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An engineering systems model for the quantitative analysis of the energy-water nexus

William Lubega and Amro M. Farid

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. A previous work presented 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). In this work, models have been developed that characterize the various transmissions of matter and energy in and between the electricity and water systems.

1 Introduction

Water and electricity are inextricably linked, and as a consequence have to be addressed together[12]. Extraction, treatment and conveyance of municipal water and treatment of wastewater are 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 Simultaneously, large volumes of water are withdrawn and consumed from water sources everyday for electricity generation processes.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 these 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[17]:(i) growth in total demand for both electricity and water driven by population growth; (ii) growth in per capita demand for both electricity

William Lubega
Masdar Institute of Science and Technology, Abu Dhabi, e-mail: wlubega@masdar.ac.ae

Amro M. Farid
Masdar Institute of Science and Technology, Abu Dhabi, e-mail: afarid@masdar.ac.ae
MIT Technology Development Program e-mail: amfarid@mit.edu

and water driven by economic growth; (iii) distortion of availability of fresh water due to climate change; and (iv) multiple drivers for more electricity-intensive water and more water-intensive electricity.

These trends raise concerns about 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, scarcity in either water or energy will create aggravated shortages in both.

A number of discussions on the energy-water nexus have been published in recent years. The two approaches that have predominantly been taken in the literature to discuss this topic are: (i) discussions of various policy options [12, 13, 15, 16, 17, 18, 20]; and (ii) evaluation of the electricity-intensity of water technologies and the water-intensity of electricity technologies [2, 5, 6].

In this paper, a foundation is laid for an engineering systems approach to studying the nexus, through the presentation of *first-pass* engineering models of the various salient exchanges of matter and energy in and between the electricity and water systems. The paper builds upon qualitative models previously provided in [9]. The majority of the presented models are developed using the bond graph methodology [8] which readily facilitates the inter-domain modeling necessitated by the heterogenous nature of the energy-water nexus.

In Section 2, the models are presented alongside system activity diagrams for an integrated view of the electricity and water engineering systems. Section 3 presents an illustrative example in which the developed models are used to analyze the exchanges of energy and water in a given geographical region. Section 4 offers some insights that can be acquired with the aid of the discussed approach. Finally, Section 5 concludes the work and presents directions for future work.

2 Modeling

This section builds upon the previously developed qualitative model of the energy-water nexus[9] and proceeds in three parts: delineation of the system boundary followed by the quantitative modeling of the respective electricity and water system functions.

2.1 System Boundary and Context

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. The labels A through J represent key flows of interest and are discussed in Section 4.

Electricity, potable water, and wastewater are all primarily stationary within a region's infrastructure; in contrast, the traditional fuels of natural gas, oil, and coal are open to trade. Consequently, the fuel processing function, though it has a significant water footprint, is left outside of the system boundary. An advantage of this choice of system boundary is that the three engineering systems all fall under the purview of grid operators; and in some nations, such as the United Arab Emirates,all three grid operations are united within a single semi-private organization. The sys-

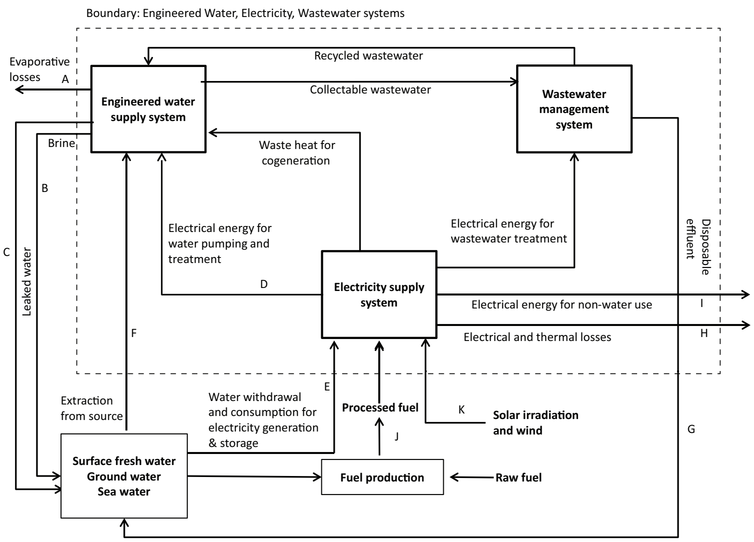

Fig. 1 System Context Diagram for Combined Electricity, Water & Wastewater Systems

tem 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.

The following conventions are adopted in the bond graphs found in the following sections:

Engineered Water System:

- $F_{W_j} \in \mathbf{F_W}$ is water flowing through a pipe j
- $E_{W_i} \in \mathbf{E_W}$ is the pressure at a node i.
- $F_{Wnet_i} \in \mathbf{F_{Wnet}}$ is the water injected into the network at a node i.

Electric Power System:

- $F_{P_j} \in \mathbf{F_P}$ is current flowing through a transmission line j.
- $E_{P_i} \in \mathbf{E_P}$ is the voltage at a node i.
- $F_{Pnet_i \in \mathbf{F_{Pnet}}}$ is the current injected into the network at a node i.

2.2 Electricity system functions

The four most prominent electricity generation technologies are shown in figure 2. These technologies have varying water withdrawal and consumption footprints. Thermal generation requires large volumes of water for cooling purposes and is one of the chief concerns associated with the energy-water nexus. Hydroelectric power incurs evaporative losses due to the increase in exposed surface area created by the dam reservoir. Solar and wind generation do not have any significant water requirements in operation.Bond graph models of solar, wind and hydroelectric generation

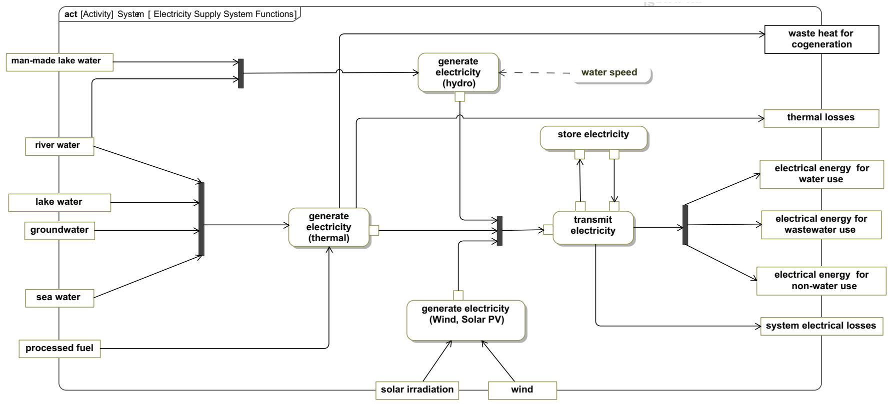

Fig. 2 Activity Diagram of Electricity System Functions

are presented below. Development of a thermodynamic bond graph model of thermal power generation is the subject of future work.

2.2.1 Generate Electricity-hydro

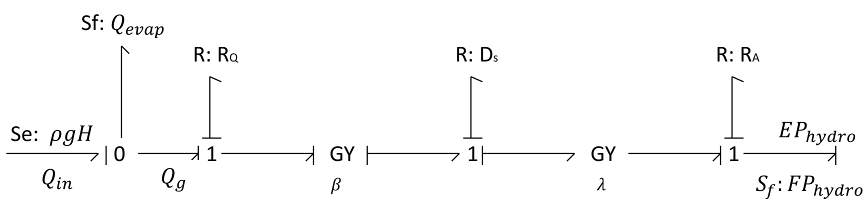

Fig. 3 Bond graph representation of hydroelectric power generation

Figure 3 shows a bond graph model of a hydroelectric power generation station in which a water drop H drives a turbine, represented here by an ideal gyrator with modulus β. The turbine, in turn, drives a generator, represented also by an ideal gyrator with modulus λ. From the model, the voltage generated by the power station $E_{P_{hydro}}$ and the water withdrawn for generation Q_g can be determined as:

$$\begin{gathered} E_{P_{hydro}} = -\left[\frac{\lambda R_Q(\lambda^2 + D_S R_A) + \beta^3 R_A}{\beta^2 \lambda}\right] F_{P_{net_{hydro}}} + \left[\frac{\rho g(\lambda^2 + D_S R_A)}{\beta \lambda}\right] H \\ Q_g = \frac{\lambda}{\beta} F_{P_{net_{hydro}}} \end{gathered} \tag{1}$$

where R_Q,D_S and R_A represent resistances and dampings of the penstock, turbine shaft and generator respectively. Of interest is the rate of water withdrawal Q_{in} from the source water body to support a given level of power generation as this requirement can impose a constraint on power generation. This withdrawal is given by: $Q_{in} = Q_{evap} + Q_g$; where Q_{evap} is the rate of water evaporation from the dam reservoir, a flow dependent on reservoir surface area, and ambient temperature and humidity conditions.

2.2.2 Generate Electricity - Wind

A bond graph model of a wind turbine is provided in [1]. Figure 4 reproduces the model with the simplifying assumptions that the wind turbine is operating in the steady state, that there is no stiffness between components and that all dampings are equivalent.

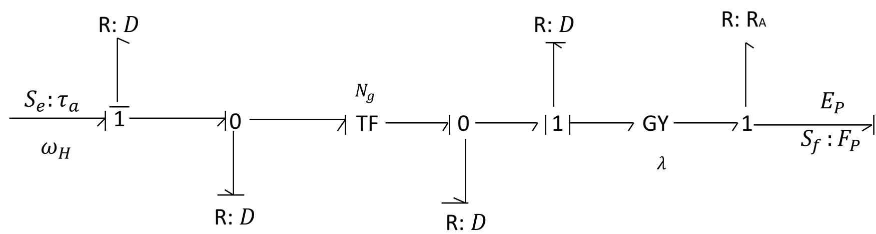

Fig. 4 Bond graph representation of wind turbine

From the model, the voltage, $E_{P_{wind}}$, imposed on the electrical distribution network by n identical, co-located wind turbines connected in series can be determined as:

$$E_{P_{wind}} = -\left[nR_A - \frac{n\lambda^2(3D - N_g^2)}{2D(N_g^2 + DN_g^2 - 3D)}\right] F_{P_{wind}} + \left[\frac{n\lambda DN_g(N_g^2 - 1)}{2D(N_g^2 + DN_g^2 - 3D)}\right] \tau_a \quad (2)$$

where

- N_g is the gearbox ratio of the wind turbine gearbox
- D is the damping of the various mechanical components and interfaces in the wind turbine
- τ_a is the aerodynamic torque exerted on each wind turbine, a function of the wind speed V, air density ρ_a, blade radius R and a dimensionless torque coefficient C_T given by [1]:

$$\tau_a = \frac{1}{2}\rho_a \pi R^3 C_T \times V^2$$

2.2.3 Generate Electricity - Solar photovoltaic

Figure 5 is a simple bond graph model of solar photovoltaic installation approximated as a current source, a linear resistance, and a gyrator. In this model, the gyrator represents both the inverter switching circuit and the DC-to-DC conversion circuit. The function of the former is approximated by the change of causality from flow source to effort source effected by the gyrator while that of the latter is effected by the magnitude of the gyrator modulus. The resistance represents electrical losses in both processes.

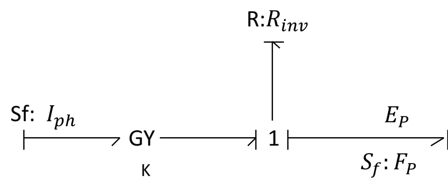

Fig. 5 Bond graph representation of solar PV installation

From the model, the voltage $E_{P_{solar}}$ imposed on the electrical distribution network by n such co-located installations connected in series can be determined as:

$$E_{P_{solar}} = -nR_{inv}F_{P_{solar}} + nKI_{ph} \tag{3}$$

where

- R_{inv} represents energy losses in the inverter
- K is the gyrator modulus
- I_{ph} is the photogenerated current induced in each solar PV installation. The photogenerated current is dependent on various material properties and the incident photon flux which is related to the solar irradiance and solar cell surface area[10].

2.2.4 Transmit Electricity

The transmission of electricity through an electricity distribution network can be easily described with the aid of an edge-node incidence matrix A_P, with the following equation:

$$\mathbf{F_{Pnet}} = A_P^T C_P A_P \mathbf{E_P} \tag{4}$$

where:

- C_P is a diagonal conductance matrix with each diagonal entry $C_{P_{jj}}$ being the conductance of transmission line j.
- $A_{P_{ji}} = 1$ if current in transmission line j leaves node i, $A_{P_{ji}} = -1$ if current in transmission line j enters node i, $A_{P_{ji}} = 0$ otherwise.

In typical power flow analysis, Equation 4 is multiplied by a diagonal matrix of bus voltages to yield the power flow equations.

2.3 Water system functions

An activity diagram for the engineered water supply system is shown in Figure 6. All water grid functions apart from storage 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. Models of three of the indicated water supply options are presented below. A model of thermal desalination is to be developed in future work. Electricity consumption for municipal water use is not modelled as it represents a plethora of different processes that are typically not under the purview of grid operators.

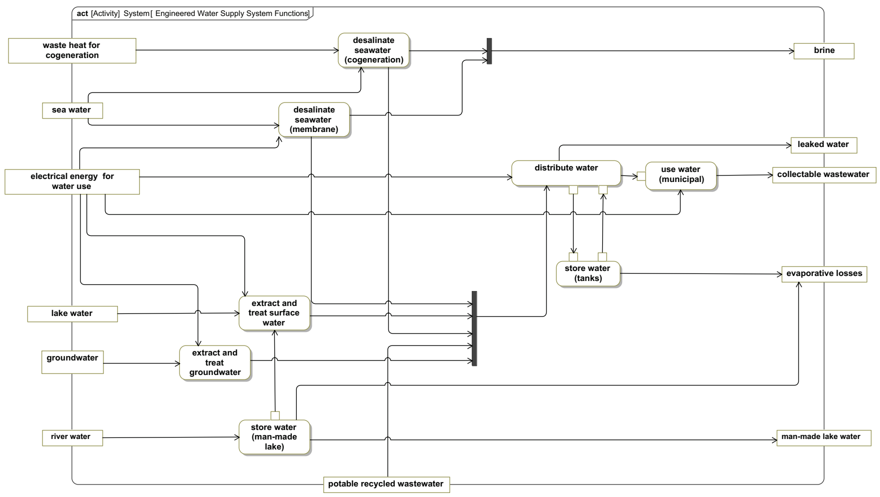

Fig. 6 Activity Diagram of Water System Functions

2.3.1 Extract and treat ground water

The extraction and treatment of ground water can be effectively modelled as a pump as pumping consumes more than 98 percent of power at a ground water treatment plant [5].

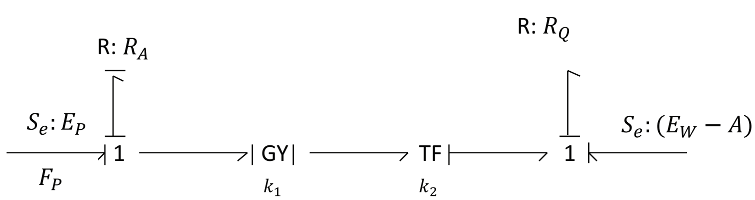

Fig. 7 Bond graph representation of pump

A bond graph model of a displacement pump that imposes a fixed pressure increment $(E_W - A)$ on a fluid is shown in Figure 7. The gyrator and transmer are representations of a motor and pump respectively. R_A and R_Q represent electrical and fludic resistances in the motor and pump. From this bond graph representation, the current drawn by a groundwater treatment plant can be determined as:

$$F_{Pnet_g} = \frac{\rho g K(E_{W_g} - A_g) + R_Q E_{P_g}}{K^2 + R_A R_Q} \tag{5}$$

where A_g is elevation of the aquifer from which the groundwater is drawn above the selected piezometric datum, $K = k_1/k_2$ and E_{W_g} is the pressure to which water is pumped for distribution—a design parameter of the water distribution network.

2.3.2 Extract and treat surface water

Similar to a groundwater treatment plant, a surface water treatment plant can be modelled as a pump. The current drawn by a surface water treatment plant can, therefore, be determined as:

$$F_{Pnet_s} = \frac{\rho g K(E_{W_s} - A_s) + R_Q E_{P_s}}{K^2 + R_A R_Q} \tag{6}$$

where A_s is elevation of the surface water body above the piezometric datum.

2.3.3 Desalinate seawater (membrane)

Reverse Osmosis, the dominant membrane desalination technology [7], is a pressure-driven process. A pressure-differential ΔP_{diff} that exceeds the natural osmotic pressure ΔP_{osm} must be developed across the membrane. The rate of water flow Q, across the membrane is then given by [19]:

$$Q = \frac{\kappa S(\Delta P_{diff} - \Delta P_{osm})}{d}$$

where κ is the membrane permeability coefficient for water, S is the membrane area and d is the membrane thickness. From an energy perspective, the reverse osmosis process can, therefore, be approximated by a pump that increases the pressure of water by ΔP_{diff} to sustain the flow $Q = F_{Wnet_{ro}}$. Further pumping is required to increase the piezometric head of the desalinated sea water from sea level A_{ro} to a design pressure $E_{W_{ro}}$ for distribution. A reverse osmosis plant can, therefore, be described with the following equations:

$$\begin{aligned} F_{Wnet_{ro}} &= \frac{\kappa S}{d} \times (\Delta P_{diff} - \Delta P_{osm}) \\ F_{Pnet_{ro}} &= \frac{\rho g K(E_{W_{ro}} + \Delta P_{diff} - A_{ro}) + R_Q E_{P_{ro}}}{K^2 + R_A R_Q} \end{aligned} \tag{7}$$

ΔP_{osm} is dependent on the dissolved solute concentration and is given by the van't Hoff equation [14] $\Delta P_{osm} = iMR$, where i is the van't Hoff factor, M is the molarity of the dissolved salts and R is the universal gas constant. The brine output can be determined from the average recovery ratio of the process. The recovery ratio RR is defined [3] as the ratio of the permeate (filtrate) to the feed seawater. The brine output can, therefore, be expressed as:

$$\text{Brine output} = \frac{F_{W net_{ro}}}{RR}(1 - RR) \tag{8}$$

The recovery ratio of a single reverse osmosis element is typically between 10 and 15% [3].

2.3.4 Distribute Water

The distribution of water through a water distribution network can be described with the aid of an edge-node incidence matrix A_W, with the following equation:

$$\mathbf{F_{Wnet}} = A_W^T C_W A_W \mathbf{E_W} \tag{9}$$

where:

- C_W is a diagonal conductance matrix with each diagonal entry $C_{W_{jj}}$ being the conductance of pipe j.
- $A_{W_{ji}} = 1$ if water in pipe j leaves node i, $A_{W_{ji}} = -1$ if water in pipe j enters node i, $A_{W_{ji}} = 0$ otherwise.

3 Illustrative Example

In this section, the models developed are used to solve for the various exchanges of matter and energy between the engineering systems. In particular, the inputs and outputs of interest, previously labelled in Figure 1 are found subject to the demands for water and electricity and the the respective topologies. Figure 8 presents a conceptual illustration of a geographical region served by a number of different water and power sources for demonstration of the quantitative engineering systems model. The water distribution system is modelled as consisting of three water sources, as indicated, equidistant from aggregated demand node of $3m^3/s$ or approximately 70 million gallons a day. The required hydraulic pressure for the distribution is provided entirely by pumping to the clearwell at the treatment plants; in other words, there are no additional pumps in the distribution network.

The electricity distribution network for this example is modelled with the standard IEEE14 bus system [11] with the following modifications:

1. The 40MW generator at bus 2 is replaced with a 100MW generator representing a hydroelectric power plant
2. The synchrononous compensators at buses 3,6 and 8 are replaced with 10MW generators representing a solar PV plant, a wind power power plant and a thermal power plant respectively. The generator at slack bus 1 is taken as a thermal power plant.
3. The reverse osmosis plant, groundwater treatment plant, and surface water treatment plant are attached to the network at buses 4,5 and 14

As machine constants, available inputs from the environment, and demands for both water and electricity are not determined by the effort and flow variables in

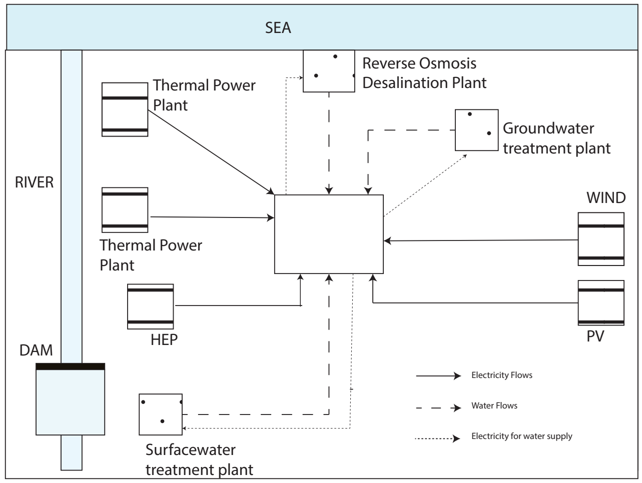

Fig. 8 Illustration inspired by Egypt
(HEP- Hydroelectric generation plant, PV-Solar Photovoltaic plant, WIND- Wind power plant)

either system, they are included in the model as parameters. A summary of the parameters and variables associated with the various modeled functions is given in Table 1 below. Subscript i in Table 1 refers to source nodes, while subscript j refers to demand nodes. The values of $\mathbf{E_{P_i}}$ are endogenously determined by the *'Generate electricity'* functions.

Table 1 Variables and Parameters

Function	Parameters	Variables
Generate electricity - hydro	$H, Q_{evap}, R_A, R_Q, D_S, \lambda, \beta$	$E_{P_{hydro}}, F_{Pnet_{hydro}}$
Generate electricity - wind	$V, C_T, R, N_g, D, \lambda$	$E_{P_{wind}}, F_{Pnet_{wind}}, \tau_a$
Generate electricity - solar PV	K, R_{inv}	$E_{P_{solar}}, F_{Pnet_{solar}}$
Transmit electricity	C_P, A_P, $\mathbf{F_{Pnet_j}}$	$\mathbf{E_{P_j}}$, $\mathbf{F_{Pnet_i}}$
Groundwater treatment	$R_A, R_Q, K, A_g, E_{W_g}$	F_{Pnet_g}, F_{Wnet_g}
Surface water treatment	$R_A, R_Q, K, A_s, E_{W_s}$	F_{Pnet_s}, F_{Wnet_s}
Reverse osmosis	$R_A, R_Q, K, A_{ro}, E_{W_{ro}}, \Delta P_{osm}, \kappa, S, d, RR$	$F_{Pnet_{ro}}$, $F_{Wnet_{ro}}$
Distribute water	C_W, A_W, $\mathbf{F_{Wnet_j}}$, $\mathbf{E_{W_i}}$	$\mathbf{E_{W_j}}$, $\mathbf{F_{Wnet_i}}$

4 Discussion

The model in Section 3 was implemented in GAMS and solved with the CONOPT solver. The values of the various inputs, outputs and exchanges, previoulsy labelled with the letters A through J in Figure 1, are shown in Table 2. The matter and energy flows not labelled with letters in Figure 1 are the subject of ongoing work and were not included in the model. Water withdrawal (E) and consumption (E^*)for thermal generation were modelled by means of empirically determined water withdrawal and consumption rates of $0.9m^3/MW$ and $0.7m^3/MW$ respectively for natural gas combined cycle plants with closed loop cooling systems [17]. Fuel energy consumption ($JMWth$) was modelled by means of a typical heat rate of $0.0072MJ/MWh$ for a natural gas combined cycle plant[4]. As the wastewater system has not been modelled it is assumed that all water delivered to the aggregated demand node is returned to natural water bodies(G) in an untreated state. Electrical losses (H) are determined from the power flow analysis.

Table 2 Model Output

A	B	C	D	E	E^*
$1m^3/s$	$6.3m^3/s$	$0.3m^3/s$	$29MWe$	$170m^3/s$	$132m^3/s$

F	G	H	I	J	K
$3.3m^3/s$	$3m^3/s$	$8MWe$	$230MWe$	$386MWth$	$20MWe$

As an illustration of the insights that can be obtained from this approach, various measures of aspects of the nexus, that can be used to inform planning decisions,can be expressed in terms of energy and matter flows determined from the model:

- Ratio of useful electrical energy to priced energy resource consumption given by $(D+I)/J = 67\%$
- Ratio of energy wasted by electrical power system to priced energy resource consumption given by $H/J = 2\%$
- 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 $(A+C+E^*)/(E+F) = 77\%$
- Proportion of water withdrawn that is returned with significantly altered quality which is therefore a measure of environmental impact given by $(B+G)/(E+F) = 5\%$

5 Conclusions and Future Work

This work has presented bond graph models of various elements of the engineered electricity and water systems and demonstrated their utility in a coupled engineering system model of these two connected systems. In future work, thermodynamic and chemical bond graph models will be developed to model the thermal generation, electricity and water cogeneration and wastewater treatment functions. In addition a numerical method will be developed to solve for the variables of interest in place of the GAMS solver used in this work.

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