A Reference System Architecture for the Energy-Water Nexus
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Abstract—The energy-water nexus has been studied predominantly through discussions of policy options supported by data surveys and technology considerations. As the degree of coupling between the energy and water systems is affected by the design and operation of various engineered system components, our understanding of the nexus and ability to tackle its associated challenges would be enhanced by a system of systems engineering model. Such a model however requires, first, the development of an appropriate system architecture that clearly identifies the relevant flows of matter and energy and the defining system parameters. This paper presents a reference system architecture for this purpose developed and presented with the Systems Modeling Language (SysML). Once instantiated, this architecture can serve three purposes. First, the presented graphical models can serve qualitative discussions on where and how the supply and demand of water and energy are interdependent. Second, within the operations time scale, the SysML models can support the development of automated IT and control solutions that integrate energy and water management. Finally, at a planning time scale, the models can inform quantitative decisions on how to best grow and reconfigure the water, wastewater and energy infrastructure.

Index Terms—Architecture, Power Systems, Water Resources, Wastewater, Sustainable Development

I. INTRODUCTION

The supply and demand of water and electricity are inextricably linked and consequently should be addressed together. Extraction, treatment and conveyance of municipal water and treatment of wastewater are both dependent on significant amounts of electrical energy. It has been estimated [1] that currently between 1% and 18% of electrical energy used in urban areas worldwide is for treatment and transportation of water and wastewater —the spread being due to differences in topography, conveyance distances and water treatment processes. Simultaneously, large volumes of water are withdrawn and consumed from water sources everyday for electricity generation processes. In the United States, withdrawals for thermal power plant cooling account for 45% of all fresh water withdrawals [2], more than any other sector. Hydroelectric generation, the second most prominent electricity generation technology (16% of global generation, second to 80.3% thermal generation [3]) incurs significant evaporative losses as more water evaporates from dam reservoirs than from free flowing rivers due to the increased surface area and stillness; it has been estimated [4] that in the United States, evaporation of $14 \times 10^6 m^3$ per day can be attributed to hydroelectric reservoirs, which is about three times the daily water consumption of a large US city like New York.

This energy-water nexus, which couples the critical systems upon which human civilization depends, has existed since the first implementations of the electricity, water and wastewater systems. The coupling, however, is becoming increasingly strained due to a number of global mega-trends [5]: (i) growth in total demand for both electricity and water driven by population growth (ii) growth in per capita demand for both electricity and water driven by economic growth (iii) distortion of availability of fresh water due to climate change (iv) multiple drivers for more electricity-intensive water and more water-intensive electricity such as enhanced water treatment standards, water consuming flue gas management processes at thermal power plants and aging infrastructure which incurs greater losses. These trends raise concerns over the robustness of the electricity and water systems today and their sustainability over the coming decades. There is a risk, if the nexus is not optimally managed, that scarcity in either water or energy will create aggravated shortages in both.

There are however several opportunities to improve the resilience and sustainability of these critical systems through integrated management. Losses in the water and electricity systems (leaked water, electrical losses and thermal losses), for example, have embedded electrical energy and water consumption respectively and thus losses in one system are essentially, and possibly more importantly, losses in the other. This creates the opportunity for rethinking financing for elimination of losses in either system which is typically a key constraint. Water supply portfolio management provides another illustration; use of energy-intensive water supply options can be deferred to seasons of low electrical demand. On a diurnal timescale, water storage can be used as a relatively centralised demand smoothing lever, reducing the requirement for electricity storage which is less technologically developed and incurs greater losses. Furthermore, an effort to reduce a deleterious environmental effect such as carbon emissions or excessive water withdrawals can be achieved by means of changes in either system, with one system perhaps providing a cheaper alternative.

It is clear that the energy-water nexus is a multifaceted challenge that calls for a holistic system of systems approach for its effective study and management. To this end it is necessary to develop a descriptive system architecture to clarify the flows of matter and energy between the electricity, water and wastewater systems and between these systems and the environment, and furthermore to identify the parameters of the elements of these three systems that are germane to...
this challenge. This paper presents an instantiable reference system architecture for this purpose. Section II presents a brief review of issues covered in various existing publications on or related to the energy-water nexus. In Section III, internal block, activity and block definition diagrams are presented for an architectural view of the electricity, water, and wastewater engineering systems. Section IV describes the major research thrusts that can be taken to build on the presented architecture. Section V concludes the work.

II. BACKGROUND

Olsson’s 2012 book [1] is perhaps the first book dedicated entirely to the energy-water nexus. It covers the major coupling points between the energy and water systems as well as the interactions of the nexus with population growth, climate change and food supply. Governments and major international organizations have recognized the importance of the energy-water nexus and produced reports [4]–[6] discussing potential future challenges and technology options. In keeping with the typically local nature of energy-water nexus issues, publications have evaluated policy options for specific locations such as Texas [7] and California [8] in the United States, and the water-scarce, energy-rich Middle East and North Africa (MENA) region [9].

Estimates of unit electricity requirements (kWh/m³) for surface water treatment, groundwater treatment and representative wastewater treatment processes have been provided in volume 4 of the Electric Power Research Institute’s (EPRI) Water and Sustainability series [10]. Unit water requirements for different thermal power plants depending on cooling technologies and fuel types can be found in [11] as well as in volume 3 of the aforementioned EPRI series [12]. The unit requirement estimates provided in all these studies are based on data collected from representative surveys of water treatment plants and thermal power plants.

The studies mentioned above highlight the two approaches that have predominantly been taken in the literature to comment on and study the energy water nexus: (i) discussions of challenges, technologies and policy options and (ii) primarily empirical evaluations of the electricity-intensity of water technologies and the water-intensity of electricity technologies. Empirically determined constants, however, are black box models that do not provide an indication of underlying factors. They are also dependent on data that must be collected in extensive and expensive surveys. High-level qualitative discussions provide a good overview of possible solutions but it remains for engineering models to realise them. There is thus a need and an opportunity to augment the study of the energy-water nexus with hybrid physics-based system of systems models which would address both these deficiencies. The use of physics-based models of the engineered components of these three systems will provide greater insight than the black box empirical unit requirements thus enabling integrative system design. Modelling the three systems together as opposed to in isolation as is traditionally done enables the elucidation of effects of one system on another and on the environment that would not be immediately apparent in traditional models of electricity, water and wastewater systems. Efforts have been made towards physics-based models in [13], [14] in which formulations for estimating water use by thermal power plants based on the heat balance of the plant have been derived; and towards an integrated operational view of the water and power networks in [15]–[17] in which simultaneous co-optimization of the economic dispatch for power and water is presented. To unlock the full potential for integrated analysis, planning and control of the electricity, water and wastewater systems, a fully descriptive engineering system of systems model is required; such a model has to be built on an appropriate descriptive system architecture as presented in Section III.

It must be mentioned that the energy-water nexus is part of a larger energy-water-food nexus [18]. Both energy and water are required for food production and increasing use of biofuels has introduced, in some parts of the world, competition between food and biofuel production for land use and irrigation water. This work focuses only on energy (specifically electricity) and water as the objective is to support development of engineering models of the nexus. Any models and quantitative measures thus developed however have applicability in water resource planning for agriculture [19] and can be integrated with scientific food production models for a complete scientific view of the energy-water-food nexus.

III. MODELING

This section presents the models of the energy-water nexus as a reference system architecture. First, the system boundary and internal block diagram are described in Section III-A. Next, attention is given to modeling the system function, concept and form of the electricity, water and wastewater systems in subsections III-B, III-C and III-D respectively. The system function presented and discussed in subsection III-B builds on work hitherto presented in [19], [20].

A. System Boundary and Internal Block Diagram

The energy-water nexus has developed to be a major sustainable development challenge in part because the engineering of an industrial facility gives limited attention to the other industrial facilities upon which it depends. The required input and subsequent output flows are specified during the facility’s design without the awareness that such flows cause suboptimal performance of the multi-facility system as a whole. Furthermore, given that cost/benefit and ROI analyses are often conducted purely within the scope of the facility design as a project, it is not clear that any design changes would occur even with greater awareness of the holistic system performance. For this reason, an appropriate system boundary for consideration of the energy-water nexus must be chosen judiciously.

Fig. 1 chooses the system boundary around the three engineering systems of electricity, water and wastewater. It also depicts the high level flows of matter and energy between them and the natural environment. The valued products of electricity, potable water, and wastewater are all stationary within the region’s infrastructure; in contrast, the traditional fuels of natural gas, oil, and coal are open to trade and consumption by another sector if not consumed by the local thermal power generation. Consequently, the fuel processing
Fig. 1: System Internal Block Diagram for Combined Electricity, Water & Wastewater Systems

function is left outside of the system boundary. Agriculture, mining and decentralised water and wastewater municipal technologies [21], [22] have also been excluded such that the selected system boundary only encompasses functions and objects that fall under the purview of grid operators and that thus lend themselves to both engineering analysis and centralised planning or control. The system internal block diagram shown in Fig. 1 makes it possible to relate a region’s energy consumption to the required water withdrawals in a complex input-output model. A clearly drawn system boundary further raises awareness of the importance of cumulative water and energy losses that tax a region’s natural water resources with no added benefit.

B. System Function

To provide further insight into the processes that realize the overall functionality of these three systems of interest and that thus create the energy-water nexus, the system function of each shall now be discussed individually. From an engineering standpoint, all three systems (and the coupling points between them) involve only the flow of matter and/or energy, therefore the SysML activity diagram has been selected to model this flow-based behaviour [23]. The functions are defined with an action-object convention thus each identified function depicts an activity that transforms an object (matter or energy, in this case) from one state to another [24].

1) Electricity System Function: Fig. 2 is an activity diagram for the electricity supply system. The water inputs for the thermal and hydro power generation functions on the left [11], [12] are to be interpreted as withdrawals rather than consumption. Unlike thermal and hydroelectric power, wind and photovoltaic generation, the dominant non-hydro renewable generation technologies, do not directly consume any water in generation [25]. Wind and solar power generation are often called variable energy sources because they are characterized by intermittency and stochasticity [26], [27]. To support their adoption, utility-scale electricity storage is often discussed as a key enabler. Pumped hydro storage — for which water is required — is the most developed storage technology, accounting for 95% of global grid storage capacity [28]. Other grid storage options such as various battery technologies and compressed air energy storage (CAES) have shown promise but are characterized by lower efficiencies, capacities, and lifetimes [29]. Therefore, although substitution of thermal generation with renewables will certainly have a positive impact on the water footprint of electricity generation, it cannot be said that it will completely uncouple the energy-water nexus as there will be a resultant increase in the water footprint of electricity storage.

2) Water System Function: An activity diagram for the engineered water supply system is shown in Fig. 3. Of the five indicated water supply options, desalinated sea water is the most energetically expensive to produce. The dominant desalination technologies are Reverse Osmosis (RO) which accounts for 60% of global desalination capacity followed by Multi-stage Flash (MSF) Distillation which accounts for 27% [30]. RO is a process in which semipermeable membranes act as filters allowing fresh water to pass while holding back dissolved salts. Electrical energy is utilized in RO plants for pumping to generate the significant hydraulic pressure required to overcome the natural osmotic pressure which would cause
filtered fresh water to flow back across the membranes. The specific electric energy requirement for RO varies with the salinity of the seawater but is typically in the range of 3 to 5 kWh/m³ [30], [31]. MSF, a thermal process, is more energy intense than RO, however large scale MSF distillation is typically integrated with thermal generation in cogeneration plants with the desalination process deriving its requisite thermal energy from steam extracted from along the power plant turbine at the appropriate pressure and temperature [31]–[33]. Determination of the specific energy requirement in this case is complicated by the need to apportion the primary energy consumed between the electricity and water generation processes. In addition, for comparison purposes, it is impossible to compare heat, which is of low energy grade, with electric power. The solution commonly employed [31], [33] is to express the energy associated with the steam input to the desalination plant in terms of an equivalent loss of electric power that would otherwise have been generated by the steam. With this approach the specific energy requirement of MSF desalination has been estimated to be between 10 and 20 kWh/m³ [31]. In contrast to these two desalination techniques the specific energy requirements for groundwater and surfacewater treatment have been estimated [5] to be, on average, 0.16 and 0.06 kWh/m³ respectively.
Treated and desalinated water is then distributed to end users with the aid of pumps within the distribution system. The amount of electrical energy required depends on the conveyance distances, the topography and the volume of water being transported. The additional pumping energy required for water storage either to serve as a security buffer or to minimize operational costs where time-of-use electricity tariff structures exist, is explicitly shown in Fig. 3, as time displacement of this energy presents a demand side management opportunity as discussed in Section I. The activity diagram clarifies the sources of water loss and alteration. An issue of concern in public water distribution systems is pipe leakages; often estimated in double-digit percent losses. In absolute terms, this accounts for approximately 32 billion cubic meters of treated water per year [34]. As shown in Fig. 1, leaked water eventually finds its way to the water table and is thus not truly lost. However, that it is displaced from its original source signifies that it is not necessarily easily recoverable and, in addition, the embedded energy in the water up to the point of leakage is lost. Furthermore, as mentioned in the electricity system discussion, stored water in man-made lakes and open air storage tanks suffer from evaporative losses that may be measured in water or embedded energy terms. The output of brine from desalination facilities also provides a significant source of altered water with potential environmental impacts on the water bodies to which it is returned. Finally it must be mentioned, that in addition to supply and conveyance, energy is utilized in conditioning water for end use applications such as heating, cooling, pressurizing or purifying. In some cases, this energy consumption is greater than in supply and distribution functions. In California, for instance, it has been estimated that 5% of all consumed electrical energy is used for water supply while 14% is used for activities involving or related to domestic water use such as water heating and clothes washing [4]. Energy intensities for various categories of domestic and commercial water uses have been estimated [35] and range from zero to as much as 50 kWh/m³. End-use devices and processes that minimize water consumption can therefore conserve energy both upstream in supply and conveyance, and downstream at the point-of-use.

![Activity Diagram of Wastewater system functions](image)

**Fig. 4: Activity Diagram of Wastewater system functions**

3) **Wastewater System Function:** Wastewater collection, as shown in Fig. 4, typically does not require electric power input. Wastewater is typically conveyed by gravity-flow sewers [1] as wastewater treatment plants are built at low elevations, close to the water bodies into which effluent is to be discharged. The wastewater system, however, does require electric power for treatment: various types of electric motor-driven equipment including pumps, blowers and centrifuges are used in wastewater treatment operations. In addition to the standard processes of filtration and biological decomposition, a wide range of processes with different energy requirements such as chemical precipitation, ion exchange, reverse osmosis and distillation [36] are variously employed in different wastewater treatment plants to eliminate specific residual constituents as required by local environmental discharge regulations and reuse quality requirements. Attempts to quantify the per-unit energy requirements for wastewater treatment have typically classified treatment plants in four representative categories. The per-unit energy requirements for these categories have been estimated by survey [5], [10], [36] as given in Table I. While treated wastewater, has in the past, predominantly been returned directly to surface water bodies as disposable effluent as shown in Fig. 4, wastewater reuse offers sizable potential energy benefits. The most prominent wastewater reuse categories are agricultural irrigation, landscape irrigation, groundwater recharge and industrial processes [36], [37]. Groundwater recharge has an energy benefit, in that it prevents the depletion of aquifers close to the surface and thus the need to extract water from deeper ones. The integration of recycled wastewater into the industrial water supply system has been implemented in Singapore under the NEWater scheme [5], [38] which supplies water, that in addition to conventional biological treatment and filtration processes, has been purified with ultraviolet, microfiltration and reverse osmosis technologies making it suitable for industrial applications requiring water of high purity. It has been shown [9] that, in several MENA countries, recycled wastewater has the potential to meet nearly all industrial water demand. Direct water reuse through blending of recycled wastewater into the potable water supply is far less common but has been successfully employed in water scarce Namibia since 1968 [38]. However, pathogen transmission concerns and public sentiment [36] have thus far prevented widespread adoption of direct water reuse in most places. In regions where water is reused for irrigation or industrial purposes but not blended into the potable water supply, the recycled wastewater must be distributed —with an energy cost—to users through a separate water distribution system as shown in Fig. 4. For completeness, the less common case of direct water reuse is also shown.

**Table I: Wastewater treatment energy requirements**

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<thead>
<tr>
<th>Treatment type</th>
<th>kWh/m³</th>
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<tr>
<td>Trickling filter</td>
<td>0.25</td>
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<td>Activated sludge</td>
<td>0.34</td>
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<td>Advanced</td>
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<td>Advanced with nitrification</td>
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C. **System Concept**

Once the system function has been well understood, the development of an energy-water nexus reference system architecture turns to the allocation of system function to system form in the system concept. The electricity, water and wastewater systems may all be characterized as large flexible systems as defined by Suh’s Axiomatic Design theory [39]. In other words, system functions can be realized by one or more modules which may evolve over a planning time.
scale. This allocation of system function to form can be graphically represented using the SysML language [23] or equivalently captured in a binary axiomatic design knowledge base with the functions along the row and the component modules along the columns [39]. At the meta-level, Table II shows a nearly diagonal knowledge base where each system function corresponds to its intuitive type of facility. Thermal desalination plants and pumped-hydro storage facilities are the exception in that they realize two functions. Additionally, the realization of the water storage function is classified by the need for water storage tanks, man-made lakes, and pumped-hydro facilities. These facilities serve as the basis of the class diagram description of form in the next section.

D. System Form

In order to translate the functions identified in Section III-B into an engineering system model, parameterized models of the form elements identified in Section III-C must be developed. This section describes the parameters of these system elements that any such models should characterize. As with Section III-B each of the three systems will be discussed in turn. To model these object characteristics, the SysML block definition diagram [23] has been selected. With this diagramming tool, each modelled object is characterized by value properties which are quantifiable characteristics of the object and reference properties which are parts that are not owned by the object.

1) Electricity System Form: From an energy-water nexus perspective, the key parameter of interest for thermal generation plants is the unit water requirement (m³/kWh) for withdrawal, consumption or both depending on the objective of the modelling effort. This requirement is dependent on the heat load placed on the cooling system and thus the heat rate of the plant. The heat rate and fuel heating value (kJ/kg) ultimately determined the required fuel flow rate. Thermal cooling systems are of three types: once-through, recirculating and less commonly dry [5]. For an open loop system, an effluent temperature limit (K) to protect the aquatic ecosystem determines the volume of water that must be withdrawn to carry away a given heating load. The water consumption caused by the evaporation of the water that is released back into the environment at an elevated temperature can then be estimated using models of evaporation from reservoirs. There are several such models and a discussion on these is beyond the scope of this work; the reader is referred to [40] for such a discussion. For recirculating cooling systems, the water withdrawal consists of two components [41], [42]: make-up water for evaporation and blowdown. Blowdown is required to keep the concentration of impurities in the cooling tower within acceptable limits to prevent fouling and scaling and thus ensure effective heat transfer. The ratio of the acceptable concentration of impurities in the cooling tower to the concentration of these impurities in the make-up water, referred to as the number of cycles of concentration [41], [42], controls the rate of blowdown discharge and thus contributes to the rate of water withdrawal. In areas where the make-up water is of high purity, the number of cycles of concentration will be higher and thus water withdrawals will be lower.

The evaporation from the cooling tower is dependent on the vaporization enthalpy (kJ/kg) of the water as the heat is carried away by evaporating water at saturation temperature —this is in contrast to open-loop systems in which the heat is carried away by a temperature increment and for which the specific heat capacity (kJ/kg · K) is thus the water property of interest.

Wind and solar photovoltaic power plants, for purposes of an energy-water nexus model, need only be characterized by their electrical characteristics as they do not consume water in operation. Particularly of interest is their ability to provide reactive power and their integration into reactive power support [43], as users’ reactive power demand (VAR) currently necessitates the operation of synchronous generators in thermal and hydroelectric power plants which do have a water footprint. Hydroelectric power plants have a specific flow rate requirement (m³/kWh) given the dam reservoir height (m) and turbine efficiency. In the event that this flow rate cannot be sustained for a desired power output level, due to drought for example, the power output must be lowered.

From a consumptive point of view, the quantification of the potentially significant water evaporation from the reservoir requires an evaporation model [40]. Alternatively evaporation isolines constructed from annual-average pan evaporation data [44], [45] can be used together with the coordinates and surface area of the reservoir to determine evaporative losses. Either approach would yield an evaporation rate (m³/s). If this rate is divided by the power output, it yields a specific evaporative loss (m³/kWh) for the hydroelectric plant; average values of this specific evaporative loss for the United States obtained with the pan evaporation data approach are provided in [44]. Dividing by the power output however, suggests that there is causality between the power generation and the water consumption which is not the case, as the rate of evaporation from a particular reservoir will not be altered if the dam is generating below or at its full capacity. Furthermore the water stored in the reservoir is often used not only for power generation but for water supply and recreation and thus the evaporation cannot be fully ascribed to electricity generation. The water consumption is therefore a characteristic of a particular dam, not of the power generation process and the evaporation rate is preferred as a parameter of a dam from an energy-water nexus perspective.

An electrical power system model must also, from an energy-water nexus perspective, characterize transmission and distribution losses by means of an impedance (Ω) as these losses have embedded water withdrawals and consumption. If a dynamic model incorporating storage is desired, the capacity (kWh), rating (kW) and efficiency of the storage is required; if the storage is pumped-hydro — which is effectively a hydroelectric power plant run in two directions — the evaporation rate, and specific flow rate requirement as obtained for the hydroelectric power plant, are also required.

2) Water System Form: The surface water bodies and aquifers that supply the surface and groundwater treatment plants are characterized most importantly from an energy perspective by their elevation (m) and depth (m) respectively as this determines the energy requirement for pumping the
TABLE II: Electricity, Water and Wastewater Systems Knowledge Base

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(TDP=Thermal Desalination Plants, MDP=Membrane Desalination Plants, SWETP=Surface Water Extraction and Treatment Plants, GWETP = Groundwater Extraction and Treatment Plants)

![Fig. 5: Form of Electricity Supply System](image)

untreated water to the treatment plant. Sea water is, in addition, importantly characterised by its salinity (ppm) as this determines the energy required for desalination: in the case of reverse osmosis, the salinity of the sea water determines the osmotic pressure which has to be overcome by a pump to drive the water across the membrane while in the case of thermal desalination this salinity determines the elevation of the boiling point above that of pure water and thus contributes to the thermal energy required for evaporation [33].

Pumping consumes 98 percent of the power at a surface water treatment plant [10] and an even higher proportion at a groundwater treatment plant; these plants can therefore be viewed from an energy perspective as consisting purely of a series of pumps as shown in Fig. 6, for which the parameter of interest with regards to energy consumption is the efficiency. These pumps must be appropriately sized for the capacity of the plant ($m^3/s$) to raise the water to the plant’s storage tank elevation (m) for distribution.

Reverse Osmosis desalination is a pressure driven process as discussed in Section III-B and thus a reverse osmosis plant can also be viewed as consisting of pumps. Thermal desalination plants, since they operate by heating and evaporating sea water have a specific energy requirement ($kWh/m^3$) —determined as discussed in Section III-B—that is dependent on the salinity, specific heat capacity ($kJ/kg\cdot K$), vaporization enthalpy ($kJ/kg$), and temperature ($K$) of the sea water. In addition, the transmission of heat from a heat source (usually steam from a power plant) to the sea water requires the maintenance of
a temperature gradient referred to as a terminal temperature difference (K) that is dependent on the design of the heat exchanger but is usually designed to be in the range of 2 – 6 Kelvin [33].

Piping infrastructure, from an energy perspective, acts as a resistor, dissipating hydraulic energy provided by pumps. The pressure drop across a pipe is determined typically by one of two formulations: the Darcy-Weisbach equation and the Hazen-Williams equation [46]. Both formulations provide a pipe resistance \( (Ns/m) \) that is dependent on the pipe diameter, length and material. Also of concern from an energy perspective is the proportion of water that leaks out of the pipe that can be modelled by a leakage coefficient, that is to say a pipe leaks a particular fixed proportion of the water it conveys. For greater precision however, leakage can be modelled as being pressure dependent [47] which opens up opportunities to explore reduction of leakage (and thus energy losses) through the management of pressure.

Users (or demand nodes) are of course characterized by their level of demand \( (m^3/s) \) (which may also be modelled as being pressure dependent [47]) and their elevation \( (m) \) both of which determine the energy required to service these users. There are two types of water storage both of which are characterized by a capacity \( (m^3) \): tanks, which are covered and that therefore do not have evaporative losses (with their embedded energy) and artificial reservoirs that do have an evaporation rate \( (m^3/s) \) that can be determined in the same manner as for hydroelectric reservoirs.

3) Wastewater System Form: The wastewater management system’s form is represented in Fig. 7. The collection portion of the system consists of a largely passive sewer network, as mentioned above, that does not require parameterization from an energy perspective. The wastewater treatment plants, however, have a unit energy requirement \( (kWh/m^3) \) as provided for representative processes in Table I. As discussed, in most cases, there is an independent recycled wastewater network to serve specific users. This network is similar to the conventional water distribution system consisting of pumps, pipes, and storage characterized in the same way.

E. Parametrics

The equations that relate the value properties of the blocks identified in Section III-D can be defined using the SysML Constraint Block type and thus depicted using a SysML Parametric Diagram [23]. This would yield a reference architecture that includes the physics-based models alluded to in Section II and elaborated upon in Section IV. However as a very large number of such constraint blocks would be required to model the entirety of relationships for the energy-water nexus, this functionality has not been presented in this paper. These parametrics however can readily be implemented in several model based systems engineering tools.

IV. DISCUSSION

While the presented descriptive architecture certainly aids a qualitative discussion of the various aspects of the energy-water nexus as in the previous section, its chief benefit is in the facilitation of the development of a hybrid engineering system model of the energy-water nexus to support planning and control applications.

A. Engineering Systems Model Development

At the most basic level, the mass and energy flows depicted in the activity diagrams could be used together with empirically-determined values of the water intensities of electricity generation technologies and electricity intensities of water and wastewater system elements such as those provided in the studies mentioned in Section II to develop an input-output model for the electricity, water and wastewater systems in unison. Such a model, readily implemented in a spreadsheet, could provide a guide as to whether environmental resources are adequate to meet societal needs with respect to these three systems. From an engineering perspective however, it is desirable to replace the empirically determined intensities with physics-based models. These models would provide insight
into the underlying factors determining the various intensities thus opening the door to exploration of how these intensities could be tuned for maximum system-wide benefit. Finally, since the engineered wastewater, electricity and water systems have, at their cores, three connected grids, the topologies of which contribute to their degrees of coupling, a hybrid system-of-systems model could be developed. This model, and an associated numerical solution technique could, where the three grids are sufficiently coupled, be beneficially used in place of simple mass and energy balances to provide greater control and planning fidelity. Such a system-of-systems model, built on this work, utilizing bond graph representations of the various coupling and boundary points, has been presented [48].

B. Integrated Planning and Control

A hybrid model of the three discussed systems, once developed, would yield a set of descriptive equations that could be used to support an integrated approach to planning in various ways: (i) as part of an optimization procedure to determine the best system design and upgrade choices across the three systems to achieve a desired output subject to a set of environmental constraints (ii) to establish which system choices have the greatest effect on a desired output or input by means of differential calculus, and (iii) integration with models of population and climate dynamics to study the potential evolution of the environmental effects of and coupling between the three systems. The developed model would also find application in an integrated approach to operations control of the three systems. A system-of-systems model, as described, would facilitate utilization of the water and wastewater systems —which are significant and relatively centralized electrical loads —as demand response levers, particularly with the greater demand flexibility requirement necessitated by large scale integration of renewable energy sources. Another potential application would be optimal dispatch of water and power from cogeneration plants subject to demands, topologies of other source nodes, in both the water and power networks.

V. CONCLUSIONS AND FUTURE WORK

This work has developed an architecture for the energy-water nexus in the engineered electricity, water and wastewater systems that describes how these systems interact with each other and with the environment. The presented graphical models can aid qualitative discussions on the nature of the coupling between these systems as well as opportunities for improved holistic management as demonstrated through the discussion presented here. Furthermore, the SysML models support the development of engineering models of the nexus that characterize the parameters described in Section III-D for integrated control and planning of the electricity, water and wastewater systems as discussed in Section IV. Ongoing work [48] is on the development of such engineering models [48]. In addition, as discussed, any quantitative measures obtained from the engineering systems model have applicability in water resource planning for agriculture [19] while the reference architecture can itself be enhanced to include food production systems for a full system architecture of the energy-water-food nexus.

REFERENCES
