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A Meta-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. At a technological level, there have been attempts to optimize coupling points between the electricity and water systems to reduce the water-intensity of technologies in the former and the energy-intensity of technologies in the latter. To our knowledge, there has been little discussion of the energy-water nexus from an engineering systems perspective. As the energy-water nexus presents a large scale, multidisciplinary problem with various technological and non-technological dimensions, efforts for coordinated control, operation & planning of the energy and water systems would benefit from the modeling platforms developed in systems engineering. This paper presents a meta-architecture of the energy-water nexus in the electricity supply, engineered water supply and wastewater management systems developed using the Systems Modeling Language (SysML). This meta-architecture serves to elucidate the nexus for qualitative discussions. Once instantiated such an architecture can serve as a conceptual framework upon which quantitative planning and control approaches can be based.**

I. INTRODUCTION

Water and electricity are inextricably linked and as a consequence both have to be addressed together[1]. Extraction, treatment and conveyance of municipal water and treatment of wastewater are both dependent on significant amounts of electrical energy. Simultaneously, large volumes of water are withdrawn and consumed from water sources everyday for electricity generation processes. 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[2]:

1) growth in total demand for both electricity and water driven by population growth
2) growth in per capita demand for both electricity and water driven by economic growth
3) distortion of availability of fresh water due to climate change
4) multiple drivers for more electricity-intensive water and more water-intensive electricity

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 that if the nexus is not optimally managed, then scarcity in either water or energy will create aggravated shortages in both.

An appreciation of the scale of the challenge presented by the energy-water nexus can be acquired by a consideration of the degree of coupling between the two systems. In the United States, withdrawals for thermal power plant cooling account for 45% of all fresh water withdrawals [3], more than any other sector. Hydroelectric generation, the second most prominent electricity generation technology (16% of global generation, second to 80.3% thermal generation[4]) incurs significant evaporative losses as more water evaporates from dam reservoirs than from free flowing rivers due to the increased surface area and stationary position. It has been estimated [5] that in the United States, evaporation of 3.8 billion gallons per day can be attributed to hydroelectric reservoirs.

It is important at this point to distinguish between water *withdrawal* and water *consumption*. Water withdrawn is defined as the total volume of water removed from a water source while water consumed is defined as the volume of water removed for use and not returned to its source[6]. The bulk of water withdrawn for thermal power plant cooling is returned to the original water source; water consumption by the thermal power plants in the United States accounts for a relatively lower 3% of total water consumption [3]. This is not to say though that the dependence of thermal power plants on cooling water is not of importance. The reliance of thermal generation on copious water withdrawals makes them vulnerable to water shortages as was the case in

France (2003) and Texas (2011) when power plants were forced to draw down output during prolonged droughts, creating electricity shortages at times that demand was spiking due to air conditioning. Such water shortages are likely to become more frequent in certain areas with the effects of climate change. Furthermore, in these same areas, over the long term, even the relatively low water consumption levels become a sustainability concern with falling precipitation levels.

In evaluating the water footprint of thermal generation, it is also necessary to consider the water required for fuel production. Water is consumed in coal and uranium mining for dust suppression, water jet cutting and cooling of equipment. Average consumption has been estimated to be between 1 and 6 gal/MMBTU for both fuel types[7]. Water is also required for fuel processing. Water consumption has been estimated at 2 gal/MMBtu for natural gas processing and 7 to 8 gal/MMBtu for uranium processing [5].Finally, mention must be made of thermal pollution by *once-through* power plant cooling systems which can kill fish and harm aquatic ecosystems[2].

On the other end of the nexus, it has been estimated [1] that currently between 1% and 18% of electrical energy use in urban areas worldwide is for treatment and transportation of water and wastewater. This fairly large spread is due to differences in local topography and conveyance distances as well as differences in the amount of energy required for the extraction, desalination, and treatment of surface, ground and sea water.

It is important to note that the challenges presented by the energy-water nexus are location specific. The mix of available water sources, electricity generation options, local effects of climate change, and societal requirements together determine the sustainability and robustness concerns associated with the nexus. This paper presents an instantiable meta-architecture for the purpose of analyzing aspects of the energy-water nexus within a specific region. Section II presents a brief review of issues covered in various publications on or related to the energy-water nexus. In Section III, system context and activity diagrams are presented for an integrated view of the electricity, water, and wastewater engineering systems. Section IV offers some insights that can be acquired with the aid of the presented diagrams. Section V concludes the work and presents potential directions for future work.

II. Background

A number of discussions on the energy-water nexus have been published in recent years. Olsson's 2012 book [1] is perhaps the first book dedicated entirely to this topic. 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[2][5][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[8] and California[9] in the United States, and the water-scarce, energy-rich Middle East and North Africa (MENA) region [10].

Estimates of unit electricity requirements (*kWh/gal*) 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 [11]. Unit water requirements (*gal/kWh*) for different thermal power plants depending on cooling technologies and fuel types can be found in [12] as well as in volume 3 of the aforementioned EPRI series [13]. 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. An alternative approach has been taken in [14] and [15] in which formulations for estimating water use by thermal power plants based on the heat balance of the plant have been derived.

The studies mentioned above highlight the two approaches that have predominantly been taken in the literature to discuss the energy water nexus: 1) discussions of policy options and 2) evaluation of the electricity-intensity of water technologies and the water-intensity of electricity technologies. This work describes the nexus in the engineered water, wastewater and electricity systems with the aid of systems engineering modeling diagrams. The diagrams provide the clear and holistic views required for the development of accurate models for control, operations and planning applications.

III. Modeling

This section presents the models of the energy-water nexus as meta-system architecture. First, the system boundary and context are described in Section III-A. Next, much attention is given to modeling the system function of the electricity, water and wastewater systems as activity diagrams in III-B. Finally, III-C describes the system form and concept.

A. System Boundary and Context

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.

Figure 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. Interestingly, 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 function is left outside of the system boundary. Another advantage of this choice of system boundary is that the three engineering systems all fall under the purview of grid operators. Furthermore, in some nations all three grid operations are united within a single semi-private organization. In the United Arab Emirates for example, motivated by the cogeneration of electric power and desalinated water, combined electricity and water authorities have been established by the different emirates.

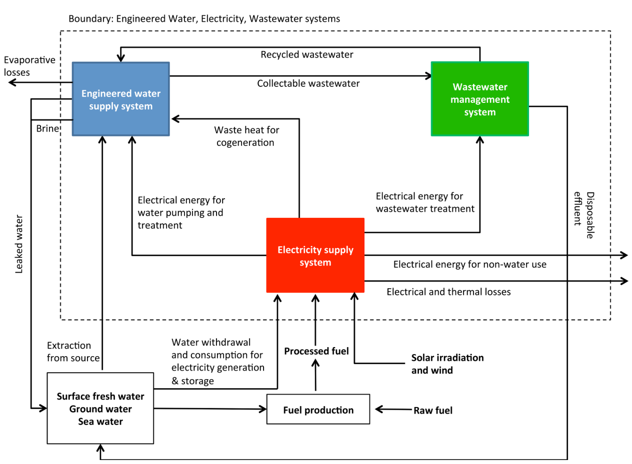

Fig. 1. System Context Diagram for Combined Electricity, Water & Wastewater Systems

The system context diagram shown in Figure 1 also 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 also raises awareness of the importance of cumulative water and energy losses that tax a region's natural water resources with no added benefit! Even more interestingly, the analysis can proceed inside the system boundary to address the loops of precious energy and water between the three systems that consequently do not cross the system boundary as useful products.

B. System Function

Figure 2 is an activity diagram for the electricity supply system, with functions defined using the *action-object* convention. As both withdrawal and consumption are of concern, the flows from the boundary inputs in the water domain to the electrical system functions can represent either, depending on the problem being addressed. Unlike thermal and hydroelectric power, wind and photovoltaic generation, the dominant non-hydro renewable generation technologies, do not directly consume any water in generation[7]. Wind and solar power generation are often called variable energy sources because they are characterized by their intermittency and unpredictability[16]. To support their adoption, utility-scale electricity storage is often discussed as key enabler. Of the various electricity storage technologies, pumped hydro storage is the most developed, accounting for 95% of global grid storage capacity [17].

The evaporative losses associated with pumped hydro reservoirs can be significant depending on local temperatures and humidity. Other grid storage options such as various battery technologies and compressed air energy storage (CAES) have shown promise but are characterized by relative immaturity, lower efficiencies, capacities, and lifetimes[18]. Therefore, the often held assertion that renewable energy sources will uncouple the energy-water nexus may be exaggerated as their integration may cause an increase in the water footprint of electricity storage.

An activity diagram for the engineered water supply system is shown in Figure 3. All water system functions apart from storage (and some forms of usage) are dependent on electrical energy input. Pumping, either for extraction or distribution, is responsible for the bulk of the energy consumed by the water system. An issue of concern in public water distribution systems is pipe leakages, which has been estimated at to be greater than 32 billion cubic meters of treated water per year[19]. As shown in Figure 1, leaked water eventually finds its way to the water table and is thus not actually lost. However, what is wasted is the embedded energy in the water up to the point of leakage.

Of the three 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 distillation (MSF) which accounts for 27%[20]. 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

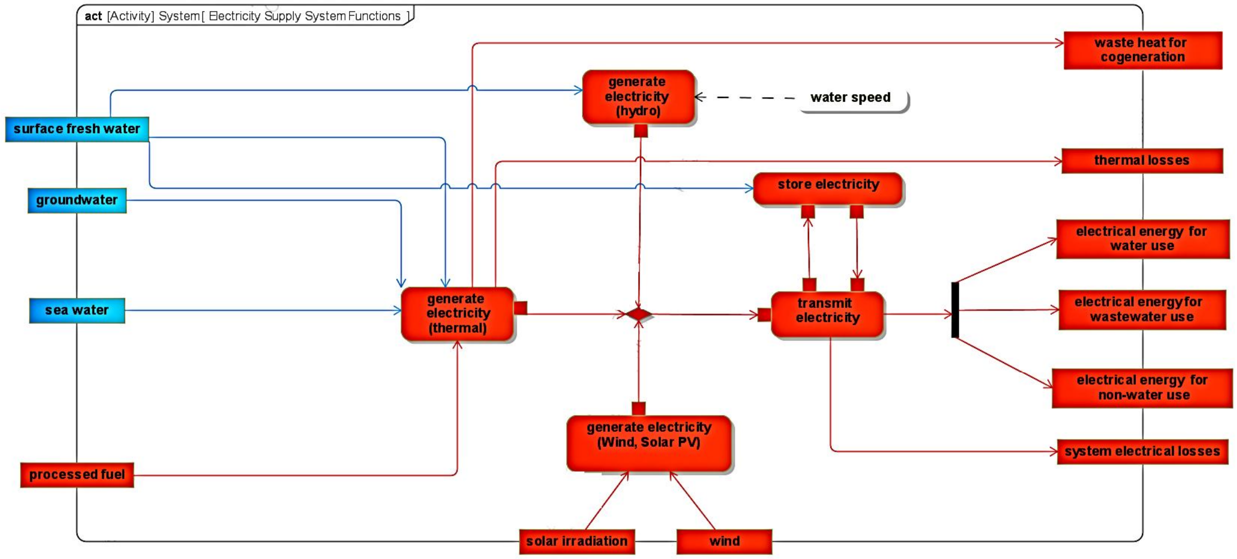

Fig. 2. Activity Diagram of Electricity System Functions

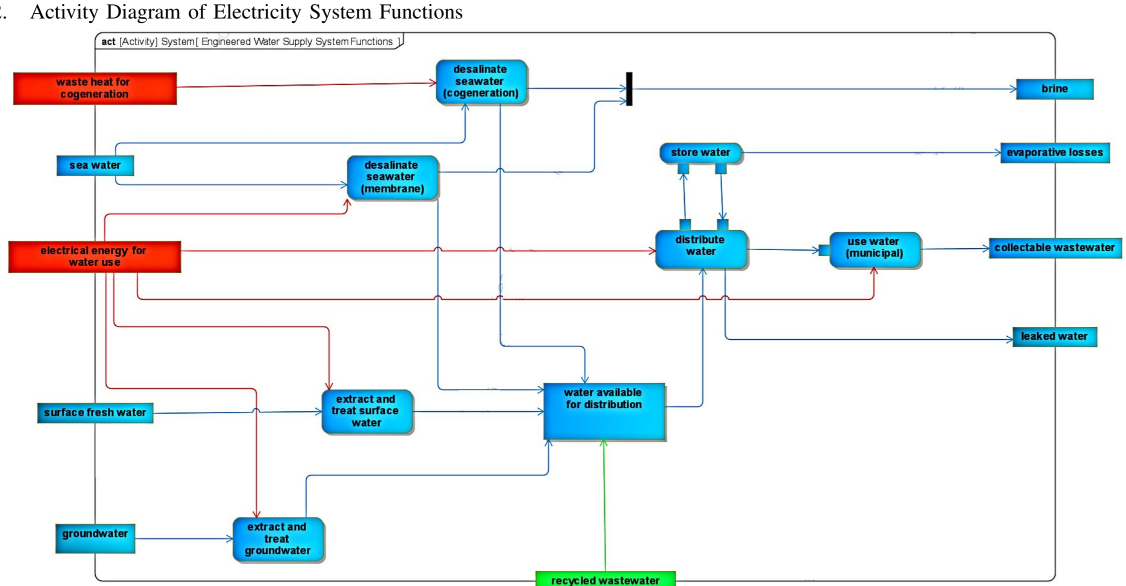

Fig. 3. Activity Diagram of Water System Functions

pressure required to overcome the natural osmotic pressure which would cause filtered fresh water to flow back across the membranes. MSF, a thermal process, is more energy intense than RO, however large scale MSF distillation is typically integrated with thermal generation in cogeneration plants utilizing waste heat from the electricity generation process[21].

In addition to supply and conveyance, energy is utilized in conditioning water for end use application such as heating, cooling, pressurizing or purifying. In some cases, more energy is consumed in end-use conditioning than in supply. In California, for instance, it has been estimated that 5% of all consumed electrical energy is used for supply while 14% is used for activities involving or related to domestic water use such as water heating and clothes washing[5].

Energy intensities for various categories of domestic and commercial water uses have been estimated[22]. The intensities range from zero to as much as 200 MWh/million-gallons-used. 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.

Wastewater collection, as shown in Figure 4, typically does not require electric power input. Wastewater is typically conveyed by gravity-flow sewers 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 [23] 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 [11] as given below:

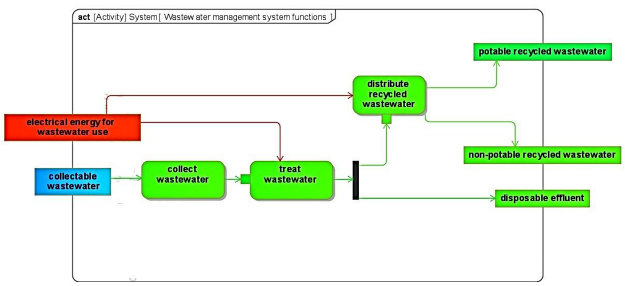

Fig. 4. Activity Diagram of Wastewater system functions

TABLE I. WASTEWATER TREATMENT ENERGY REQUIREMENTS

Treatment type	kWh/m^3
Trickling filter	0.25
Activated sludge	0.34
Advanced	0.4
Advanced with nitrification	0.5

Large scale wastewater recycling offers sizable potential energy benefits. Integration of recycled wastewater into the potable water supply system has been implemented in Singapore and Namibia[24]. However, pathogen transmission concerns and public sentiment[23] have thus far prevented its widespread adoption. The most prominent wastewater reuse categories are agricultural irrigation, landscape irrigation, groundwater recharge and industrial processes. It has been shown in [10] that, in several MENA countries, recycled wastewater has the potential to meet nearly all industrial water demand. Given these two disparate uses of recycled wastewater, Figure 4 reflects the potential for a full network of recycled non-potable wastewater different from the wastewater that would re-enter the potable water supply system.

C. System Form and Concept

There is generally a one-to-one mapping of functions described in the activity diagrams above to elements of form in the electricity, water and wastewater systems. An extensive discussion of the form and concept of these systems is therefore not required. A key feature of these components, however, is that they constitute significant infrastructural investments. This introduces a legacy constraint in efforts to reduce the water-intensity of electricity system elements and electricity-intensity of water system elements through technological improvements. An important lever, therefore, in managing the challenges associated with the energy-water nexus is enhanced adoption and capability of decentralized water and electricity system supply options such as onsite *greywater* recycling and rainwater harvesting for water supply[24], and distributed electricity generation.

IV. DISCUSSION

The context and activity diagrams presented in the previous section provide succint yet clear and holistic depictions of the energy-water nexus in the engineered water, wastewater and electricity systems. These depictions aid qualitative analysis as they facilitate communication but also as they enable easy identification of even interconnections that are not always apparent. For example, it is seen that the losses in the water and electricity systems (leaked water, electrical losses and thermal losses) have embedded electrical energy and water consumption respectively. Losses in one system are thus essentially also losses in the other. This creates the opportunity for rethinking financing for elimination of losses in either system which is typically a key constraint. The cost of fixing leaky water pipes, which as highlighted above cause significant losses, should be justified not only in terms of reduced electrical bills for water utilities but also in terms of reduced requirements for installed generation capacity and operating reserves, as well has reduced greenhouse gas emissions. Storage considerations provide another illustration of the type of analysis made possible by these clear depictions. Figure 3 shows that the only function in the water system that does not require electrical energy input is water storage. In contrast, electricity storage does require water and incurs evaporative losses. Evaporative losses from water storage are less than evaporative losses from pumped hydro reservoirs because water storage is more distributed and often covered. Furthermore, pumped hydro storage presents siting difficulties and has large capital costs. A logical conclusion is that water storage can be used as a proxy for electricity storage in demand smoothing, particularly with the storage imperative created by the integration of renewable energy sources into the electricity supply system.

In addition to aiding qualitative analyses, the models provide a conceptual framework upon which engineering models of these systems and the nexus can be built. Efforts at quantifying the interdependencies associated with the nexus have, as discussed above, been based almost exclusively on empirical surveys. There is an opportunity to transition from this empirical approach to a priori predictive approaches based upon engineering models. These would have a myriad applications in holistic engineering design and analysis of these three coupled systems.

Finally, optimally managing the nexus requires models that support accurate cost-benefit analyses of various options. Engineering models based on a holistic systems analysis, as presented by these depictions, provide the detail necessary for appropriate attribution of shared value across typical but artificial system boundaries for the evaluation of design and policy options.

V. Conclusions and Future Work

This work has demonstrated the utility of SysML for elucidating the energy-water nexus in the engineered electricity, water and wastewater systems. Future work will construct models of the coupling points between the systems and use this meta-architecture to develop operations, control and planning applications.

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