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Managing the energy-water-food nexus for sustainable development

1. Nexus approach to address the close linkages between energy, water and food

Energy, water and food are all basic human needs. The three are intricately related. For example, globally, food production accounts for about 70% of water abstractions and 90% of water consumption, respectively [1]. In 2014, primary energy production and power generation accounted for roughly 10% of total worldwide water abstractions [2]. About 30% of global energy use is for food production and its supply chain [3], and 8% for water withdrawal and transportation, and sewage treatment [4].

Due to the close linkages between energy, water and food, a nexus approach has been a main research topic in recent years and becomes a global concern [5–7]. Researchers often use different terms to refer to the nexus: while energy experts speak of the energy-water-food (EWF) nexus, hydrologists often say water-energy-food (WEF) nexus, and agronomists may like to use food-energy-water (FEW). We consider all these terms have the same meaning.

A milestone event for the EWF nexus research was the Water-Energy-Food Security Nexus Conference hold in Bonn, Germany, in 2011, which started using the nexus terminology for the first time [8]. The Bonn conference concluded that securing food, energy and water supply are intricately related. A comprehensive insight into the EWF nexus is key to developing a better understanding of the relationships among the three elements, and providing comprehensive strategies for sustainable solutions [9]. This conference also concluded that a multidisciplinary approach should be used to understand the EWF nexus.

Since the Bonn conference, the nexus research has drawn increasing global concerns. In 2013, the United Nations Economic and Social Commission for Asia and the Pacific released the report *Water-Food-Energy Nexus in Asia and the Pacific Region* [10]. In 2014, the Food and Agriculture Organization of the United Nations illustrated the nexus from a food-security perspective and suggested that the nexus should be treated as a reference for policy making on food security and agricultural sustainable development [11]. Future Earth (2014–2023), a ten-year scientific project initiated by the International Science Council and the International Social Science Council, set up a unique knowledge-action network (http://www.futureearth.org/future-earth-water-energy-food-nexus) on the EWF nexus to advance our scientific understanding and derive implications for efficient and sustainable resources use. The Scientific Decade 2013–2022 of the International Association of Hydrological Sciences (IAHS) organized *Panta Rhei* opinion paper series, and invited experts to contribute to the key topic of the EWF [12].

2. Future challenges on energy, water and food security

Global energy consumption is projected to increase by 48% between 2012 and 2040 [2]. Water demand is expected to rise by 50% and 18% between 2007 and 2025 in the developing and developed countries, respectively [13]. With continuous population increase and economic growth, challenges on securing sufficient energy, water, and food supplies to meet the demand are also amplifying. The close linkages between the three sectors give rise to the need for tackling the challenges with a nexus approach. Information shared and interpreted jointly between these three sectors is important for better understanding the complexity of links and tradeoffs and developing integrated policy. The study and discussion of concepts, research methods, technological and socio-economic innovations, and policy strategies to address the nexus are needed to facilitate this understanding and develop effective responses. Furthermore, energy, water and food security cannot be analyzed without considering their relation to changing consumption patterns, global trade, climate change, resource limitations, and governance issues [14].

3. This special issue

This special issue provides latest research on the EWF nexus and identifies gaps that remain. It includes theoretical, methodological and empirical research papers on the relevant issues in science, technology and policy. The issue aims to provide in-depth thoughts about managing the EWF nexus for sustainable development and includes 24 papers. The papers can be grouped into four topics:

(1) Trends and tools in the nexus approach;
(2) Nexus framework and governance;
(3) Future clean energy technologies and systems under water and food constraints;
(4) Implementation and best practices.

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3.1. Trends and tools in the nexus approach

Schlör et al. [15] develop the Nexus City Index to assess the EWF nexus in 69 cities around the world. The authors demonstrate that this index enables decision makers to consider city resilience without ignoring the food, energy and water systems. Dai et al. [16] review methods and tools for macro-assessment in the field of the water-energy nexus, based on an extensive survey of scientific literature over the past decade. The authors find that the number of water-energy nexus studies has significantly increased, while the capacity of the scientific community to productively assess water and energy inter-linkages at a higher resolution improved as well. They also find that several studies intend to develop new methods and frameworks to simulate interactions between water, energy and other elements, but limited studies provide a singular framework for it. They also find many studies are at the stage of quantitative analysis while fewer studies are designed to support governance and implementation of solutions. This work reveals that there is an imperative need to improve our ability to classify and compare the capacities, strengths and weaknesses between existing approaches, to improve their beneficial use in improving the management of water and energy resources. Bertone et al. [17] develop a coupled Bayesian Network-System Dynamics model to assess the likely influence of novel financing options and procurement procedures on public building retrofit outcomes scenarios. As a showcase they use the case of Australian public hospitals. The authors find that a revolving loan fund supporting an energy performance contracting procurement procedure was preferred and the specific features of this preferred framework could be optimized to yield the greatest number of viable retrofit projects over the long term. This study provides evidence-based support to policy-makers advocating novel financing and procurement models for addressing a government's sustainability agenda in a financially responsible and net-positive manner. Kan et al. [18] develop a new parallel SCE-UA algorithm based on the original serial SCE-UA algorithm for parameter estimation of a water quantity simulation and forecasting model. Both the newly developed parallel SCE-UA and serial SCE-UA were implemented on the novel heterogeneous computing hardware and software systems with the Griewank benchmark function optimization and a real world IHACRES RR hydrological model parameter optimization. The authors find that parallel SCE-UA outperforms the serial one and can dramatically improve the computational efficiency for model parameter calibration. This advanced parameter calibration algorithm helps us solving EWF nexus issues with high computational efficiency. Logan and Stillwell [19] develop an adaptable and novel method to incorporate freshwater ecosystems into the energy-water nexus and quantify thermal pollution and the risk posed to aquatic species. The proposed method is demonstrated in an application for the Shawnee Fossil Plant on the Ohio River. The authors find that both the lateral and longitudinal location from the point of effluent mixing within the river affects the risk to aquatic species. This study helps decision-makers to identify and effectively assess tradeoffs between power generation and ecosystems sustainability. Abegaz et al. [20] provide a critical overview of research gaps, the state of the art and future research directions in sensor technology for the energy-water nexus by considering the sensor techniques, capabilities and requirements while bearing in mind the nature of the interconnection between the energy and water sectors. The authors find that conventional sensor techniques have shortcomings in many ways, including e.g. accuracy, weight, volume and power consumption. They also find that innovative researches are mainly focused on bio-technology, nano-technology and wireless networks. This study plays a critical role in addressing sensor-related challenges and shows future prospects in energy-water nexus research. Nguyen Huu et al. [21] develop a new approach of using an electrochemical deposition process to fabricate self-endurance flexible thermoelectric generators. The authors integrate the thermoelectric materials inside self-endurance flexible structures for the first time and use lateral Y-type TE cells to replace the conventional vertical p-type cells to enhance the performance of the temperature harvest. They find that the fabricated new device can generate approximately 3 $\mu W/cm^2$ of output power density given a human body temperature of approximately 37 °C and ambient temperature of 15 °C. This study promotes the development of wearable electronic devices that could be used for instance in biosensors, health care instruments, and mobile devices.

3.2. Nexus framework and governance

Parkinson et al. [22] present a multi-criteria framework for energy and water planning. The authors apply this framework for Saudi Arabia to explore preferences combining aspiration and reservation levels in terms of cost, water sustainability and CO_2 emissions. They find that potential integrated system configurations remain relatively ambitious from both an economic and environmental perspective. The cost saving identified by the authors may impact the affordability of water and electricity services. Ziv et al. [23] develop a model of the EWF nexus using fuzzy cognitive mapping (FCM) to investigate the potential impact of Brexit (i.e. United Kingdom departing from the European Union) on the energy, water and food nexus in the UK. The model is demonstrated by applying the FCM in analyzing four Brexit scenarios. They find that the demand for energy will decline relatively less than other services and strongly associates with gross domestic product (GDP). Changes in population will have the strongest effect on water and food demand. Khan et al. [24] analyze the spatial and temporal synchronization of water and energy systems with the consideration of the inherent link between these two systems. The authors develop a new, fully coupled water-energy optimization model that can hard-link the two systems in detail across spatial and temporal scales, thus tracking processes in each individual system throughout the life-cycle of each resource (water and energy) and analyzing the two resources simultaneously. The proposed coupled model is demonstrated in an example case study for Spain. This model is capable for investigation of various cross-sector issues and policies and provides great convenience for resources security assessment in the future. Fuentes-Cortés et al. [25] propose a new approach based on scalarization techniques to control the environmental impact of water usage and total direct greenhouse gas emissions in energy systems. The new method aims to find marginal prices for water and carbon emission that push systems to operate at optimal compromise solutions and is illustrated by using a case study that considers a combined heat and power (CHP) system providing hot water and electricity to a residential housing complex. The authors find that to achieve an optimal compromise between cost, water, and emissions in CHP systems, emission prices must be increased by a factor 14 and water prices by a factor 217. They also find that different resource valuation policies need to be considered to better capture system-specific trade-offs. The newly developed approach can provide better guidance for stakeholders to identify more effective incentive-based environmental protection instruments.

3.3. Future clean energy technologies and systems under water and food constraints

Shine et al. [26] apply a detailed statistical analysis for electricity and direct water consumption on 58 pasture-based commercial dairy farms in Ireland. They find that the electricity consumption largely associates with milk production, herd size (total number of dairy cows) and the number of lactating cows, while the water consumption correlates, but with less magnitude, to herd size and the number of lactating cows. This study investigates the key drivers of electricity and water consumption and facilitates the development of predictive and optimization approaches for electricity and water consumption in dairy farms. Lubega and Stillwell [27] develop a method for creating grid-scale operational policies for thermal power plants that consider the necessary factors, such as minimal thermal variances, electricity reliability, and maximum permissible water temperature increases for aquatic ecosystems. The method is illustrated by studying a representative electricity grid model under different hydrological drought and heat wave conditions in Illinois, USA. Optimal rules for thermal power plant operational policies are determined through a linear optimization method with stochastic costs. The developed method can facilitate cooperative decision making between environmental agencies, power grid operators, and power plant operators. White et al., [28] apply a transnational inter-regional input-output approach to analyze the EWF nexus in East Asia. The authors demonstrate a mismatch between regional water-energy-food availability and final resource consumption. For instance, China's trade in low value added and pollution intensive sectors uses a large amount of water, energy and food to satisfy the commodity demand of Japan and South Korea. Resource-scarce countries need to re-consider their economic development patterns for food and environmental security. Gjorgiev and Sansavini [29] establish a water-energy nexus platform to assess the energy conversion capability of a large thermal power plant under different climate conditions using different cooling techniques (i.e. once-through cooling and wet tower cooling). The impacts of water policy constraints on electrical power generation in different climate conditions are quantified and the benefits of water resource smart scheduling are identified for drought scenarios. The authors find that flexibility in the water policy constraints could help for energy generation efficiency during extreme drought conditions. This study provides implications for water policy scheduling under climate change. Zhong et al. [30] investigate the impacts of a certain land use change, i.e. producing switchgrass for cellulosic ethanol, on feedstock cost of bioenergy production and local water quality. The authors find that in west Tennessee, USA, hay/pasture lands are the preferred sources of agricultural land for conversion to switchgrass production when giving most weight to the costs, while converting corn fields to switchgrass production reduces the grey water footprint the most. This study provides the local bioenergy sector a management strategy associated with land use choices for the supply of energy crops.

3.4. Implementation and best practices

Walsh et al. [31] evaluate the financial tradeoffs for different processing strategies that produce food and fuel from algae. The authors demonstrate that the greatest returns are achieved when algal biomass is valorized as a high value fishmeal replacement. They also point out that mode selection is largely affected by output product prices when the prices for food and energy are competitive. This study provides an approach for evaluating financial tradeoffs in the food-energy nexus under different market conditions. Gaudard et al. [32] investigate the seasonal patterns and changes of the energy-water nexus with a case study of a run-of-the-river hydropower plant in Italy. The authors integrate a hydrological model, a hydropower model, two glacier inventories, six climate scenarios and five electricity price seasonal scenarios to simulate and quantify the effect of changes in price and water seasonality on future revenue distribution and its related uncertainty. This study highlights the need for considering intra-annual dynamics when investigating the energy-water nexus. Peer and Sanders [33] analyze the water consequences of transitions in the power sector in the US, e.g. energy generation from coal-fired steam to natural-gas combined cycle units, from once-through cooling to wet recirculating towers and dry cooling systems, and from traditional fresh and saline surface cooling water to reclaimed water and groundwater sources. The authors use power plant-specific fuel consumption, generation, and cooling water use data to assess changes in the water withdrawn and consumed by thermoelectric power plants across 8-digit Hydrologic Unit Code (HUC-8) watersheds between 2008 and 2014. They find that the total cooling water withdrawal and consumption volumes as well as the average water withdrawn per unit of electrical output decreased over this period. They also find that some water-scarce regions experienced increases in cooling water usage, while most of the regions experienced significant water reductions and environmental benefits, especially where coal-fired generation was retired or retrofitted. This study emphasizes the importance of evaluating water withdrawal and consumption at local spatial scales, given local differences in how water extraction and water quality changes from power plants affect downstream users. Srinivasan et al. [34] investigate water withdrawal and consumption for electricity generation in India by using a multi-model approach. Five energy-economic models are used to simulate the energy-water interactions historically and also in future projections with harmonized assumptions regarding economic and population growth, the distribution of power plants by cooling technologies, and water withdrawal and consumption intensities. The authors find that water withdrawal and consumption can be reduced by focusing on wind and solar power but will be increased by a focus on nuclear power. They also find that an expansion of hydroelectric power could increase consumptive water losses through the evaporation from the reservoirs. This study provides the implications of economic growth, power plant cooling policies, and carbon emission reductions on water withdrawals and consumption. Molinos-Senante and Guzmán [35] estimate the shadow prices of CO_2 emissions associated with energy consumption for the first time in drinking water treatment plants (DWTPs). The authors find that the average shadow price of CO_2 for DWTPs is 5.7% of the drinking water price. They identify potential reduction of CO_2 emissions and the factors that affect the shadow price of CO_2 emissions from DWTPs. This study provides crucial information that is fundamental to support environmental policy. Owen et al. [36] apply an input-output model to investigate the interaction between the energy, water and foods impacts of products through the complete supply chain. The authors analyze the twenty most important supply chains in the UK and estimate the energy, water and food impacts of demand-side strategies and resource efficiency policies. The environmental impacts of energy, water and food are quantified by using structural path techniques. This study provides a novel contribution and implications to both nexus research and environmental accounting. Shang et al. [37] use two modeling methods, i.e. routine and optimal operations, to investigate the potential of power generation of cascade hydropower station clusters on economic benefits. The models are applied for the largest mixed cascade hydropower generation system in the world, which is located in China. The authors find that there was little room for improvement in hydropower generation with current operation rules, while a joint operation could increase hydropower generation to a certain level. This study provides implications for large mixed cascade hydropower station operation strategy. Lee et al. [38] evaluate the regional water consumption factors for thermal and hydro-electricity generation in detail in the United States. The authors find that water consumption factors for electricity generation show strong spatial variability, depending on water availability in each region, and that the water consumption of hydropower (16.8 L/kWh) is much larger than for thermoelectricity (1.25 L/kWh). This study is valuable for comprehensive life-cycle analysis of water consumption for various pathways that use electricity, which is a subject for future water-energy nexus research and analysis.

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