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Quantitative engineering systems modeling and analysis of the energy–water nexus

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HIGHLIGHTS

- A quantitative, engineering systems model of the energy–water nexus is developed.
- System model built from bond graph representations of descriptive SysML functions.
- Use of physics-based models and increased scope improves on existing approaches.
- Model feasibility, advantages and application demonstrated in illustrative example.

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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 technology 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. A previous work presented a reference architecture of the energy–water nexus in the electricity supply, engineered water supply and wastewater management systems developed using the Systems Modeling Language (SysML). In this work, bond graphs are used to develop models that characterize the salient transmissions of matter and energy in and between the electricity, water and wastewater systems as identified in the reference architecture. These models, when combined, make it possible to relate a region's energy and municipal water consumption to the required water withdrawals in an input–output model.

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1. Introduction

1.1. Motivation

The energy–water nexus can be defined [1–4] as a system-of-systems composed of one infrastructure system with the artifacts necessary to describe a full energy value chain and another infrastructure system with the artifacts necessary to describe a full water value chain. Large volumes of water are withdrawn and consumed from water sources every day for electricity generation processes [5]. Simultaneously, extraction, treatment and conveyance of municipal water and treatment of wastewater are dependent on significant amounts of electrical energy [5].

This *energy–water nexus*, which couples the critical systems upon which human civilization depends, has long existed but is becoming increasingly strained due to a number of global mega-trends [6]: (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.

1.2. Literature gap

A number of discussions on the energy–water nexus have been published in recent years. Overviews of the various challenges related to the nexus, as well as discussions of various policy options for the amelioration of the risks can be found in [6–12]. Empirical

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Nomenclature

ΔT_W	permissible temperature increases of water sources
Γ_G	induced photocurrents at locations of solar photovoltaic installations
λ_G	wind speed at locations of wind farms
$\mathcal{H}_{\mathbf{G}}^{flue}$	specific sensible heat content of generator flue gas
$\mathcal{H}_{\mathbf{G}}$	lower heating value of fuel used at generators
π_W	osmotic pressure of water sources
$\dot{\mathfrak{M}}_{\mathbf{G}}$	process steam flow rate in thermal generators
$\dot{\mathbf{M}}_{\mathbf{G}}$	fuel consumption of generators
$\mathbf{I}_{\mathcal{P}}$	RMS current drawn by pumps in water distribution network
$\mathbf{I_D}$	RMS current drawn by wastewater treatment facilities
$\mathbf{I_F}$	RMS current drawn by water treatment plants
$\mathbf{I_G}$	RMS current supplied by generators
$\mathbf{I_L}$	RMS current drawn by all electrical load nodes
$\mathbf{I_N}$	RMS current drawn by pipes and pumps in non-potable recycled wastewater distribution network
$\mathbf{I_{L_0}}$	RMS current drawn by all electrical nodes excluding current for water system purposes
$\mathbf{P_D}$	pressures imposed by wastewater treatment plants on non-potable recycled wastewater distribution network
$\mathbf{P_F}$	pressures imposed by water treatment plants on water distribution network
$\mathbf{P_J}$	pressures at non-potable recycled wastewater demand nodes
$\mathbf{P_J}$	pressures at water demand nodes
$\mathbf{P_W}$	pressures of water sources
$\mathbf{Q}_{\mathcal{P}}$	water flow rate through pipes
$\mathbf{Q_D}$	throughput of wastewater treatment facilities
$\mathbf{Q_D}^{disp}$	disposable effluent production rate at wastewater treatment facilities
$\mathbf{Q_D}^{rec}$	non-potable recycled wastewater production rate at wastewater treatment facilities
$\mathbf{Q_E}$	water demand rate at non-potable recycled wastewater demand nodes
$\mathbf{Q_F}$	water supplied by water treatment and desalination plants
$\mathbf{Q_F}^{brine}$	brine produced by water treatment and desalination plants
$\mathbf{Q_G}^{evap}$	water evaporation rate associated with electrical generation units
$\mathbf{Q_G}^{in}$	water withdrawal rate by generators
$\mathbf{Q_G}^{out}$	generator effluent flow rate
$\mathbf{Q_J}$	water demand rate at demand nodes
$\mathbf{Q_S}$	water withdrawal rate from water storage units
$\mathbf{Q_S}^{evap}$	water evaporation rate from water storage units
$\mathbf{Q_W}$	water withdrawal rate from sources
$\mathbf{Q_{El}}$	water leakage rate at non-potable recycled wastewater demand nodes
$\mathbf{Q_{Jl}}$	water leakage rate at demand nodes
$\mathbf{V}_{\mathcal{P}}$	RMS voltages applied to pumps in water distribution network
$\mathbf{V_F}$	RMS voltages applied to water treatment plants
$\mathbf{V_G}$	RMS voltage at generators
$\mathbf{V_L}$	RMS voltage at electrical loads
$\mathbf{V_N}$	RMS voltages applied to pumps in non-potable recycled wastewater distribution network
p_{atm}	atmospheric pressure

evaluations of the electricity-intensity of water technologies and the water-intensity of electricity technologies have been reported and analyzed in [13–18]. Efforts have been made towards physics-based models in [19,20] in which formulations for estimating water use by thermal power plants based on the heat balance of the plant have been derived. An integrated operational view of the water and power networks has also been presented as a simultaneous co-optimization for the economic dispatch of power and water [21–27].

Less literature is available on the development of tools for integrated management of electricity and water supply systems. A decision support system for the United States based on an underlying system dynamics model is described in [28]. The model enables the exploration of various water and electricity policies and relies on statistical relationships between the independent variables of population and economic growth and the dependent variables of electricity and water demand. Recent work [29] has interfaced the well known Regional Energy Deployment System (ReEDS) and Water Evaluation and Planning (WEAP) tools to create a platform for determining the water resource implications of different electricity sector development pathways. The platform uses empirical consumption and withdrawal coefficients reported in [16] for the interface.

To the authors' knowledge however, a transparent physics-based model that interfaces a model of the electricity system to models of the municipal water and wastewater systems enabling an input–output analysis of these three systems in unison has not been presented. This work attempts to present and apply this *system-of-systems* model.

1.3. Scope

This paper adopts, as it's modeling scope, the engineered electricity, water and wastewater infrastructure as well as critical energy and matter flows across a system-of-systems boundary encompassing these three interconnected systems.

1.4. Relevance

The holistic, integrated modeling approach presented in this paper is of particular relevance to places with integrated electricity and water utilities (e.g. countries in the Gulf Cooperative Council (GCC)). The model enables the evaluation and comparison of different technology levers across the three systems of interest thus informing management and government policy around water, environment and energy. The modeling approach may also be applied to regions with separate electricity, water and wastewater utilities to demonstrate potential areas of coordination.

1.5. Contribution

In this paper, a quantitative, physics-based, engineering systems model of the energy–water nexus is developed as a first of its kind. This is in contrast to the existing literature which either has a smaller scope or uses empirical evaluations of water and energy intensity. The model uses *first-pass* but *often-cited* engineering models of various exchanges of mater and energy in and between the electricity, water and wastewater systems. Hence, the paper has a foundational nature in two regards. The *first-pass* engineering models replace the various empirical data surveys on the water intensity of energy technologies and energy intensity of water technologies [13,15]. Also, the first-pass models may be refined in the future as per the needs of the analytical application. The presented model builds upon a reference architecture previously provided in [2] and is thus a reference model that can: (i) provide a foundation for qualitative discussions in the general case,

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