Interactive Visualization of Interdependent Power and Water Infrastructure Operation

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***Abstract*—With increasing levels of drought across the world together with the rising demand of freshwater and energy consumption, the interdependence between power and water sectors is becoming increasingly important. However, as power and water facility operators have traditionally operated their systems in isolation, there is a lack of understanding of the interactions and information exchanges between these systems. This paper bridges this information gap by developing 2D and 3D visualization prototypes for interdependent power and water distribution systems. These prototypes aim to display and monitor a variety of water and energy variables, and to increase the observability and controllability for power and water distribution system operations. Visualization results show that the proposed prototypes successfully monitor the energy requirements for meeting the energy and water demands and capture operational decisions that can improve energy efficiency and reduce operating costs of interdependent systems.**

I. INTRODUCTION

Urban critical infrastructures such as water, energy, transportation and communication systems coupled with commercial and government response facilities play an essential role in a functioning society. In recent years, a great deal of interest has focused on embedding resilience and sustainability into the design and regulatory frameworks of such infrastructures. Recent advancement in the study of interdependent power and water systems has paid particular attention to identifying their interactions, understanding the implications of such interactions towards energy efficiency, as well as securing the water and energy resources.

Water is utilized in the energy sector for mining, fuel production, hydropower, and power plant cooling, while energy is used in water facilities for treatment and distribution of water. Although the synergies between energy and water systems are well-identified, these systems have been traditionally operated in an uncoordinated fashion, where typical decisions are made in isolation from one another without always considering the energy and water tradeoffs between sectors. However, it is increasingly recognized that a coordinated effort between power system operators and the water facilities they serve could create a great opportunity for increasing the energy efficiency of the water industry and reducing the operating costs of both power and water infrastructure.

To achieve such coordination in design and engineering, visualization tools could aid in decision making by enabling the interactive exploration of interconnections between energy and water systems. Such visualization tools should be able to monitor the energy and water requirements of power and water facilities as well as to identify potential operational cost and energy efficiency savings that could result via coordinating the operation of these interdependent infrastructures.

In this paper, we present our effort in modeling and visualizing interdependent power and water infrastructure. We first highlight the interdependence between power and water distribution systems, and then identify challenges and opportunities related to modeling and visualizing interdependent networks. Our ultimate objective is to extend our insights to the visualization of multi-layer infrastructure networks.

A. Interdependence of Power and Water Distribution Systems

Water distribution systems (WDSs) are energy-intensive infrastructure that consume energy for treating, storing, and distributing water over large geographical areas. Especially in states that suffer from water shortages, such as California, WDSs can account for up to 18% of the state's total electricity needs [1]. Approximately, 80% of this total electricity consumption is used for water pumping [2]. The main WDS processes which require energy for water pumping are displayed in Fig. 1; each process is further elaborated below.

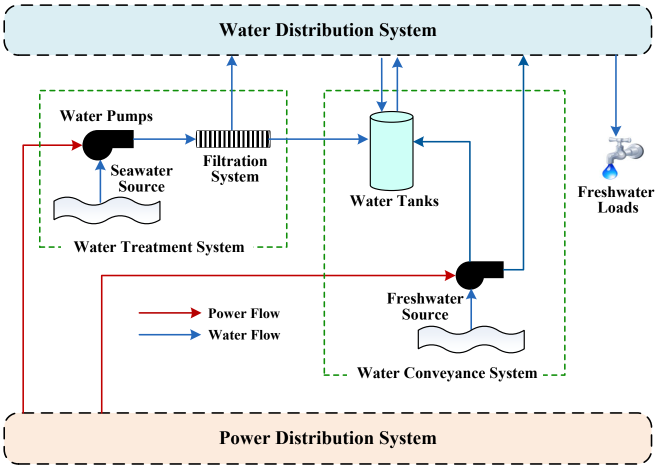

Fig. 1. Independence of power and water distribution systems.

1) Water treatment: Water treatment systems improve the quality of water by removing contaminants, salt, and other microbes before end use consumption. In this process, the water from a pressurized solution is separated from the solutes by flowing through a membrane [3]. In order to ensure freshwater productivity, high pressure pumps are utilized on the feed side of the membrane to pressurize brackish water.

2) Water conveyance: Water conveyance systems assure the transport of water from the main intake structure (e.g., water treatment plants, underground freshwater reservoirs) to the end-users via a network of pipes, water tanks and pumps. More specifically, water pumps consume electricity to raise pressure head needed to overcome friction losses and elevation difference [4]. In addition, water pumps operate to balance water load fluctuations as well as to store water in the tanks.

B. Opportunities

Multi-layer infrastructure network visualization can be used as decision-making tools by power and water distribution system operators (DSOs) to help them better understand, interpret, and communicate the interrelationships and trade-offs emerging from the complex operation of interdependent power and water distribution systems. In energy-water nexus management, various optimal decisions need to be addressed jointly. These decisions are mainly focused on coordinating the energy consumption of WDSs, including water treatment and conveyance systems, with power distribution systems operation for minimizing the operating costs of both systems and improving their energy efficiency.

Multi-layer network visualization can also be used to monitor failures associated with the components of interconnected power and water systems as well as monitor the availability of water and energy resources. As power and water infrastructures operate interdependently, the failure of one system would lead to cascading failures that propagate to the dependent one. In this context, visualization tools could be utilized to monitor drought conditions, extreme natural events, climate projections, and components' function to detect and inform for potential systems risks and failures, as as well as create optimal operational strategies that can minimize the service loss of power and water infrastructures in the case of an event.

In addition, a key opportunity is to link visualization tools to an optimization engine that allows users to impose different operational constraints (e.g., minimum desired water consumption levels) to a multi-layer network directly via the visualization interface to meet specific system optimization objectives. This would require developing advanced optimization algorithms with model predictive control capabilities in combination with visual interactions that can jointly solve the power and water flow operational problem in a computationally tractable and visually informative manner.

To this end, we summarize the desirable characteristics to be supported by a visualization tool for interdependent power and water distribution systems. A visualization tool should:

- Monitor the amount of energy consumed by the water pumps for supplying the water demand of the WDS, and capture how the increase of water demand would increase energy consumption;
- Monitor the volume of water stored in the water tanks, and their water charge and discharge flow rate schedules;
- Monitor the power produced by distributed energy resources (e.g., solar generating units) connected to the power distribution buses;
- Monitor the power flow in power distribution lines and the voltages at power distribution buses, and provide information when the maximum and minimum allowable power flow and voltage limits are exceeded;
- Monitor the water flow rate in water distribution pipes and the pressure head at water distribution nodes, and provide information when the maximum and minimum allowable water flow rate and pressure limits are exceeded;
- Monitor the retail and wholesale energy prices.

By monitoring the above information, power and water DSOs could identify sustainable energy-water resource management strategies in supplying the energy and water demand of their systems. Specifically, an effective visualization tool could enable power and water distribution system operators to optimize their decisions by:

- Shifting the electric consumption of the water pumps to periods of low energy prices and/or to periods of high solar power generation;
- Storing freshwater in the tanks during periods of low energy prices and release the stored freshwater to supply the water demand during periods of high energy prices;
- Recovering higher amounts of freshwater from the water treatment systems during periods of low energy prices and/or during periods of high solar power generation.

By coordinating the scheduling decisions of their systems, power and water DSOs could reduce their daily energy consumption and operating costs, and increase the overall energy efficiency of their systems, leading to significant economic and environmental benefits.

C. Challenges

Traditionally, power and water distribution systems have been designed to operate independently. Power and water DSOs are concerned that a joint operation between their systems may adversely impact the reliable provision of power and water services, which is the primary objective of these critical infrastructures. For instance, although reducing the energy consumption of pumps during periods of high energy prices would lower the operating cost of the power distribution system, it may pose a threat to reliably supply the water demand of the water distribution system due to insufficient pressure head gain produced by the pumps. Therefore, decisions that optimize the operation of one system may not always be supported by the operational constraints of the other. Thus, to fully grasp the potential benefits from co-operating power and water systems in parallel, potential visualization and modeling tools have to consider the operational constraints of both systems, and accurately establish the connections among each engineering layer.

Another demanding task is to guarantee that power and water visualization tools would allow rapid translation of massive data to understandable forms. Visualization tools should be able to store, analyze, and process power and water data, and create optimal operation strategies for power and water DSOs in a short period of time.

II. MODELING POWER-WATER INFRASTRUCTURE

Power and water distribution systems are typically modeled as directed graphs $G=(\mathcal{V},\mathcal{E})$, consisting of a set $\mathcal{V}$ of vertices and a set $\mathcal{E}$ of directed edges connecting the vertices. In water distribution systems, the set of vertices, also referred to as *water distribution nodes*, represents water reservoirs, tanks, and freshwater loads, while the set of edges represents water distribution pipes, pumps, water treatment plants, and valves. Similarly, in power distribution systems, the set of vertices, also referred to as *power distribution buses*, represents distributed energy resources, substations, and electric loads, while the set of edges represents power distribution lines, circuit breakers, and the complex impedance and admittance.

Each water distribution pipe is characterized by a unique volumetric flow rate that measures the volume of water passing through it per unit of time, while each water distribution node is characterized by a unique pressure head which is expressed in units of length. Similarly, each power distribution line is characterized by a unique complex power and current flow, while each power distribution bus is characterized by a unique voltage angle and magnitude values. Water distribution pipes are subjected to pressure head losses caused by surface friction forces acting against water's motion and are usually described by the empirical Hazen-Williams or Darcy-Weisbach formulas [4]. Likewise, power distribution lines are subjected to active and reactive power losses associated with the complex impedance of each line. The connection between interdependent power and water distribution systems is established by assuming that a water pump is electrically connected to one bus of the power distribution system.

III. RELATED WORK

We review the most relevant work in visualizing power and water systems and multi-layer infrastructure systems.

1) Power and water systems visualization: Commercial visualization and modeling tools include Powerworld [6] and CYME [7], and DigSilent [8], which are designed to simulate power transmission (e.g., Powerworld) and distribution (e.g., CYME) operations.

Tools that model and visualize the operations of WDSs provide an integrated environment for running hydraulic and water quality simulations. The modeling provides information such as the flow of water in each pipe, the pressure at each node, the height of water in each tank, and the concentration and propagation of a contaminant. Visualization results are produced in a variety of formats, including color-coded network maps, data tables, time series graphs, and contour plots. One of the most popular public domain, water distribution system modeling and visualization platforms is the EPANET [9]. Freund et al. [10] built upon the 2D circular node visualization [11] to visualize WDSs. Their new system provided superior visualizations and ease of use for domain scientists when compared to EPANET. However, water distribution system visualization tools are specialized to display information only related to hydraulic variables, while variables associated with their interdependent power distribution systems are completely ignored.

2) Multi-layer infrastructure network visualization: The *Water-Energy-Food (WEF) Nexus tool* [12] explicitly quantifies the interconnections between the water, energy and food resources, while capturing the effects of population growth, changing economies and policies, and climate change. Variations of the WEF Nexus tools have been developed (e.g., [13], [14], [15]. A GIS-based visualization [16] precisely maps the correlation between energy requirements, carbon intensity, and water uses across the state of California. A system modeling language (SysML) is utilized in [17] to visualize the various exchanges of water and energy in and between the electricity and water systems. Energy-Water Sankey diagrams are used in [18] to visualize the interconnections between energy and water in the broader context of both systems and capture the magnitude of energy and water flows in the United States on a national scale.

3) Multi-layer network visualization: We give a few examples of tools developed for multi-layer network visualization in general, see [5] for a survey using various taxonomies. Pymnet [19] represents a network as a snapshot, allows the user to customize each layer, and provides analytics through simple function calls; however, it does not support node attributes or time-varying visualization. Multinet.js [20] provides a simple interface to upload an edge list along with a timestamp for each edge encoding the time it first appears; it supports node attributes exploration and time-varying visualization. While excellent at visualizing social networks, Multinet.js does not provide the ability to visualize nodes in geolocations or relative locations needed for infrastructure analysis. MuxViz [21] provides different visual mappings such as concentric rings, node-link diagrams, or geolocation overlays. It can also animates changes in the nodes and edges over time. However, it has limited capabilities in encoding multiple variables associated with each vertex and it largely ignores correlations between time-varying instances.

IV. VISUALIZATION DESIGN

We describe design choices for visualizing a two-layer, interdependent infrastructure network composed of a pair of power and water distribution systems. Our 2D and 3D visualization prototypes are illustrated in Fig. 2 and Fig. 3, respectively. Visualization of the network is rendered with D3.js and its 3D plug-in.

A. Data and Visual Encodings

As illustrated in Fig. 3(d) (and similarly in Fig. 2(d)), the power distribution system (red layer) consists of 33 buses, including 1 substation bus and 32 distribution buses (represented by red elongated rectangles). The electricity demand of the coupled power and water distribution system is provided

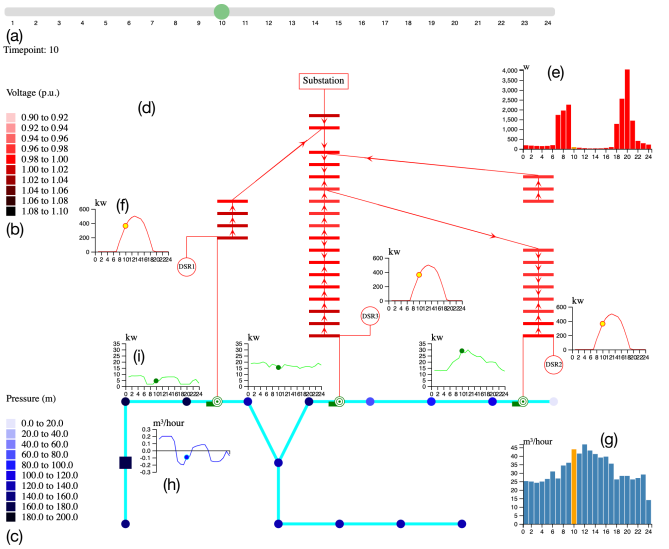

Fig. 2. A 2D visualization prototype of a power-water infrastructure network.

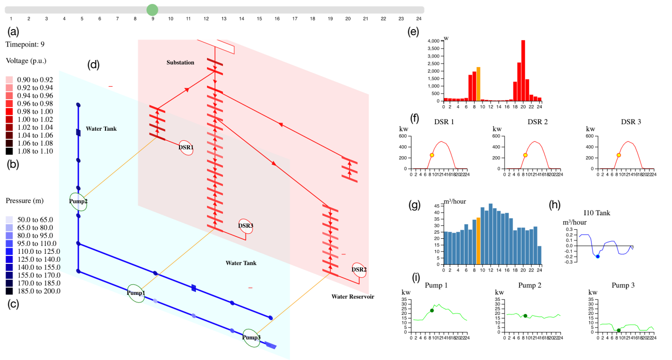

Fig. 3. A 3D visualization prototype of a power-water infrastructure network.

by the upstream transmission network, represented by the substation bus, as well as by 3 distributed solar resources (red ellipsoids) which are connected to the distribution buses via power electronic inverters and are labeled as DSRs. The distribution buses are connected with each other via power distribution lines which are characterized by animated arrows representing the directions of power flow. For each bus, its voltage magnitude is characterized by the intensity of its color.

The water distribution system (blue layer) consists of 15 nodes (blue squares), including 9 regular water nodes (filled circles), 2 water storage tanks (filled squares), 3 water load nodes, and 1 reservoir node (filled trapezoid) representing the only freshwater source to the system. The water nodes are connected by 14 edges, including 11 water pipes (thick lines) and 3 pumps (green ellipsoids). For each water distribution node, its pressure is characterized by the intensity of its color. Power distribution lines (in orange) between the pumps and specific power distribution buses connect the two layers.

Furthermore, in Fig. 3 (and similar in Fig. 2), the visualization outputs of the two-layer network are available for 24 hours, including the hourly energy consumption of the power distribution system (e), the hourly water consumption of the water distribution system (g), the hourly power generated by each DSR (f), the hourly charge (positive) and discharge (negative) water flow rates of the water tank (h), and the hourly energy consumption of each water pump (i).

B. 2D vs. 3D Representation

In the 2D representation (Fig. 2), the power distribution system (in red) and the water distribution system (in blue) are shown side by side on a single layer. Water pump stations, which connect the above two systems, are colored in green. As a small network, the layout of the water distribution nodes and power distribution buses can be manually (or semi-automatically) designed to avoid the overlapping of vertices and edges between the two interconnected systems.

In the 3D representation (Fig. 3), the two systems reside within different layers: red layer for the power and blue layer for the water distribution system. The pump stations are positioned within the water distribution system layer. The connection between the two systems are visualized by orange lines connecting the pump stations of the water distribution system layer to the corresponding buses of the power distribution system layer. The two-layer network can be viewed from different angles by movement of the mouse, which minimizes the confusion that might be caused by crossing of edges in the 2D visualization of a multi-layer network.

C. Time Series Visualization

To visualize the time-varying variables of the network, a time slider is provided for the selection of specific time point across 24 hours (Fig. 2(a) and Fig. 3(a)). When different time points are selected, the direction of the power flow in distribution lines (d), the voltage magnitude at each power distribution bus, and the pressure head at each water distribution node change accordingly. Moreover, summary plots of the variables associated with each layer are visualized over the whole time frame by utilizing bar charts and line charts, with the values of the currently selected time point highlighted.

V. VISUALIZATION RESULTS AND OBSERVATIONS

We present the visualization results of our study, as illustrated in Fig. 3. In (e), two electricity consumption peaks are observed in the power distribution system, one in the morning (6:00 - 9:00) and the other one at night (18:00 - 21:00). In (f), the three DSRs produce electricity during solar availability hours (7:00 - 19:00) and the peak is around the noon. During solar availability hours, the electricity demand of the power distribution system is mainly supplied by the three DSRs and only a small portion of that demand is supplied by the upstream transmission network. The peak of water consumption happens during noon hours (10:00 - 13:00), as shown in (f). In (i), the power consumption schedule of pump 1 follows the profile of the water consumption. However, this is not the case with pumps 2 and 3. Pumps 2 and 3 increase their power consumption during low energy price periods (1:00 - 5:00 and 10:00 - 16:00) to store water in the tanks. On the other hand, they reduce their power consumption when energy prices are high (6:00 - 9:00 and 18:00 - 21:00) as the water demand of the WDS during these hours is supplied via releasing water from the tanks. This is also reflected in (h), water tanks are charged (positive values) during high energy price hours; they are discharged (negative values) during low energy price hours. These results show that the proposed visualization tool not only tracks the energy and water consumption of each system but also monitors how the coordinated operation between the two systems could modify the operation of the flexible components (i.e., water storage tanks, water pumps) to achieve operating cost savings without violating systems' operational constraints.

We also compare our 2D and 3D visualization prototypes. In 2D (Fig. 2), the connections between the two-layer networks are visually more appealing in the sense that the user can directly relate the power lines that connect the distribution buses with electric water pumps. In addition, the 2D representation allows the user to make connections between the visual domain observations and their relevance to the power and water distribution system components. The network output information (e.g., via line graphs and bar charts) can be positioned next to the corresponding component, allowing the user to better understand the context of the visualization results from a system's perspective. One main disadvantage of the 2D representation is its limitation to display more than two layers in a single screen. As the 2D representation is using a single layer approach to visualize interdependent power and water distribution systems, adding an another system (e.g., food, transportation, gas) on top of existing layers would likely lead to visual clutter. On the other hand, an interactive 3D representation (Fig. 3) allows the user to visualize multiple interdependent systems, each of which is represented by a different layer. Although it appears to be visually more complex, the 3D representation allows the user to gain a global view of the multi-layer structure while maintaining the topological relationships between systems. It can encode both pairwise and higher-order interactions across layers. However, as a 3D environment has three degrees of freedom, it could pose challenges for the user to navigate (e.g., finding the optimal viewing angle) across layers. In general, 3D representations provide the user a greater sense of exploration with a multiple-layer network, as well as a better insight on the hidden interactions between the interconnected layers.

VI. CONCLUSION

In this paper, we present visualization prototypes of a small-scale, time-varying, two-layer power-water infrastructure network. Visualization results demonstrate that these prototypes could successfully track the energy requirements for meeting the energy and water demands as well as monitor how these two interdependent systems interact to reduce their daily operating costs via co-optimizing the schedules of the WDSs components. We expect many opportunities in encoding time-varying operational data on multi-layer infrastructure networks, for information tracking, operational optimization and multivariate analysis.

For future work, we would like to include a more extensive usability study of our approach, including adding extra layers and incorporating geographic information. For example, as electric vehicles become more and more popular, more and more charging stations are installed in the transportation network. In this context, the power distribution network can be connected with the traffic/transportation network of a community/city via the charging stations. Visualization of such a multi-layer network will be very useful in the setting of developing smart cities. Another example is the food network which is connected with both power and water distribution networks for irrigated water use and agricultural production.

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