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Sensor technologies for the energy-water nexus – A review

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ABSTRACT

In this paper, a comprehensive review of the sensing technologies, capabilities and requirements in the energy-water nexus is presented considering the interdependence of variables in the interconnected energy and water sectors. Conventional sensor technologies that are used in the energy and water sectors of today are critiqued from the perspectives of accuracy, weight, volume, power consumption, commercial availability, data storage capabilities, ability to communicate with established electronic interfaces and portability of operation for remote sensing. The impacts of having multiple parameters, indefinite variables and/or unresolved dependencies in sensing energy usage for water applications and in sensing water usage for energy applications have been investigated. The paper also reviews innovative research developments on sensor technologies in the energy-water nexus that are based on bio-technology, nanotechnology and wireless networks and that could possibly resolve sensing challenges such as the interdependencies of variables in the energy-water nexus. In addition, a network of sensor technologies that are most appropriate to each sector in the nexus is presented to improve the operational efficiency of the energy-water nexus.

1. Introduction

The interconnection between energy and water is increasingly being highlighted in recent literature. This is because scientists, policy makers and resource managers are realizing that with climate uncertainties and growing demands, these two essential resources can no longer be viewed independently. A thorough understanding and assessment of their interdependency must be considered to sustain global water and energy security.

There is no question that several fields of research are required to enhance sustainability in the energy-water nexus, and advancing sensor technologies is just one of them. The need for better, low-cost sensors was highlighted during a 2016 White House Water Summit [1], and in Department of Energy's (DOE) Water-Energy Nexus report [2]. However, a comprehensive review on the topic is yet to be conducted. The general targets of sensor technologies in the energy-water nexus revolve around increasing the efficiency and resilience of various production and treatment processes, reducing water and energy losses from industrial, agricultural and residential uses, and harvesting the loss of energy from water and energy related operations. The DOE has set a strategy for addressing challenges across the energy-water nexus through six primary targets outlined in its report [2]:

1. *Optimize the freshwater efficiency of energy production, electricity generation, and end use systems.*
2. *Optimize the energy efficiency of water management, treatment, distribution, and end use systems.*
3. *Enhance the reliability and resilience of energy and water systems.*
4. *Increase safe and productive use of non-traditional water sources.*
5. *Promote responsible energy operations with respect to water quality, ecosystem, and seismic impacts.*
6. *Exploit productive synergies among water and energy systems.*

The first and the second targets focus on optimizing the water usage efficiency for energy production, electricity generation and end use, and optimizing the energy usage efficiency for water management, treatment, distribution and end use. Considering thermoelectric power generation as an example related to the first target, in the United States alone, total withdrawals for thermoelectric power accounted for 45 percent of total water withdrawals, 38 percent of total freshwater withdrawals, and 51 percent of fresh surface-water withdrawals for all uses in 2010 [3]. Total water withdrawals for thermoelectric power were 161,000 million of gallons of water used per day (Mgal/d), 99 percent of which was withdrawn from surface water sources, predominantly freshwater. Related to the second target, electricity consumption by public drinking water and wastewater utilities for pumping, conveyance, treatment, distribution, and discharge was 56.6 billion kWh, or 11.5% of primary energy and 21.6% of electricity consumption for

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water end use, respectively in 2009 [4]. By 2016, the energy used for water treatment was more than 100 million kWh per day, an increase of 30% from 1996 levels [5]. Moreover, wastewater treatment plants and drinking water plants accounted for 3–4% of energy use in the US [6]. There are several opportunities to increase the efficiency of these processes, which will require advanced sensor technologies, as well as the identification of alternative freshwater and energy sources.

The third target is related to enhancing the reliability and resilience of existing energy and water systems. Both water and energy infrastructure in the United States are aging, and could therefore create vulnerabilities and increase operational risks. However, effective use of sensors could reduce these risks, and help with assessing vulnerabilities in existing infrastructure. For example, smart sensors could be used to identify vulnerabilities and risks of energy and water operations. In addition, networks of remote, automated sensors could help in prioritizing repairs to aging energy and water infrastructure [2].

The fourth target is related to the safety and productive use of non-traditional water sources. It addresses the use of non-conventional water sources, such as domestic wastewater, seawater, and brackish groundwater, for energy production. Though this is already being implemented, a more widespread acceptance of non-traditional water sources might increase by developing low-cost, in-situ sensors that are capable of monitoring the water quality.

The fourth target is also related to the beneficial reuse of water produced during oil and gas extraction. Produced water that is trapped in underground formations and which is brought to the surface along with oil or gas extraction is by far the largest volume byproduct or waste stream associated with oil and gas exploration and production [7]. Around 21 billion barrels (bbl) (1 bbl equals 42 U.S. gallons) of produced water are generated each year in the United States from close to 1 million actively producing wells. This represents about 57 million bbl/day, 2.4 billion gallons/day, or 913,000 m^3/day [7]. However, the details on the generation and management of produced water are not very well understood on a national scale [8]. More than 50 billion bbl of produced water are generated each year at thousands of wells in other countries. Based on the ratio of water-to-oil volume, the worldwide average estimate is from 2:1 to 3:1, while the U.S. estimate is 5.1 to 8:1 [7].

Measuring the accurate water production during oil and gas extraction is challenging because the amount of produced water is variable during the life span of an oil well. For example, early in the life of an oil well, the oil production is high and water production is low, whereas over time, the oil production decreases and the water production increases [7]. Since many U.S. fields are mature and past their peak production, many older U.S. wells have produced water to oil ratios that could be around 50:1. The produced water to oil volumetric ratio may be even higher as water is not always measured directly using conventional sensor technologies [7,8].

The fifth target is related to responsible energy operations with respect to water quality, ecosystem, and seismic impacts. It highlights the various impacts energy operations could have on water quality and aquatic ecosystems. In these areas, innovative sensor technologies and developments are required to measure the exact impact and to raise the public awareness.

The sixth target is related to exploiting productive interactions among water and energy systems. It addresses forming co-operations between the water and energy systems, such as using the energy system's waste products for water related operations, or extracting energy from waste products from water related operations.

Each of the outlined targets requires the investigation of numerous variables in the energy-water nexus that could be used to measure the efficiency of energy and water usage and related losses in conventional and emerging technologies. A careful investigation of each of the variables could enable the development and implementation of advanced sensing techniques and modern and accurate sensor technologies that could measure not only a few of the variables, but could also reveal the interdependence of variables across various sectors in the energy-water nexus. In addition, the efficiency improvement of the various sectors will require multi-sensor platforms whose practical implementation will need a careful consideration in both energy and water sectors. The impact of the research on sensor technologies could go up to assessing the health of the ecosystem and evaluating if there are quantifiable effects of climate change on water availability and energy production Therefore, this review of sensor technologies will play a critical role in addressing the sensing related challenges across the energy-water nexus and could potentially indicate future prospects in fields that are closely related to the energy-water nexus.

2. Objective of the review paper

The objective of this review paper is to provide a critical overview on the state of the art, research gaps and future research directions in sensor technologies for the energy-water nexus. Existing sensor capabilities are reviewed in Section 3, whereas the sensor requirements in the nexus are identified in Section 4. In addition, sensor research directions with merit are indicated in Section 5.

3. Sensing capabilities in the energy – water nexus

A timeline of existing sensor technologies whose developments are most related to the energy-water nexus is presented in Fig. 1. The figure shows sensor developments as early as the 1600s and reviews the progress that has followed from that time. The sensor technologies indicated in the timeline include (1) thermometers invented in 1612 [9], (2) mass flow meters invented in 1835 [10], (3) photometers invented in 1861 [11], (4) surface acoustic wave sensors invented in 1885 [12], (5) thermostats invented in 1883 [13], (6) pressure transducers invented in the 1930s [14], (7) tensiometers invented in 1908 and their application developed in the 1920s [15], (8) resistance-bridge type accelerometers invented in 1923 [16], (9) polarographic sensors originated in 1922 [17], (10) optical sensors for dissolved oxygen (DO) first developed in 1931 [18], (11) biosensors invented in 1956 [19], (12) piezoelectric based sensors invented in 1880 [20], (13) proximity switches invented in 1958 [21], (14) fiber optic sensors patented in the mid-1960s [22], (14) chemi-resistors invented in 1985 [23], (15) humidity sensors invented in 1973 [24], (16) optical nano-sensors invented in 1996 [25], (17) biosensors in analogy to the definition of chemo-sensors introduced by IUPAC in 1997 [26], (18) synthetic nano-sensors developed in 1999 [27], (19) spectroscopy based nanotechnology and (20) wireless sensor networks that are being used for collaborative and real time sensing applications in the 21st century. Considering the wide ranges of sensing technologies in the energy-water nexus, a classification scheme has deemed necessary to identify the energy-water nexus into various sectors, which could then be used as a relevant approach to group the sensing capabilities and requirements in the nexus.

There are various schemes to classify the energy-water nexus into sectors. In this review paper, a classification scheme is used that identifies sectors where energy is used for water application, sectors where water is used for energy application, and a sector where energy and water are used for agriculture. Based on this classification, ten distinctive sectors have been identified in the

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