

# Powering & Watering Agriculture: Application of Energy-Water Nexus Planning

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## Text

**Abstract**—This paper seeks to motivate an innovative approach to support new and sustainable solutions for increasing agricultural productivity in developing nations. Specifically, it holistically tackles the energy-water nexus as an engineering system and proposed the development of an integrated planning framework which stakeholders in developing countries can use to make decisions that support agricultural capacity. Thus far, the literature has focused on (i) discussions of various policy options (ii) technical surveys of energy and water intensities. In contrast, 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). Its quantization is then applied on a conceptual example inspired by the Egyptian geography. The paper concludes with useful measures that can be directly incorporated into agricultural capacity planning. In so doing, the paper begins efforts for coordinated control, operation and planning to overcome this large-scale, multidisciplinary problem made up of technical, economic, and social dimensions.

## I. INTRODUCTION

Clean energy and water are two essential resources that any society must securely deliver in order to develop sustainably; i.e. meet its economic, social and environmental goals. To meet these needs, nations all over the globe have responded with their own unique implementations of three engineering systems: the electrical supply system, the engineered water supply system and the wastewater management system. These three engineering systems inextricably intertwine the two resources of water and energy in what is often called the energy-water nexus [1]. A large quantity of energy is required to extract, treat and distribute clean water while a large quantity of water is required to generate energy. In addition, several domestic, commercial, and industrial activities simultaneously use water and energy. In the United States, water-related energy use accounts for 13

percent of the nations electricity consumption [2] while power generation accounts for 49 percent of the nations total water use [3]. Hydroelectric generation incurs significant evaporative losses as more water evaporates from dam reservoirs than from free flowing rivers due to their increased surface area and stationary position. In the United States, approximately 3.8 billions gallons per day are estimated to evaporate from hydroelectric reservoirs [4]. These couplings between engineering systems can lead to cross-sectorial vulnerabilities where an energy shortage can become a water shortage and water shortage can become an energy one. Furthermore, water shortages directly impact agricultural productivity.

It is important 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 [5]. 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 [6]. 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) [7] and Texas (2011) [8] 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.

While these issues are highly relevant to the mature

infrastructure of developed nations, retrofitted technical solutions generally make incremental improvements to the already established environmental impact. Developing nations, however, find themselves relatively early in the development of their electricity, water and wastewater systems and thus have the opportunity to dramatically affect the trajectory of their water and energy consumption. Here, the well-known systems engineering heuristic applies: 80% of the technical solution is defined within the first 20% of the design and planning activity. Therefore, the energy-water nexus issue pertains particularly to developing nations as they seek to economically develop.

The energy-water nexus also raises sustainability issues and questions of a nations resilience in the face of global changes and mega-trends [7]. Developing nations, in particular, project strong water and electricity demand growth driven by population growth. Economic growth and the associated improvements in individual lifestyles also imply a subsequent intensification in the per capita demand of water and energy. Furthermore, the hot and arid climates found in many developing nations amplify the coupling of water and energy use. As a result, typical water deficits may intensify into aggravated water scarcity. Global climate change projections foresee further distortions in the availability and consumption of fresh water. Those developing nations that take early planning measures in their infrastructure development will be in a better position to sustainably mitigate energy-water nexus impacts in the coming decades.

As developing nations commit to increasingly mature electricity, water and wastewater infrastructure, they must do so sustainably without undermining the foundations upon which their economies are built. A domestic agriculture sector forms the core of many developing nations economies, and given the frequent presence of relative economic comparative advantage, is a key pillar in their food security policies. Nevertheless, the water consumption used by the electricity, water and wastewater systems threatens to undermine the very water used to sustain a nations agriculture capacity. Furthermore, given that electricity, water, and wastewater facilities have large surface footprints and often require proximity to natural water, they tend to be placed on arable land. Such sighting practices further diminish the foundations of the agriculture sector.

Although, the Energy-Water Nexus has recently caught the attention of numerous agencies, rarely, is it holistically researched in terms of an integrated framework for its management, planning and regulation as an interdisciplinary concern. The two approaches that have predominantly been taken in the literature to discuss this topic are: (i) discussions of various policy options [1], [4], [5], [7], [9]–[11]; and (ii) evaluation

of the electricity-intensity of water technologies and the water-intensity of electricity technologies [12]–[14]. The first approach is often based upon incentivization mechanisms and the latter approach acts *a posteriori* based upon on-the-ground measurements well after the infrastructure has been built. Instead, this paper for the first time proposes that the energy-water nexus be addressed *a priori* in an integrated planning framework based upon engineering models. Such a framework can be used by developing nations to sustainably plan their energy-water nexus as an integrated infrastructure system without degrading their intrinsic agricultural capacity. Furthermore, such a framework would have a myriad of applications in the holistic design and analysis of these three coupled systems.

The remainder of the of paper proceeds as follows. Section II presents some of the intrinsic challenges to Energy-Water Nexus modeling. Next, Section III provides instantiable meta-architecture for the purpose of analyzing aspects of the energy-water nexus within a specific region. It includes system context and activity diagrams for an integrated view of the electricity, water, and wastewater engineering systems. Section IV then describes some initial quantitative results based upon an illustrative example inspired by the Egyptian geography. Section V brings the paper to a close with conclusions on how such a model may be best applied to planning agricultural capacity.

## II. CHALLENGES TO INTEGRATED ENERGY-WATER NEXUS MODELING

Given the background in the previous section, the challenge becomes: “How can agricultural capacity be sustainably developed given that energy-water nexus infrastructure competes for water and land resources?” Here, it is important to recognize that the electricity, water and wastewater infrastructure systems fall under the classification of engineering systems which DeWeck et al define as: a class of systems characterized by a high degree of technical complexity, social intricacy, and elaborate processes aimed at fulfilling important functions in society [15]. In other words, addressing the technical complexity alone is often insufficient to bring about effective and measurable holistic change. Rather, methods from the necessary engineering disciplines must be seamlessly intertwined with the economic and social context in which these infrastructure systems operate. For this reason, the challenges can be viewed as both technical as well as economic.

From a technical perspective, the main challenge behind the energy-water nexus is that engineers are typically trained within disciplines (e.g. mechanical, electrical, chemical, civil) rather than broad-scoped problem areas such as the energy-water nexus. This often leads to silo thinking that generates piece-meal

technical solutions that are restricted by the boundaries, competences, and methods of the respective engineering field. Nevertheless, if many of the traditional methods from multiple disciplines can be combined into a single analytical framework that addresses the full scope of the technical problem, then new, effective solutions can be developed that target the main technical barriers at the heart of the problem. Such a holistic interdisciplinary approach would highlight which technical efforts would bring about the greatest water and land availability for agricultural capacity. Such an approach would also require an integrated technical modeling framework that draws upon engineering knowledge from electrical, mechanical and civil/water engineering. Furthermore, as seen from various policy studies [9]–[11], 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.

That enough technical disciplines can be combined into a single technical analytical framework is no guarantee that the technical solutions that it recommends will be implemented. Recalling the social intricacy of engineering systems, effective and measurable holistic change requires facilitating the decision-making processes that adopt the recommended technical solutions. Here, it is critical to demonstrate the partiality of typical decision-making methods for technical solutions. For example, rarely do cost-benefit analyses and ROI calculations consider that a renewable energy project has demonstrable impacts on water and land availability that directly translates into measurable financial benefits in the agriculture sector. Even if the true benefits and impacts of technical solutions were to be demonstrated in a single decision-making process, it does not necessarily mean that there exists a decision-making entity with sufficient jurisdiction for its implementation. In many nations, large-scale decisions that affect agriculture are under the jurisdiction of the American equivalent of the Department of Agriculture. They must take the environment as it is given to them irrespective of the utilities and government departments that address the water and energy value chains. Therefore, any technical solution must recognize the context of decision-making is one in which multiple stakeholders must be brought to the table for coordinated decision-making on shared benefits and costs.

### III. MODELING

This section takes a systems engineering approach to present models of the energy-water nexus as a meta-system architecture from the perspective of agriculture planning. First, the system boundary and context are described in Section III-A to provide a holistic view.

Next, much attention is given to modeling the system function of these three engineering systems in III-B so as to initiate the development of accurate models for operations and planning applications.

#### 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.

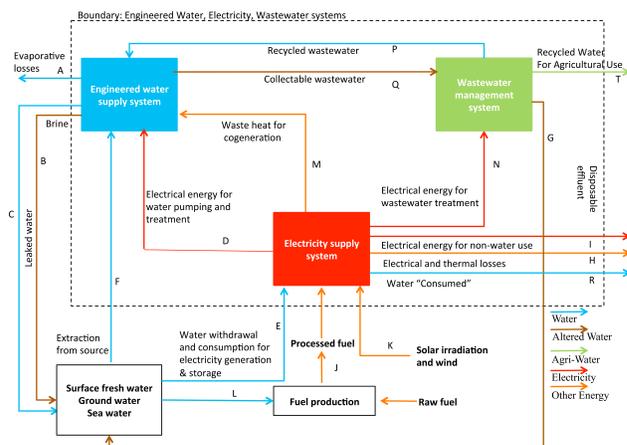


Fig. 1: System Context Diagram for Combined Electricity, Water & Wastewater Systems

Figure 1 chooses the system boundary around the three engineering systems of electricity, water and wastewater [16]. 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.

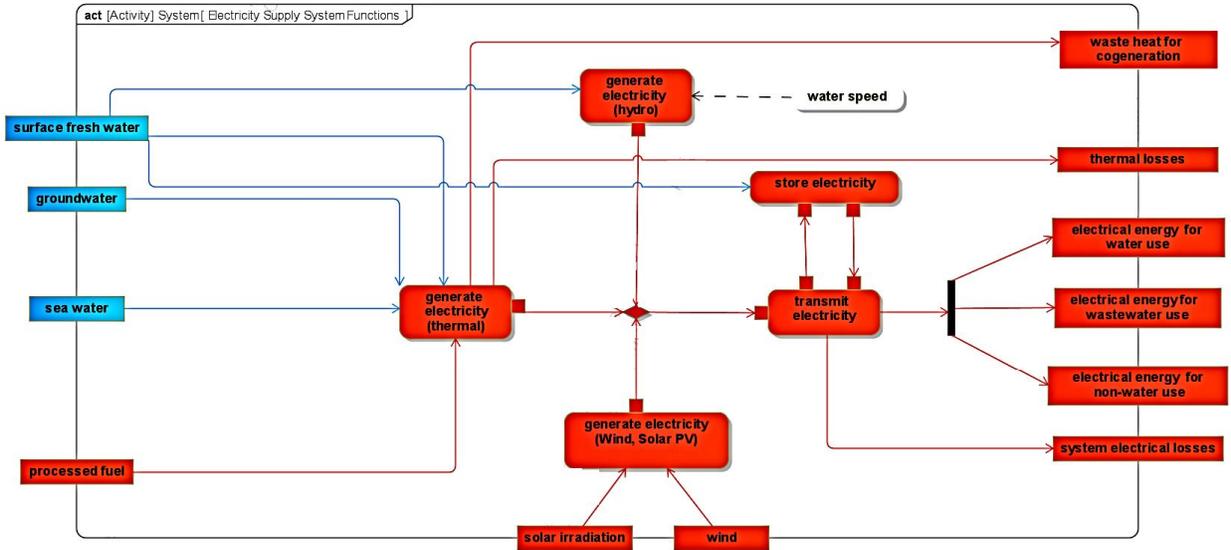


Fig. 2: Activity Diagram of Electricity System Functions [16]

Figure 1 shows a judiciously chosen system boundary that joins the scopes of grid operators. Such a context diagram makes it possible to relate a region's energy consumption to the required water withdrawals in a complex input-output model; thus raising awareness of the cumulative water and energy losses that tax a region's natural water resources and agricultural capacity. For example, the ratio  $(D + N)/(D + H + I + N)$  measures the degree of electrical coupling between the three systems. Such a measure represents a critical load on the electric grid but which ultimately can be reduced as water leakages are eliminated from the water system. If  $S$  is taken as a sustainable steady-state water withdrawal that the region's environment can support, then  $(E + F)/S$  is the percentage of which the region's infrastructure requires for operation. Naturally, a substantial portion of the remainder would be used for agriculture.  $(A + C + R)/(E + F)$  represents the ratio of water displaced from its original source to the infrastructure water withdrawal. Similarly,  $(B + G)/(E + F)$  is the proportion of water withdrawn that is returned with significantly altered quality; a measure of environmental impact. Finally,  $(P + T)/Q$  is a relative measure of productively used wastewater. A strong proportion of which can be used for agriculture.

### B. System Function

Figure 2 is an activity diagram for the electricity supply system, with functions defined using the *action-object* convention. Much discussion on reducing the water intensity of thermal power generation has focused on a transition to wind and photovoltaic generation which do not directly consume water [17]. While such a strategy may provide significant gains, it is important

to consider that renewable energy has a variable nature [18] and may require utility-scale electricity storage as a key enabler. Of the available technologies, pumped hydro storage accounts for 95% of global grid storage capacity [19] but may incur significant evaporative water losses depending on local temperatures and humidity. 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. Here, the common thread is the electrical energy input required for pumping. This is an issue of public concern given that water distribution systems often face double digit percent losses in pipe leakages; in absolute terms more than 32 billion cubic meters of treated water per year [20]. For countries with significant water deficits, desalinated sea water has been the only solution despite its relatively high energy intensity [21]. The two dominant process technologies of reverse osmosis and multiple-stage flash distillation consume approximately 5 and 14 Whrs/gallon. Finally, energy is utilized in conditioning water for end use applications such as heating, cooling, pressurizing, or purifying [4]. Depending on the application 0-200Wh/gallons of electricity may be used [2]. End-uses devices and processes that minimize water consumption can therefore have an additional positive effect by reducing the need for water-intensive power generation.

The wastewater system shown in Figure 4 typically does not require electric power input in conveyance but

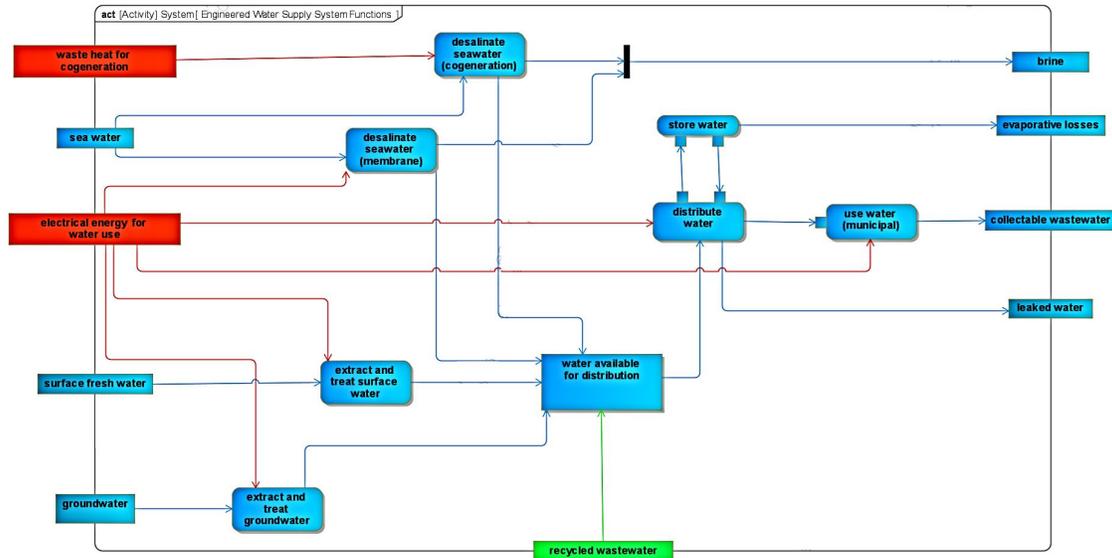


Fig. 3: Activity Diagram of Water System Functions [16]

rather in treatment. Wastewater usually uses gravity-flow sewers to reach treatment facilities at low elevations near water bodies where effluent is to be discharged. Once at the treatment facilities, electric power is required for a wide range of equipment that include pumps, blowers, and centrifuges to support processes including filtration and biological decomposition [22]. Attempts to quantify per-unit energy requirements have been estimated by survey [12].

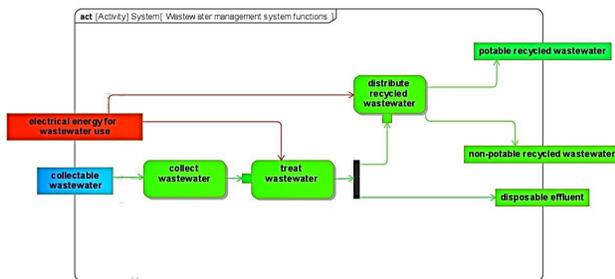


Fig. 4: Activity Diagram of Wastewater system functions [16]

Large scale wastewater recycling offers sizable benefits to sustained agricultural capacity. The most prominent wastewater reuse categories are agricultural irrigation, landscape irrigation, groundwater recharge. Furthermore, It has been shown in [9] that, in several MENA countries, recycled wastewater has the potential to meet nearly all industrial water demand. Finally, the integration of recycled wastewater into the potable water supply system has been implemented in Singapore and Namibia [23]. However, pathogen transmission concerns and public sentiment [22] have thus far prevented its widespread adoption. Given these potential 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.

#### IV. ILLUSTRATIVE EXAMPLE

The qualitative models presented in the previous section have been quantified to solve for the various exchanges of matter and energy between the engineering systems [24]. Figure 5 presents a conceptual illustration of a geographical region inspired by Egypt and subsequently calculates the measures previously described in Section III-A.

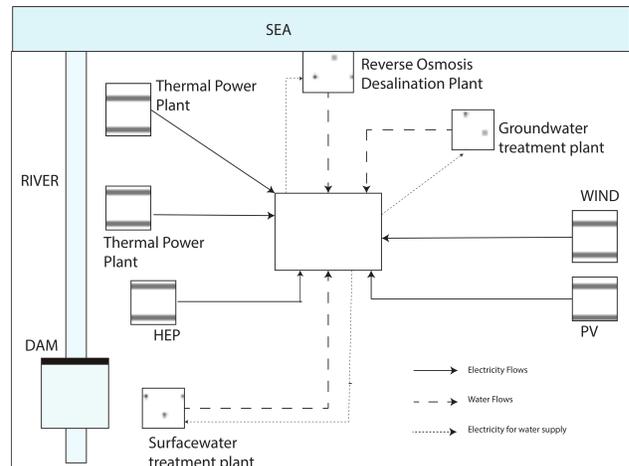


Fig. 5: Illustration inspired by Egypt [24]

- A measure of the degree of coupling between the electricity and water systems given by

$$D / (D + H + I) = 10.8\%$$

- Water supply required to sustain the two engineered systems given by  $E + F = 173.3m^3/s$
- Ratio of water displaced from its original source to total water withdrawn for water and electricity systems given by  $(A + C + R)/(E + F) = 77\%$
- Proportion of water withdrawn that is returned with significantly altered quality which is therefore a measure of environmental impact given by  $(B + G)/(E + F) = 5\%$

## V. CONCLUSIONS & FUTURE WORK

This paper has demonstrated the need for an integrated energy-water nexus engineering system model for the sustainable development of a region. One immediate application of such a model would be the long term planning of agricultural capacity particularly in developing nations relatively early in the development of their electricity, water and wastewater infrastructure. Such a model can relate a region's energy consumption to the required water withdrawals in a complex input-output model. Measures of the degree coupling, environmental impact, productive use of water withdrawals were developed and subsequently applied on a hypothetical system inspired by the Egyptian geography. Most worthy of note, is that if a region's sustainable water withdrawal rate is known then the proportion withdrawn for infrastructure operation can be assessed and planned. Naturally, a substantial portion of the remainder would be used for agriculture and could increased if deemed insufficient for sustainable agriculture capacity. One would approach would be to improve the relative measure of productively used wastewater. Efforts are underway to further develop and test this nascent model and later apply it for sustainable development planning applications.

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