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Quantitative modeling of interconnections associated with sustainable food, energy and water (FEW) systems

Ebrahim Karan [a,*], Somayeh Asadi [b]

[a] Department of Applied Engineering, Safety, and Technology, Millersville University, Osburn Hall, PO Box 1002, 40 East Frederick Street, Millersville, PA 17551, USA
[b] Department of Architectural Engineering, Pennsylvania State University, 104 Engineering Unit A, University Park, PA 16802, USA

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ABSTRACT

The increasing costs of energy and water, fossil fuel depletion, and food shortages caused by climate change challenge long-term sustainability of food, energy, and water (FEW) systems. In working toward sustainable development, a fundamental question for deciding on whether and how to invest in FEW systems is “how sustainable FEW systems are?”. In order to measure sustainability across the FEW systems, an integrated sustainability index (SI) is developed. The SI is comprised of three components; food, energy, and water. These components each consist of different sub-components (e.g. transportation fuel for energy component) that make up integrated FEW systems. The sustainability of an FEW system can be calculated using the integrated FEW SI, but a more thought provoking question is to understand how each sub-component affects overall sustainability of the system. This cannot be achieved without formulating the interconnections associated with FEW components. This study formulates interconnections associated with FEW components. In an effort to increase the degree to which the results would generalize to FEW systems with different scales, the calculations of the study are performed for a sustainable FEW system that can consistently yield food for a family of four (two adults and two children) and supply its own water and energy needs from sustainable sources. Also, the sustainability is measured for two systems located in two different climates; one is relatively cloudy and humid and the other is sunny and arid. The results show that the highest sustainability improvement in both climates is associated with irrigation sub-component. Not only a sustainable water supply for irrigation sub-component improves the sustainability of water component, it also improves food sustainability and consequently energy sustainability. This finding can be explained by the fact that the irrigation sub-component is a resource supplier for grain sub-component, and that is a resource supplier for transportation fuel sub-component.

1. Introduction

The increasing costs of energy and water, fossil fuel depletion, and food shortages caused by climate change have left us with no choice but to accelerate the world’s transition to sustainability. In the coming decades, we are likely to see increasing pressure on the food, energy, and water (FEW) demands from increasing population and rising threat on the FEW supplies from climate change. As discussed in a recent report published by the International Renewable Energy Agency (IRENA), patterns of FEW systems are changing and the move to more sustainable supply systems may be inevitable (Ferroukhi et al., 2015). Increasing populations as well as resource scarcity challenge long-term FEW systems sustainability. Previously, many researchers had studied and analyzed sustainability across the FEW sectors in a fragmented and isolated way. Recent studies show that FEW systems are highly interconnected, and improving system function while ensuring sustainability cannot be borne by research on food, energy or water systems individually (Daher and Mohtar, 2015; Kurian, 2017; Larcom and van Gevelt, 2017). More nexus-wide research is needed to pursue both understanding the behavior of FEW systems and developing technological enablers necessary to improve the system performance.

A sustainable FEW system is defined as a system that can

* Corresponding author.
E-mail addresses: ebrahim.karan@millersville.edu (E. Karan), asadi@engr.psu.edu (S. Asadi).

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consistently meet its food, energy, and water demands with sustainable inputs rather than using non-renewable sources. A food production system can be sustainable if it relies on renewable water and energy technologies. Collecting water from precipitation, recycling wastewater, and desalinating seawater are the most sustainable methods of water supply. Renewable energy sources such as solar, wind, biogas, and geothermal are considered as sustainable sources of energy. Measuring sustainability across FEW systems is difficult because interactions between FEW sectors are complex and not fully understood and the metrics such as indicators, indexes, and benchmarks are still evolving.

Over the past years, many researchers and organizations have recognized the importance of sustainability and realized that unless they measure sustainability they do not know if it is getting better or worse. They have been striving to develop a comprehensive set of metrics, scorecards, ratings, and tools for measuring and tracking sustainability. The formal development of sustainability metrics began in 2001 with the United Nation (UN)'s Commission on Sustainable Development that published a list of about 140 indicators to cover economic, environmental, institutional, and social aspects of sustainable development (UN, 2001). Perhaps the most relevant sustainability indicators to the FEW nexus are composite or aggregate indicators that represent one single comparable index for the evaluation of a multitude of aspects. Krajnc and Glavic (2005) developed a standardized composite sustainable development index to track integrated information on economic, environmental, and social performance of the company with time. Willis et al. (2016) developed an integrated FEW index that is comprised of three sub-indices; one each for food, energy, and water. Each sub-index is comprised of two or more indicators reflecting dimensions related to availability and accessibility. Although previous efforts have paved the way for the assessment and modeling of FEW nexus, but they relatively present calculations for the two-sector linkages (e.g. energy-water or food-water). As discussed by Chang et al. (2016), the comparability of different sustainability metrics needs to be further improved by integrating and harmonizing FEW system boundaries, definitions, and methodologies adopted for quantification.

The objective of this paper is to formulate interconnections associated with FEW components. Food, energy, and water components each consist of different sub-components (e.g. transportation fuel for energy component) that make up integrated FEW systems. The proposed formulation is independent of the system scale, although it is solved with United States (U.S.) population data (which is over 323 million at the time of the study) to demonstrate its applicability to large-scale FEW systems. The scale of FEW systems can be as small as a greenhouse and as large as a city or a country. In an effort to increase the degree to which our results would generalize to FEW systems with different scales, the calculations of the study are performed for a sustainable FEW system that can consistently yield food for a family of four (two adults and two children) and supply its own water and energy needs from sustainable sources. This typical household family also allows us to better understand the dynamics among the nexus.

Fig. 1 shows integrated FEW systems, their components and sub-components in this study. Interconnections within the integrated FEW systems are shown by connecting lines and interactions with built environments by self-loop back to the FEW sub-components (e.g., electricity consumption in the residential sector, not associated with food or water). In Fig. 1, numbers above each line refer to the quantity of the resource supplied from a sub-component. They are normalized and weighted by total energy (measured in kWh or Btu), water (measured in lit or gallon), and food (measured in kg or pound) consumptions at the national level (EIA, 2017b; Maupin et al., 2014; USGS, 2010). We might use these

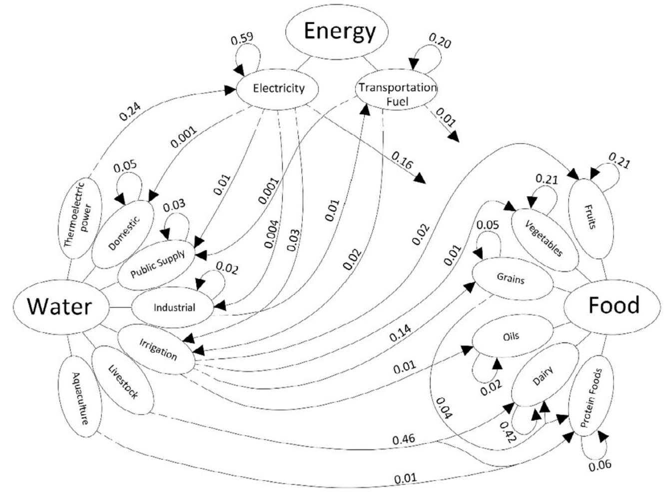

Fig. 1. Interconnections associated with FEW Systems.

quantities to gauge the relative importance of each sub-component in a FEW system but we are not able to understand how each sub-component affects overall sustainability of the system. Using the results of this study, we will update these numbers with contribution of each sub-component on the overall sustainability of the system.

The paper is structured as follows. After this introduction, the next section describes how sustainability of FEW systems is measured. This is followed by a description of the research method and explanations of sustainability indices for FEW components and FEW nexus. Calculations of the sustainability indices for food, energy, and water components for two systems located in two different climates are then presented. Finally, a summary and the conclusion of the paper are presented.

2. Methods and materials

The challenge of understanding FEW policy interactions, and addressing them in an integrated manner, appears daunting. Given the interconnections between FEW resources, a holistic approach to understanding the state of these resources can improve economic efficiency, resource efficiency, population livelihood, and public health. The first step toward developing integrated FEW system modeling is to quantify these interconnections. Metrics can help to formulate them and to measure key facets of sustainability, enabling us to make decisions about how best to become more sustainable. This section presents a novel framework for such a support tool.

As seen in Fig. 1, the FEW sub-components exist in many different forms. To deal with this inconsistency and to ensure the ultimate goal of system sustainability, we define an index to compare the impact of each decision variable on the system's output. Although decision variables may appear to be quite different with respect to FEW sub-components (e.g. what to plant, size of solar system, decisions regarding water treatment method), but their impact on the sustainability of the FEW system can be measured and compared by the cost of achieving sustainability across the FEW system. A metric is needed to investigate the relationship between the sustainability and cost. This cannot be achieved without formulating the interconnections associated with FEW components. A sustainability index (SI) is defined as the probability of meeting food, energy, or water demand as follows: