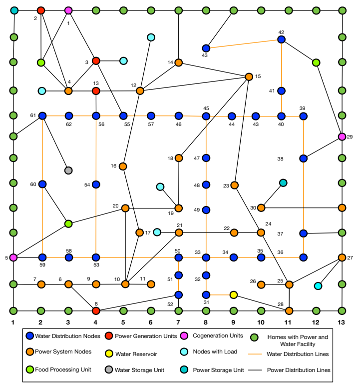


Fig. 2. Topological description of the Trimetrica smart EWF nexus test case, showing topology of: power, water and food systems. It represents water, food, and power distribution networks with a cyber-control layer.

water, respectively. While the co-production facilities may be either thermal desalination or hydroelectric requiring the fuel source in the former one. The coupling of respective plants is done as a result of their production cost considering the limits and binding constraints. The fresh water can be obtained from the ground source, a storage station, or a desalination plant, respectively. The water and co-generation facilities draw water from their independent sources. The energy-water nexus model also applies an independent water source as mentioned in Anytown water distribution network UK [16].

III. PROBLEM FORMULATION

A. Direct Current (DC) Optimal Power Flow (DC-OPF)

The research in OPF methods has gained attention due to the limitations built into the economic load dispatch problems. Generally, the economic load dispatch methods have been used to minimize the power generation cost by considering the generation and distribution at the single bus. Regarding the implementation point of view, this, however, may create problems in power distribution networks. Because, the power system operation does not only require the supply, demand, and capacity constraints but also requires the constraints on the transmission network. Furthermore, the incorporation of transmission network constraints can improve system stability by reducing overall system losses. The cost function $C_{pi}(x_{pi})$ of commonly used DC-OPF problem formulation [5], [11]:

$$min \quad C_{pi}(x_{pi}) = \sum_{t=1}^{T} \sum_{i=1}^{n_{pp}} \{C_{pi,t}(x_{pi,t})\} \tag{1}$$

$$P_{gi,t} - P_{Di,t} = \sum_{y=1}^{n} \{B_{yz}(\delta_y - \delta_z)\}, \forall t \in T, \tag{1a}$$

$$P_{gi,t}^{min} \leq P_{gi,t} \leq P_{gi,t}^{max}, \forall t \in T, \tag{1b}$$

$$p_{yz,t}^{min} \leq p_{yz,t}(B_{yz}(\delta_y - \delta_z)) \leq p_{yz,t}^{max}, \ \forall \ t = 1, ..., T \tag{1c}$$

$$\delta = 0, \ \& \ |V_i| = 1p.u., , \tag{1d}$$

where, i, j, k denote indices and $C_{pi}(x_{pi})$, $C_{wj}(x_{wj})$ and $C_{ck}(x_{ckp,ckw})$ are cost functions of power, water and cogeneration plants, respectively. $P_{gi,t}$, $P_{Di,t}$ are power generation and demand, B_{yz} is bus incidence matrix, δ denotes power angle, and $P_{gi,t}^{min}$, $P_{gi,t}^{max}$ are min. and max. limits on power generation. Eq. (1a) is the cost minimization objective function, eq. (1b) gives the power generation and demand balance, eq. (1c) provides power flow limits, eq. (1d) shows that δ is zero at reference bus, and node voltages are set to the unity p.u in DC-OPF case.

B. Optimal water flow

Despite having some similarities in the domain of optimal water flow, it has to be explored to the same extent [17]. Some researchers explore the water distribution network from the design and optimization point of view [18]. While designing a water distribution network, it is required to ensure the continuity of water flow. In another way, water in-flow must be equal to out-flow. Another important factor is the inclusion of the pressure loss factor between all nodes in the water network. We consider a water supply network that is composed of pipes, pumps, junctions, valves, reservoirs, and tanks. Valves and pumps are considered two different subsets and each pipe contain one valve and pump. The water network is modeled by a directed graph $\mathcal{G} = (\mathcal{N}, \mathcal{L})$. Where, $\mathcal{N}$ denotes a set of nodes comprising junctions, tanks, and reservoirs, respectively. While, $\mathcal{L}$ is a set of directed pipes a, b and b, a for each pair of node. The operation time period is considered for $t \in T$. Let $|\jmath|$ denotes a set of junctions $|\jmath| = \mathcal{J}$, where a constant water demand D_{wt} (in m^3/s) is applied at each junction over the t. It is also considered that water demand for all $|\jmath|$ is know for t, and Q_{ab} denotes pipes to carry non-zero flow of water from node a to node b such that $(a, b) \in \mathcal{J}$. At each junction, the associated constraints in the water distribution network as:

$$F_{ab} = \sum_{a=1}^{n_w} Q_{ab} + D_{wa} = 0,\ \forall\ j = 1, ..., m_w, \tag{2}$$

$$H_a - H_b = R_{ab} Q_a |Q_b|^{n-1}, \tag{3}$$

$$Q_{ab} = \tfrac{H_a - H_b}{R_{ab}^{0.54} |H_a - H_b|^{0.46}}. \tag{4}$$

$$H_j^{min} \leq H_{j,t},\ \forall\ j = 1, ..., m_w, \&\ t = 1, ..., T \tag{5}$$

where eq. 2 denotes water flow balance, which must be equal to zero, m_w denotes the total number of pipes, F_{ab} is total flow, Q_{ab} is water flow, D_{wa} is water demand, H_a is the nodal head, R_{ab} is the resistance coefficient, and n is the water flow exponent. Eq. (2) shows the water flow balance, eq. (3) gives the pressure loss in water pipes, and eq. (4) calculates the net flow among all nodes, and eq. (5) denotes that pressure head H_j must satisfy the minimum allowable flow over t. It is further defined as $\mathbf{H}^{min} = \{H_j^{min} |\jmath| \in J\}$ and $\mathbf{D} = \{D_{wa} |\jmath|| \in J, t \in T\}$. Here, the value of the water flows exponent n depends on the optimal selection of the head loss relationship. In literature [17], there are two widely used equations for the calculation of pressure head loss: (i) Darcy Weisbach relationship [19] where n=2, and (ii) Hazen Williams relationship where the value of n=1.852 [17]. Both, Hazen-Williams and Darcy-Weisbach equations are equally feasible in calculating pressure head loss. The former calculates pressure head loss without intensive calculations. However, the latter provides more accurate results. The primal problem eq. 6 can be described as:

$$min \quad \sum_{t=1}^{T} C_{G,t}(x_{pi}, x_{wj}, x_{ck}) =$$
$$\sum_{t=1}^{T} \left\{ \sum_{i=1}^{n_{pp}} C_{pi,t}(x_{pi}) + \sum_{j=1}^{n_{wp}} C_{wj,t}(x_{wj}) + \sum_{k=1}^{n_{ck}} C_{ck,t}(x_{ckp,ckw}) \right\}, \tag{6}$$

where, $C_{pi,t}(x_{pi,t}), C_{wj,t}(x_{wj}), C_{ck,t}(x_{ckp,ckw})$ represent the cost-coefficients of i^{th} power generation plant, j^{th} water production plant, and k^{th} co-generation facility over t, respectively. The cost function can take any one of the functional forms. These cost functions are generally quadratic in nature and taken as decision variables which are given in eq. (7):

$$\begin{gathered} C_{pi,t}(x_{pi}) = a_{2i} x_{pi}^2 + a_{1i} x_{pi} + A_{0i} \\ C_{wj,t}(x_{wj}) = a_{2k} x_{wj}^2 + a_{1j} x_{wj} + A_{0j} \\ C_{ck,t}(x_{ckp,ckw}) = a_{11k} x_{ckp}^2 + a_{22k} x_{ckw}^2 + a_{12k} x_{ckp} x_{ckw} + \\ a_{1k} x_{ckp} + q_{2k} x_{ckw} + a_{0k} \end{gathered} \tag{7}$$

Eq. (6) is subject to the constraints associated with power, water, and co-generation facilities. Regarding power generation and demand P_{D_i}, the general flow balance equation (eq. 8) can be modified when we specifically add a term for the co-generation facilities:

$$0 = P_{D_i} - \left\{ \sum_{k=1}^{n_{cp}} I_{cky} x_{ckp} - \sum_{i=1}^{n_{pp}} I_{piy} x_{pi} + \sum_{y=1}^{n_p} B_{yz} (\delta_y - \delta_z) \right\}$$
$$\forall y = 1, ..., m_p. \tag{8}$$

Similarly, the co-generation facilities add another term to the water balance equation as is given as:

$$0 = D_{wa} - \left\{ \sum_{k=1}^{n_{cp}} I_{ckt} x_{cwk} - \sum_{j=1}^{n_{wp}} I_{wjt} x_{wj} + \sum_{a=1}^{m_w} F_{ab} \right\}$$
$$\forall y = 1, ..., m_w. \tag{9}$$

$$D_{wa} = \left\{ D_{wa,t}^{pi} + D_{wa,t}^{wj} + D_{wa}^{ckp,t} + D_{wa,t}^{ckw} \right\}, \forall t \in T,$$
$$\forall i \in m_p, j \in m_w, k \in m_{cp}. \tag{10}$$

$$u_{pi,t} + w_{pi,t-1} - v_{pi,t} = w_{pi,t}, \forall y \in m_p, t \in T. \tag{11}$$

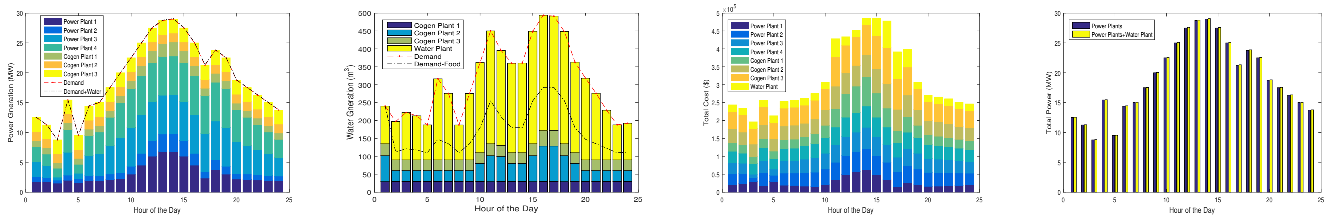
$$u_{ckp,t} + w_{ckp,t-1} - v_{ckp,t} = w_{ckp,t}, \forall y \in m_{ckp}, t \in T. \tag{12}$$

$$u_{cwk,t} + w_{cwk,t-1} - v_{cwk,t} = w_{cwk,t}, \forall y \in m_{cwk}, t \in T. \tag{13}$$

$$u_{pi,t} + v_{pi,t} \leq 1, \forall y \in m_p, t \in T. \tag{14}$$

$$u_{ckp,t} + v_{ckp,t} \leq 1, \forall y \in m_{ckp}, t \in T. \tag{15}$$

Eq. 9 gives water production and supply balance including co-production facilities. Eq. 10 denotes total water demand at all facilities, eqs. 11, 12 and 13 denote the switching states of dispatchable generators in power, water and cogeneration facilities. Where, u, v and w denote the start-up, shut-down and ON/OFF states of all generators. Where, eqs. 14 and



(a) (b) (c) (d)

Fig. 3. (a) Power generation and demand profile, (b) Water generation and demand profile, (c) Cost incurred by different units and (d) total power obtained from all facilities over the period of 24 h.

15 ensure that dispatchable generators and other resources to fulfill the demand capacity cannot start-up and shut-down, simultaneously. Now, the energy required for water supply system is calculated as:

1) Power & water generation limits: As the objective function is minimized w.r.t power and water generations limits on all types of facilities. Therefore, these power and water generation limits are gathered and written are follows:

$$\begin{gathered} MinGenPP \leq X_p \leq MaxGenPP, \\ MinGenWP \leq X_w \leq MaxGenWP, \\ MinGenCPP \leq X_{cpp} \leq MaxGenCPP, \\ MinGenCPW \leq X_{cpw} \leq MaxGenCPW, \\ MinGen\sigma_v \leq X_{cpw} \leq MaxGen\sigma_v. \end{gathered} \tag{16}$$

Generally, in power flow problems, it is important to impose generation limits on all types of plants. Eq. (16) limits the power and water generations of all types of facilities. These limits help to minimize the instabilities in production plants.

2) Power & water flow limits: The power and water flow limits are given as follows:

$$\begin{gathered} MinPFlow_{ij} \leq B_{ij}(\delta_i - \delta_j) \leq MaxPFlow_{ij} \\ MinWFlow_{tu} \leq Q_{tu} \leq MaxWFlow_{tu}. \end{gathered} \tag{17}$$

Just like power generation limits given in section III-B1, power and water flow limits are essential parameters to reduce the line losses. Eq. (17) shows that the total capacity of power and water flow rate could be incorporated as the upper production limit of the respective plant. In contrast, these could also be selected according to the plant's environmental license limit from a hydrological perspective.

IV. Simulation Methodology

The optimization model discussed in section II has been tested on a publically available dataset taken from Anytown water distribution network [16], [20], IEEE standard bus system and food demand are taken from Ellis et al.[15]. There are two important reasons for the selection of these data sets: (i) the timings of power and water peaks reflecting their real-time usage, and (ii) the limits of power and water demands are selected in such a way to get fast convergence of the optimization technique. The supposed system model consists of four power, three co-production, and one water plant. The MATLAB and GAMS languages are used together to solve the mathematical optimization program having nonlinear objective function and smooth monotonic constraints. The former is used for data handling, while the later is used for optimization using built-in CONOPT and CPLEX solvers. These solvers have the ability to handle large scale nonlinear optimization problems [21]. The GAMS displayed this kind of solution.

```
--- Cplex Time: 0.02sec (det. 24.30 ticks)


Optimal solution found
Objective:           1566.042189

--- Reading solution for model allocs
--- Executing after solve: elapsed 0:00:00.294
--- airsp.gms(170) 6 Mb
*** Status: Normal completion
--- Job airsp.gms Stop 07/28/21 15:24:33 elapsed 0:00:00.295
```

V. Results and Discussion

Figs. 3a and 3b give the power and water profiles over 24 hours. The optimization program is completed with fast convergence time. The considered water and power demand profiles can represent the worst optimization conditions than other commonly used profiles in daily life. Here, the co-production plants are used as the "first choice" in managing the power and water demands. While the independent power and water plants are essentially used to manage the demand during peak hours. Fig. 3a shows the power drawn by the power and water networks. Here the power consumed by the water network is calculated which shows the moderate water quantity, which can be seen by the difference between the red and black dotted lines (in the web version). The power and water input profiles are selected to visualize the real power and water demand profiles of daily life. It can also be seen that the peak in power demand profile is generally found in the afternoon when most of the industrial load is turned on. However, according to the figures, the peak could be created from h_{10} to h_{16}. And the lowest level of power demand is found from h_1 to h_3. Similarly, water demand has high peaks in h_6, h_{10}, to $h_{16} - h_{18}$, respectively. The first peak is usually due to irrigation use and the second peak is due to industrial and commercial use. Fig. 3c shows the total cost of generation incurred by all plants in 24 h. At first view, the obtained results seem cross-intuitive showing a comparatively higher cost when the demand is also higher and vice versa. This arises because the co-production plants have a higher cost as compared to the independent plant's incomplete terms for all production stages. Similarly, heat cost in co-production plants is comparatively lower. So, there is no dominant difference between the cost of all generation plants. Furthermore, it is also observed that the water and power demands swing during the given period, co-generation facilities not only run close to full capacity but also follow the respective product ratio constraint to provide incentives. From the figure, it can be visualized that the power-to-water demand ratio set points swing between 4-9 MW/m^3. While co-generation facilities set points to swing between 2-9 MW/m3 depending on demand variations. As a result, the individual power and water plants are turned on as "second choice" during on-peak hours to reduce total cost. Finally, fig. 3d gives the power generation profile of combined power and water facilities.

VI. Conclusion

In this work, we have analyzed the developed model for the EWF nexus in the presence of limits on transmission lines to a joint optimization program for the optimal flow of energy and water. This program builds upon the previous work by incorporating line limits without a storage facility. The former one restricts its scope due to inconsideration of: (i) line limits, (ii) agriculture facility and, (iii) distributed locations of generation units. The total cost of all the facilities subject to generation, transmission, and process limits is minimized. Based on the considered datasets, the optimization model composed of four power, three co-generation, and one water plant is evaluated. From the results, it can be analyzed that demand is initially fulfilled by co-generation facilities, and single product units (i.e., power & water) could be crowded out at this time. Results also reflect the impact of the co-generation facility on total cost alleviation. The OPF for the supply side seeks to minimize the use of expensive resources to reduce overall cost along with high efficiency. The joint optimization program manages the available resources in such a way that efficient resources are dispatched. However, this optimization program poses some challenges that are unlikely in single product optimization cases.

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