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Toward quantitative analysis of water-energy-urban-climate nexus for urban adaptation planning

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Water and energy are two interwoven factors affecting environmental management and urban development planning. Meanwhile, rapid urban development and a changing climate exacerbate the magnitude and effects of water-energy interactions in what a nexus defines. These factors and their mutual interactions affect how we evaluate urban developmental alternatives. In this perspective, a few pressing issues and a systems approach are discussed for quantitative analysis of the water-energy-climate-urban nexus in climate change mitigation and adaptation.

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Introduction

Various terminologies and definitions for the water-energy nexus have been used. We have adopted the distinction Velázquez *et al.* [1] made on production versus consumption, and then can discuss the energy-water nexus in relation to the environmental, societal, and economic pillars of sustainability. First, energy and water in the resource dimension are constraints to the socio-economic development. Their productions can impact environmental quality (Figure 1), and as a consequence, regulations are promulgated to avoid and manage adverse impacts. Second, adequate energy and water supply are the primary focus in urban development and operation for a desired socioeconomic outcome. The consumption also can lead to environmental impact (Figure 1), thus generating additional resource constraints to socioeconomic development. In the context of these interactions, variations of water-energy related nexus have been defined and discussed. Examples include the water-energy-climate-land and the water-energy-food nexus within the resource and the socioeconomic dimensions, respectively.

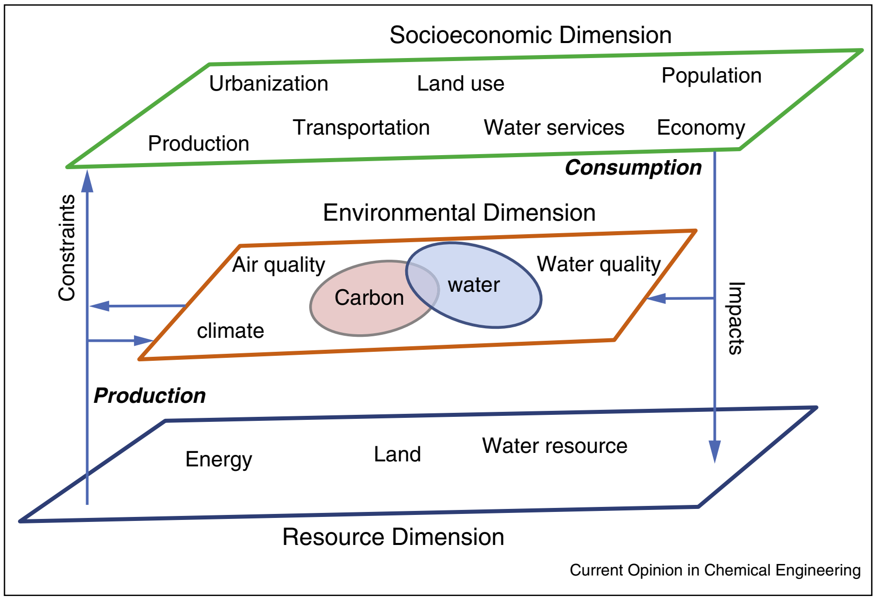
This perspective highlights several pressing issues in quantitative analysis of the water-energy-climate-urban nexus. It further points to a systems approach necessary for climate change adaptation planning and engineering in urban areas.

The nexus defined

By definition, a water-energy-urban-climate nexus analysis aims to reveal the water-energy interactions within the context of urban development and climate changes (Figure 1). The water and energy interactions have been extensively investigated across geographic regions, for industrial and transportation sectors, for a capital improvement project, and for unit processes (e.g., [2–7]); many without explicit consideration of climate impacts. The two forms of resources are mutually dependent in their production and consumption within the current social policy and energy framework. For example, water treatment and management consumes ~3–5% of energy produced in the U.S. and ~10% in the world ([2,3,8,9], references therein). Energy consumption rate is greater for long-distance water transfer, water desalination, in treatment of polluted source water, or for poorly managed storm water and wastewater systems. Water is also an energy carrier. Around 15% of total global water withdrawal is for power generation, the second largest behind 67% for agricultural productions [8–10]. Water usage in the U.S. for power generation is higher, followed by those in agricultural production [11]. Furthermore, biomass production, bioenergy generation and transport through electric grids also can be viewed as redistribution of the water resource across hydrological basins [6].

Climate change alters the resource boundary condition in a water-energy nexus analysis. In May 2013, global CO_2 atmospheric concentration exceeded 400 ppmv for the first time in several hundreds of millennium years. The greenhouse gas (GHG) emission expressed as CO_2 equivalent (CO_2-eq) increased from 27.9 to 50.1 Gt/yr in 40 years (1970–2010), and the GHG emission trend is very likely to increase global temperature by 3.6–5.3 °C within this century [8,9]. The changing climate can potentially change water availability and energy consumption in urban activities, including water production and management. Societal response through mitigation and adaptation can also change future GHG emission, resulting in a climate response and creating a new set of environmental conditions [12,13]. For instance, a future energy portfolio responding to the need in climate mitigation is

Figure 1



Schematic illustration of the water-energy nexus in relation to the resource, environmental, and socioeconomic dimensions. Solid arrow indicates direction of impacts.

moving toward low-carbon but more water-intensive forms of energy. In particular, biomass-based energy is expected to increase by 215% in 25 years to 4.1 million barrel oil equivalent per day by 2035 [9]. The corn-based ethanol renewable fuel standards in the U.S. alone would lead to an increase of water withdrawal in 2050–2059 by 10% for biomass production. The increase is largely a result of the ~1% evapotranspiration increase and ~7% crop yield decrease [14]. Mitigation and adaptation impact on water resources is particularly significant in the water-stressed regions [15,16,2].

Rapid urbanization and urban redevelopment are other significant variables within the socioeconomic dimension (Figure 1). International Energy Agency (IEA) [8] predicted a one-third increase of total energy usage in 24 years from 2011 to 2035, a slight decrease in reliance on fossil fuel energy, and a decisive shift in energy consumption toward Asian developing nations. These changes are primarily related to urban centers that only occupy ~2% of land area on Earth, but account for 70% of global energy consumption and GHG emission [17•,18,8,9]. Many of these centers are located in water-stressed areas and in low-flight coastal regions vulnerable to meteorological extreme events and sea level rise. Furthermore, urban population will reach 6.3 billion by 2050 from 3.4 billion in 2009 [15], an increase that will lead to an even greater urban contribution to global emissions. Worth noting, however, that because of the higher population density in urban centers, emission intensity and water consumption rate on a per capita basis is mostly lower than national averages [18,19••]. For these intertwining factors, the shifting of energy and water consumption into high-density urban centers creates a location-specific socioeconomic dynamics challenging future water-energy management. It also offers opportunities to reduce per capita emission rate, and thus the total global emission growth [19••]. Further decreases in per capita carbon and water intensity are possible depending on the design and implementation of effective urban planning and adaptation action, as discussed in subsequent sections.

In addition, the compounding effects of the interactions between climate change and urbanization are significant; such effects cannot be neglected in the nexus analysis. Through integrated systems modeling, several studies have identified the compounding effects on water quality and availability in urban watersheds [20,21], urban water demand, the variability of local climate, and traffic-origin short-life climate forcers (SLCFs) such as black carbon [22,23,24•,25]. U.S. EPA [26,27] published projections of future land use, housing and population in the contiguous U.S., using the integrated climate and land use scenario (ICLUS) simulations for the base, A1 and A2 emission storylines. Studies using ICLUS [28••,29] have shown that large land use changes and mega metropolitan development may jointly change climate warming trends, temperature hot-spots in the U.S., and summer-time precipitation distributions.

The nexus analysis in climate mitigation and adaptation

Climate change mitigation and adaptation have been discussed extensively in recent decades. IEA [9] developed