Extending the Energy-Water Nexus Reference Architecture to the Sustainable Development of Agriculture, Industry & Commerce

Halima Abdulla
Engineering Systems and Management
Masdar Institute of Science and Technology
Abu Dhabi, United Arab Emirates
Email: habdulla@masdar.ac.ae

Amro M. Farid
MIT Mechanical Engineering
Cambridge, MA USA
Email: amfarid@mit.edu

Abstract—Clean energy and water are two essential resources that any society must securely deliver in order to develop sustainably. Traditionally, these two precious commodities are often treated as separate uncoupled systems. However, in reality, they are very much coupled in what is commonly known as the energy-water nexus. Recently, an infrastructure-centric reference architecture of the energy-water nexus in the electricity supply, engineered water supply and wastewater management systems has been developed; first graphically in SysML and later quantitatively using bond graphs. This made it possible to relate a region's energy and municipal water consumption to the required energy and water withdrawals in an input-output model so as to directly inform the planning & operations of energy-water infrastructure operators. In order to expand the utility of the model to high level policy decision-making, this paper now extends that work to address the sustainable development of agricultural, industrial, commercial and residential activities. In such a way, it relates the economic value of fossil fuels, food, products and commerce to input and waste streams of energy and water. Such a model provides high-level guidance to the design of sustainable development policies. Furthermore, the commitment to a physical modeling approach – unlike purely economic models – also directly informs the design of energy-water nexus infrastructure to achieve these sustainable development policy goals.

I. INTRODUCTION

Clean energy and water are two essential resources that any society must securely deliver in order to develop sustainably [1], [2]. Traditionally, these two precious commodities are often treated as separate uncoupled systems. However, in reality, they are very much coupled [3]. This interlinked meta-system is often called the energy-water nexus and is defined here as:

Definition 1. Energy Water Nexus [4]–[7]: 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.

Recently, an infrastructure-centric reference architecture of the energy-water nexus in the electricity supply, engineered water supply and wastewater management systems has been

developed; first graphically in SysML [4] and later quantitatively using bond graphs [5], [8]. This made it possible to relate a region's energy and municipal water consumption to the required energy and water withdrawals in an input-output model so as to directly inform the planning & operations of energy-water infrastructure operators. Thus, it added an integrated perspective to prior works with an engineering systems perspective [9]–[11].

A. Paper Contribution

While the energy-water nexus reference architecture is of great value to energy-water infrastructure operators, it has also caught the attention of numerous policy and regulatory agencies [12]–[17]. Therefore, in order to expand the utility of the reference architecture to high level policy decision-making, this paper now extends the architecture's scope to the sustainable development of agricultural, industrial, commercial and residential activities. In such a way, it relates the economic value of fossil fuels, and agricultural, manufactured and commercial products to input and waste streams of energy and water. Such a model provides high-level guidance to the design of sustainable development policies. Furthermore, the commitment to a physical modeling approach – unlike purely economic models – also directly informs the design of energy-water nexus infrastructure to achieve these sustainable development policy goals.

B. Paper Outline

The remainder of the paper proceeds as follows. Section II reviews the recently developed energy-water nexus reference architecture and its potential applications. Section III then extends the architecture's system boundary to include agricultural, industrial, commercial, and residential activities. The paper is brought to a conclusion in Section IV.

II. BACKGROUND – THE ENERGY-WATER NEXUS REFERENCE ARCHITECTURE

This section reviews the recently developed energy-water nexus reference architecture at its highest level [4], [5], [8].

Figure 1 shows the architecture's internal block diagram. It consists of three engineering systems: the electricity, water, and wastewater systems as it draws and returns water and energy flows from both the natural surface environment and the fuel mining and production system.
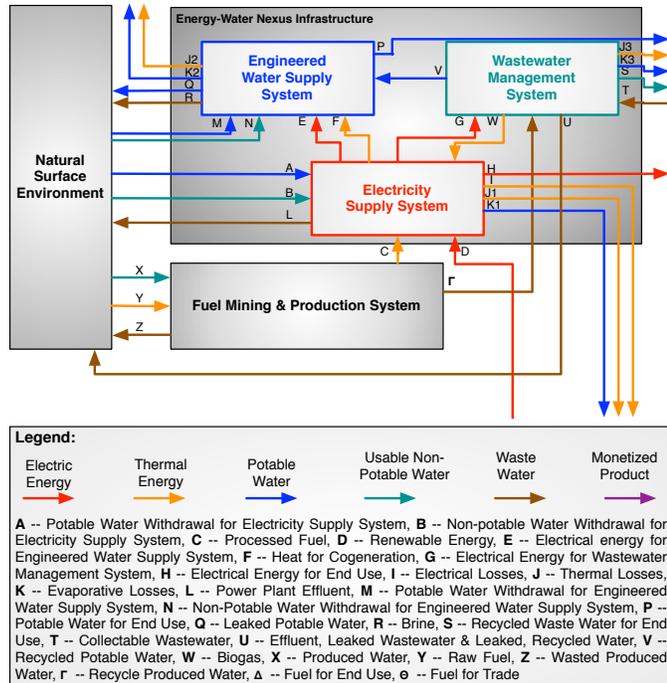

Fig. 1: Energy Water Nexus Reference Architecture Internal Block Diagram [4], [5], [8]

This system boundary was chosen so that the valued products of electricity (H), potable water (P), and wastewater (S) are all stationary within the region's infrastructure. In contrast, the fuel mining and production system for natural gas, oil and coal are open to trade or local consumption. Consequently, it was left out of the system boundary. As a result, the energy-water nexus reference architecture coincides with the scope of grid operators. The interested reader is referred to the underlying references for a full description of the architecture form, function and concept through multiple layers of graphical and physical modeling [4], [5], [8]. The reference architecture's choice of system boundary thus lends itself to integrated energy-water planning and operations methods. Furthermore, in some nations, such as the UAE, these three engineering systems fall under the purview of a *single* integrated energy and water utility. Therefore, such methods can be implemented centrally.

The SysML model can be extended to conduct two types of studies. The first type of study mimics those found in economic models. The reference architecture allows each subsystem to be treated empirically as a black-box with its respective balance of energy and water. In such a case, the associated energy and water intensities of the various system outputs are treated as given fixed constants. Such an approach can be used to conduct scenario analyses as demand for water

and energy change in the future. In the second type of study, physical models are applied analytically to each subsystem []. Consequently, energy and water balance are derived from the laws of physics. Furthermore, the energy and water intensities of the system outputs are no longer given constants but instead are also analytically derived. As recent work has shown [5], [8], these values depend not just on each subsystem's physical parameters but also the operating point of the energy-water nexus infrastructure as a whole. Therefore, the physical modeling approach can provide additional advisory capacity [18]. In planning, this includes the choice of the type and typology of the plant and its associated technology [18], [19]. In operations, the energy-water nexus can be dispatched so as to make favorable trade-offs of water and energy depending on their relative importance as decision-making criteria [6], [7], [18], [20], [21]. These potential applications are highlighted for each of the nexus' constituent engineering systems.

A. Electricity supply system

Figure 1 depicts the electricity supply system in red. It's primary function is to convert and relay processed fuel (C), renewable energy (D) and waste biogas (W) as electrical energy for end use (E,F G & H). Naturally, this process produces both electrical and thermal losses (I & J1). From an energy-water nexus perspective, this primary function also requires the withdrawal of potable and non-potable water (A & B) which may be returned to its original source as effluent (L) or lost to evaporation (K1).

The benefits of physical modeling to integrated energy-water planning and operations methods can now be highlighted (over black box modeling approaches). A black box approach takes the ratio of input and output quantities as fixed. In contrast, a physical modeling approach allows a sensitivity analysis [19] which allows the identification of several trade-off decisions in planning and operations.

- **Trade-off H vs (I & J1):** Power generation, transmission & distribution losses not only degrade the delivered power but they also increase all water quantities. Many energy efficiency technologies exist including combined cycle power plants, and flexible AC transmission systems. Furthermore, the trend towards distributed generation closer to its point of use systematically reduces line losses.
- **Trade-off H vs (E, F & G):** The electric and thermal energy exported to support the engineered water supply system and wastewater management system may be viewed as a "public infrastructure cost" which may otherwise be used to support electrical energy for end use.
- **Trade-off (K1 vs L):** Some power generation facilities have semi-open cooling systems that incur evaporative losses. In contrast once-through and fully closed cooling systems have comparatively lower withdrawals or return their withdrawals to the original source as effluent. Air cooling systems are ideal when physically feasible.
- **Trade-off (C vs D vs W):** The energy source itself has upstream impacts on the surrounding systems. Renewable

energy can be taken exogeneously as is. Failure to use waste biogas from the wastewater management system implies increased emissions & energy loss. The usage of processed fuel implies an energy and water intensity in its mining and production.

- **Trade-off (A vs B):** The water source is also of importance. The usage of non-potable water for the electricity supply system (e.g. brackish groundwater or seawater) should be systematically preferred over potable water sources.
- **Global Trade-Off:** Finally, energy storage has the potential to shift all the ratios of input and output quantities; particularly in an operations time scale.

B. Water supply system

Figure 1 depicts the engineered water supply system in blue. It's primary function is to withdraw potable water (M) and non-potable water (N) and relay it as potable water (P). In the case that the non-potable water is seawater then brine (R) may also be produced. Additionally, there is the potential to recycle water from the wastewater management system to potable quality (V). Naturally, these processes produce evaporative losses (K2) and water leakages (Q). From an energy-water nexus perspective, this primary function also requires the withdrawal of electrical energy for pumps & fans (E) and thermal energy (F) for multi-stage flash desalination. Both of these have their associated energy losses (J2).

The benefits of a physical modeling approach also appear as trade-offs in the engineered water supply system [19].

- **Trade Off P vs (K2 & Q):** Water treatment & distributions losses not only increase the required water withdrawals but they also increase all the energy quantities.
- **Trade Off K2 vs Q:** While evaporative losses and leakages represent process inefficiencies, the latter returns water to the ground (in the same geography) while the latter does not. Therefore, the construction of artificial acquifers is generally preferred over man-made lakes & reservoirs from an energy-water nexus perspective.
- **Trade Off J2 vs (E & F):** The water system's energy losses be they from treatment plants or water pipes directly increase the required energy input. Energy efficient pumps, fans, heat exchangers, and pipes directly serve to reduce these quantities.
- **Trade Off M vs N:** The environment imposes fundamental limits on the choice of water source. If potable water sources are particularly scarce (e.g. the UAE), then non-potable seawater or brackish ground water may be withdrawn at an additional energetic cost.
- **Trade Off E vs F:** Consequently, the choice of treatment technology creates a tradeoff between electrical and thermal energy input. This is most clearly seen in the choice between reverse osmosis and multi-stage flash desalination.
- **Global Trade-Off:** Finally, water storage has the potential to shift all the ratios of input and output quantities; particularly in an operations time scale.

C. Waste water system

Figure 1 depicts the wastewater management system in green. It's primary function is to collect and treat effluent (T & Γ) and return it to the environment in an improved but non-potable condition (U). Increasingly, the wastewater management systems are designed to provide recycled non-potable water (S) and a lesser extent potable water (V). Naturally, these processes produce evaporative losses (K3). From an energy-water nexus perspective, the wastewater management system requires the withdrawal of electrical energy for pumps & fans (G) but also has the potential to capture and reuse biogas for power generation (W). In both cases, these processes have their associated energy losses (J3).

Finally, the benefits of a physical modeling approach also appear as tradeoffs in the wastewater management system [19].

- **Trade Off U vs K3:** Wastewater treatment and distribution evaporative losses diminish how much water is ultimately returned to the natural environment as effluent.
- **Trade Off U vs S vs V:** The wastewater infrastructure produces up to three valuable water streams. Partially treated water is returned to the environment as effluent. Alternatively, it may be recycled to either a non-potable quality for end use or or a potable quality in the engineered water supply system.
- **Trade Off W vs J3:** The wastewater system's energy losses be they from treatment plants or water pipes directly diminish the potential for energy export in the form of biogas.
- **Trade Off W vs U:** Wastewater effluent has both fluidic as well as energetic characteristics. Its return to the environment diminishes the potential for energy export in the form of biogas.
- **Trade Off G vs (K3, S, U and W):** The wastewater infrastructure's balance of products in combination with its biogas export determine how much electrical energy is drawn from the electric power grid.
- **Global Trade-Off:** Finally, water storage has the potential to shift all the ratios of input and output quantities; particularly in an operations time scale.

D. Summary: Application to Integrated Energy-Water Infrastructure Planning & Operation

In summary, the physical modeling approach underlying the energy-water nexus reference architecture supports integrated energy-water infrastructure planning. Ultimately, the infrastructure delivers electricity (H), potable water (P), and non-potable water (S) as valuable products. These three objectives must be made at a minimum of both resource consumption and waste streams returned the environment. Achieving this balance of competing objectives requires a careful inspection of the trade-off decisions highlighted above as part of the infrastructure planning and operation. In planning decisions, the slopes of these trade-offs can be intentionally changed to support the expected requirements of electricity, potable water, and non-potable water. In operations, these slopes may

be changed, albeit to a much lesser degree, because they are nonlinear functions of the required outputs. Instead, and generally speaking, decisions in the operations time scale seek to leverage the existing trade-offs to support the combined objectives of sufficient supply, resource minimization, and waste minimization.

III. ENERGY-WATER NEXUS REFERENCE ARCHITECTURE END USE EXTENSION

With this background discussion in place, this paper now extends the energy-water nexus reference architecture to address the sustainable development of agricultural, industrial, commercial, and residential activities. This section first motivates the end use model extension and then discusses its constituent components.

A. Motivation for the End Use Architecture Extension

One motivation for the architecture extension comes from carefully inspecting the values of the infrastructure's valuable products (H, P & S). Several reports recognize that many end uses such as agriculture and manufacturing continue to use potable water despite only requiring non-potable water in their activities. Furthermore, electricity demand can often be replaced by refined fuels (Δ) such as natural gas. Therefore, these end use decisions should be investigated to avoid the imposition of unnecessary constraints on infrastructure planning.

More fundamentally, the emerging concern towards the energy-water nexus is largely driven by doubts as to whether economic objectives can be achieved *sustainably*. In other words, given a set of valuable products, one may question 1.) the degree to which the environment can sustain the associated resource consumption 2.) the degree to which the infrastructure can provide the right balance of inputs for the end use activities and 3.) the degree to which end use processes and technologies efficiently produce these valuable products. Therefore, the goal of an end use architecture extension becomes to relate economic value of electricity, fuel, and agriculture, manufactured, and commercial products to input and waste streams of energy and water. Such a model would provide high-level guidance to the design of sustainable development policies. Again, the commitment to a physical modeling approach – unlike purely economic models – contextualizes and informs the energy-water nexus infrastructure design to achieve these sustainable development policy goals.

B. Overview of the End Use Architecture Extension

Figure 2 shows the end use architecture extension. The system boundary has now been extended to include stationary facilities in the built environment of the region. These are delineated from the natural surface environment. The fuel mining & production system is now included as an integral part of the architecture. The end uses are also included and are further classified as agricultural, manufacturing, commercial and residential activities. Together, these new activities serve to identify five commercially valuable and potentially exportable products: electricity, fuel, and agricultural, manufactured, and

commercial products. Note that while the original energy-water nexus reference architecture was essentially closed to flows of energy and water within a given region, the extension is now very much open to flows of energy, water, and products with neighboring regions. Each of the functions in the architecture are now discussed in turn.

C. The Natural Surface Environment

The natural surface environment in this work is effectively modeled as a source and sink of all quantities from and to the "surface of the natural world" in a given region. In addition to the quantities previously mentioned (A, B, L, M, N, Q & R), the fuel mining and production system withdraws raw fuels (e.g. coal, oil, & natural gas) (Y) in addition to produced water (X); some of which is returned back as effluent (Z).

The modeling choice of sources and sinks has several implications. First, it avoids having to the model the natural processes which describe the behavior of the environment. This greatly simplifies the architecture qualitatively and potentially later in the associated quantitative model. Second, because the environment acts as a source of energy and water, the model implicitly assumes no capacity limit on the environment's ability to provide these quantities. While this may appear unrealistic from a sustainability lens, it allows these source and sink quantities to be back calculated as has been previously demonstrated. At that point, the associated values can be interpreted in terms of the environment's capacity to provide and receive them.

D. Fuel Mining & Production System

Figure 2 shows the fuel mining & production system as an integral part of the end use architecture extension. It's primary function is to withdraw raw fuels (Y) and deliver them as processed fuel for power generation (C), end use (Δ), and trade (Θ). A side of effect of raw fuel withdrawal is the withdrawal of produced water. It may be returned to the environment (Z) or alternatively recycled for further use (Γ). Finally, the process also produces energy losses (J5).

Again, the benefits of physical modeling serve to identify the trade-offs in the fuel mining and production system.

- **Trade Off Θ vs C vs Δ:** This trade-off arises due to the value extracted from each fuel source. Exported fuel is a major revenue source for many nations. Ultimately, its quantity is diminished by domestic consumption be it for power generation or directly in end use activities.
- **Trade Off Γ vs Z:** Produced water is a valuable by-product which may be used to recharge wells or alternative to support non-potable water use.

E. End Uses

Figure 2 also shows four types of end uses: agricultural, manufacturing, commercial, and residential activities. At first glance, all of these transformational activities are treated the same. Collectively, they consume thermal energy (Δ), electrical energy (H), potable water (P) and non-potable water (S). They also produce energy and water losses (J & K) and
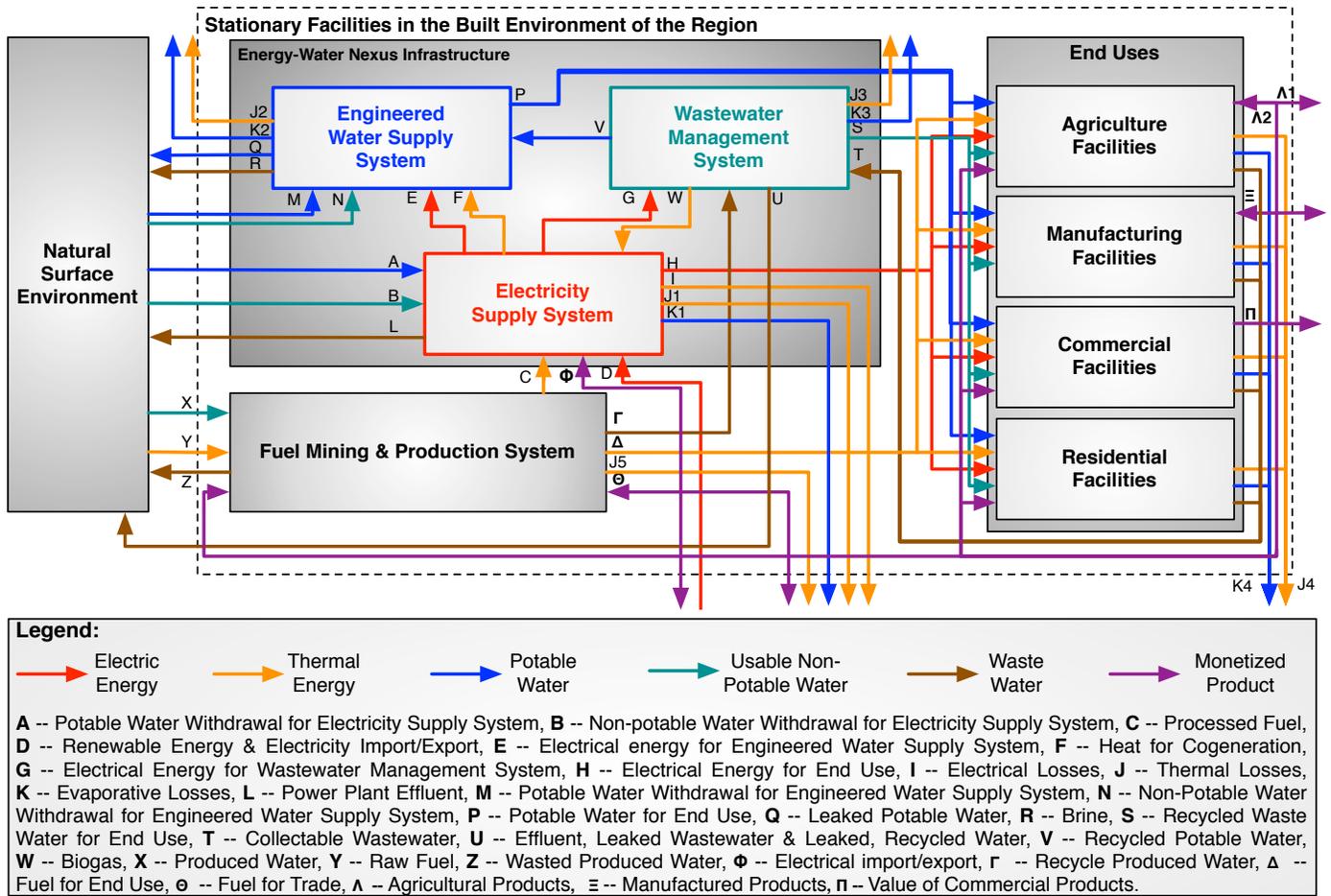
Fig. 2: Extension of the Energy-Water Nexus Reference Architecture to End Use Activities

Legend:

→ Electric Energy	→ Thermal Energy	→ Potable Water	→ Usable Non-Potable Water	→ Waste Water	→ Monetized Product

A -- Potable Water Withdrawal for Electricity Supply System, **B** -- Non-potable Water Withdrawal for Electricity Supply System, **C** -- Processed Fuel, **D** -- Renewable Energy & Electricity Import/Export, **E** -- Electrical energy for Engineered Water Supply System, **F** -- Heat for Cogeneration, **G** -- Electrical Energy for Wastewater Management System, **H** -- Electrical Energy for End Use, **I** -- Electrical Losses, **J** -- Thermal Losses, **K** -- Evaporative Losses, **L** -- Power Plant Effluent, **M** -- Potable Water Withdrawal for Engineered Water Supply System, **N** -- Non-Potable Water Withdrawal for Engineered Water Supply System, **P** -- Potable Water for End Use, **Q** -- Leaked Potable Water, **R** -- Brine, **S** -- Recycled Waste Water for End Use, **T** -- Collectable Wastewater, **U** -- Effluent, Leaked Wastewater & Leaked, Recycled Water, **V** -- Recycled Potable Water, **W** -- Biogas, **X** -- Produced Water, **Y** -- Raw Fuel, **Z** -- Wasted Produced Water, **Φ** -- Electrical import/export, **Γ** -- Recycle Produced Water, **Δ** -- Fuel for End Use, **Θ** -- Fuel for Trade, **Λ** -- Agricultural Products, **Ξ** -- Manufactured Products, **Π** -- Value of Commercial Products.

return effluent (T) back to the wastewater management system. That said, the end uses are differentiated by their products: fuel and agricultural, manufactured, and commercial products. From an economic policy lens, each of these products provide different value to a given region. And yet, from a sustainable development perspective, each of their activities share constrained input quantities (Δ, H, P & S) which must ultimately be shared.

1) Agriculture Facilities: In recent years, policy discussions on the energy-water nexus have expanded to include agricultural activities in what is often called the food-energy-water nexus. Agricultural products (Λ), most notably food, have an embedded energy and water intensity. Therefore, efforts to ensure domestic food security must be balanced by the capacity of the environment and infrastructure to provide these two quantities. Research on food-energy intensity has caused some to encourage policies that support local farming over long supply chains. Meanwhile, research on food-water intensity has often focused on the water inefficiencies of irrigation. Additionally, food-water *quality* discussions have supported greater use of non-potable water. Finally, biofuels are an important aspect of the food-energy-water nexus as they can often displace conventional fossil fuels be they domestically consumed or exported.

2) Manufacturing Facilities: Industrialization often features prominently within policy discussions to support economic development. The value associated with manufactured products (Ξ) is often significantly greater than its input quantities. That said, manufactured products vary tremendously in their energy and water intensities. For example, the recent trend towards gross domestic product diversification in the UAE has lead to investment in metals production. While steel and aluminum support the local construction industry and expand an additional export revenue stream, they have very high energy and water intensities. Complementary efforts to support industrial energy efficiency and management can help diminish these intensities. Furthermore, many industrial production facilities can directly support the use of non-potable water. Therefore, sustainable development policies recognize that the energy and water intensity of manufacturing must be balanced by the value of their products.

3) Commercial & Residential Facilities: The residential and commercial sectors include buildings such as homes and businesses and are differentiated by the the output of commercial (monetized) products (Π). Their energy consumption is dominated by heating, ventilation, and air conditioning (HVAC), lighting, water pumping, and electronic products. The first of these allows the choice of electrical or thermal energy

which also includes integrated solutions such district heating and cooling. Water consumption is required for drinking, bathing, flushing, laundry, & cooking. Of these, flushing can use non-potable water streams. Additionally, "grey water" from bathroom sinks, showers, tubs, and washing machines can be reused in agricultural activities. Note that the collectable wastewater (T) can therefore have multiple water qualities and piping. Finally, efficiency and management techniques have a high potential to reduce the overall consumption of energy and water.

4) Role of Trade: As mentioned previously, one essential aspect of the energy-water nexus reference architecture end use extension is that it is open to flows of energy and products with neighboring regions. Flows of water across borders are modeled implicitly within the natural surface environment. Moreover, these flows are assigned a monetary value as a consequence of their trade. Five such flows are identified: electricity import/export (Φ), fuel import/export (Θ), agricultural products (Λ), manufactured products (Ξ), and commercial products (Π). Together, they form income streams when exported across the system boundary and cost streams when imported. And because they have an embedded energy and water intensity, their trade effectively serves to offset energy and water demands placed on the infrastructure and environment. Additionally, their domestic usage presents an opportunity cost if not used as part of a downstream economic activity. The most pertinent example of this is found in food-energy-water nexus research where the domestic food sufficiency policy objective is balanced against its associated economic costs and environmental impacts.

IV. Conclusion and Future Work

In conclusion, this paper has revisited the recently developed energy-water nexus reference architecture in terms of physical trade-offs which may be leveraged as part of integrated energy-water planning and operations decisions. It then extended the architecture to include the sustainable development of agricultural, industrial, commercial and residential activities. The goal of the extension was related the economic value of fossil fuels, and agricultural, manufactured, and commercial products thus contributing a model capable of providing high-level guidance to the design of sustainable development policy. In such a way, infrastructure design and policy design can be coordinated and co-developed in parallel rather than sequentially. Future work will draw upon the growing energy-water nexus literature to further study each of the functions and interfaces in the architecture. This will serve to demonstrate the importance of a reference architecture and more generally of systems engineering in the energy-water nexus literature. While most studies either consider a small scope of interactions or are region specific, a reference architecture has the potential to provide a methodological foundation to this grand challenge. Finally, the end use architecture extension will be quantified just as the remainder of the architecture has in previous work [5], [8].

References

[1] US Department of Energy, "US Energy Sector Vulnerabilities to Climate Change and Extreme Weather," US Department of Energy, National Renewable Energy Laboratory, Washington, D.C., Tech. Rep., 2013.

[2] A. R. Hoffman, "The Connection: Water and Energy Security," *Energy Security*, no. March, pp. 1–6, 2012. [Online]. Available: http://www.iags.org/n0813043.htm

[3] G. Olssonn, *Water and Energy: Threats and Opportunities.* London: IWA Publishing, 2012.

[4] W. N. Lubega and A. M. Farid, "A reference system architecture for the energy-water nexus," *IEEE Systems Journal*, vol. PP, no. 99, pp. 1–11, 2014.

[5] ——, "Quantitative Engineering Systems Model & Analysis of the Energy-Water Nexus," *Applied Energy*, vol. 135, no. 1, pp. 142–157, 2014.

[6] A. Santhosh, A. M. Farid, and K. Youcef-Toumi, "The impact of storage facility capacity and ramping capabilities on the supply side of the energy-water nexus," *Energy*, vol. 66, no. 1, pp. 1–10, 2014.

[7] ——, "Real-time economic dispatch for the supply side of the energy-water nexus," *Applied Energy*, vol. 122, no. 1, pp. 42–52, 2014.

[8] W. N. Lubega and A. M. Farid, "An engineering systems model for the quantitative analysis of the energy-water nexus," in *Complex Systems Design & Management.* Paris, France: Springer Berlin Heidelberg, 2013, ch. 16, pp. 219–231.

[9] GAO, "Fresh water supply: States views of how federal agencies could help them meet the challenges of expected shortages," Tech. Rep., 2003.

[10] V. C. Tidwell, P. H. Kobos, L. Malczynski, G. Klise, W. E. Hart, and C. Castillo, "Decision support for integrated water- energy planning," SANDIA National Lab, Tech. Rep. October, 2009.

[11] S. Sattler, J. Macknick, D. Yates, F. Flores-Lopez, A. Lopez, and J. Rogers, "Linking electricity and water models to assess electricity choices at water-relevant scales," *Environmental Research Letters*, vol. 7, no. 4, p. 045804, Dec 2012.

[12] J. J. Macknick, R. Newmark, G. Heath, and K. Hallett, "A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies," National Renewable Energy Laboratory, Golden, CO, Tech. Rep. NREL/TP-6A20-5090, 2011.

[13] J. Macknick, R. Newmark, G. Heath, and K. C. Hallett, "Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature," *Environmental Research Letters*, vol. 7, no. 4, p. 045802, Dec 2012.

[14] B. Griffiths-Sattenspiel and W. Wilson, "The carbon footprint of water," River Network, Portland, OR, Tech. Rep., 2009.

[15] G. M. Thirlwell, C. A. Madramootoo, and I. W. Heathcote, "Energy-Water Nexus: Energy Use in the Municipal, Industrial, and Agricultural Water Sectors," in *Canada-US Water Conference*. Washington, D.C.: Policy Research Initiative of Canada and the Woodrow Wilson Institute, 2007, pp. 1–16. [Online]. Available: http://www.horizons.gc.ca/doclib/Thirlwell_energy_water_nexus.pdf

[16] EPA, "Cooling Water Intake Structures at Existing Facilities and Phase I Facilities," Washington DC, 2012. [Online]. Available: http://www.vnf.com/news-alerts-576.html

[17] DOE, "ENERGY DEMANDS ON WATER RESOURCES," US Department of Energy, Washington, D.C., Tech. Rep. NREL/TP-6A20-5090, 2006. [Online]. Available: http://www.sandia.gov/energy-water/congress_report.htm

[18] W. N. Lubega, A. Santhosh, A. M. Farid, and K. Youcef-Toumi, "Opportunities for integrated energy and water management in the gcc – a keynote paper," in *EU-GCC Renewable Energy Policy Experts' Workshop*, no. December, Masdar Institute, Abu Dhabi, UAE, 2013, pp. 1–33.

[19] W. N. Lubega and A. M. Farid, "An Engineering Systems Sensitivity Analysis Model for Holistic Energy-Water Nexus Planning," in *ASME 2014 Power Conference*, Baltimore, MD, 2014, pp. 1–10.

[20] A. Santhosh, A. M. Farid, and K. Youcef-Toumi, "Optimal Network Flow for the Supply Side of the Energy-Water Nexus," in *2013 IEEE International Workshop on Intelligent Energy Systems*, Vienna, Austria, 2013, pp. 1–6. [Online]. Available: http://dx.doi.org.libproxy.mit.edu/10.1109/IWIES.2013.6698578

[21] W. N. Lubega, A. Santhosh, A. M. Farid, and K. Youcef-Toumi, "An Integrated Energy and Water Market for the Supply Side of the Energy-Water Nexus in the Engineered Infrastructure," in *ASME 2014 Power Conference*, Baltimore, MD, 2014, pp. 1–11.