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Development and application of integrative modeling tools in support of food-energy-water nexus planning—a research agenda

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Abstract This paper outlines a research agenda on the development of analytical tools to support the analysis of integrated food, energy, and water (FEW) systems. The thrust of this agenda is on increasing awareness and building capacity on interdisciplinary data and mathematical modeling toward integrated planning and identification/evaluation of trade-offs and synergies in developing such systems. The research agenda consists of development of principles, algorithms, and model formulations for understanding and evaluating the potential of implementing FEW nexus approaches within a systems perspective. The proposed agenda also stresses the need for integrating areas of disciplinary expertise, the ability to identify and address shared needs of FEW stakeholders, and facilitating tailored analyses over different geographical regions and temporal scales. Outputs and products of this research are quantitative tools that focus on upstream sector planning in order to identify primary opportunities and constraints to food, energy, and water system development, indicating priorities for more detailed analysis as well as providing characterization of alternative system configuration that meet integrated FEW objectives. This research agenda should also result in an improved understanding of economic and social trade-offs among competing FEW priorities; responses to the research questions contained in this agenda are bound to support decision-making in integrated FEW system planning and particularly prioritization of FEW investments.

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Introduction: the FEW nexus globally

The interdependency between food, energy, and water (FEW) is growing in importance as demand for each of these vital resources increases. Several regions of the world are already experiencing FEW security challenges, which adversely affect sustainable economic growth. In addition, there is already evidence of the effects of climate change on the availability and demand for food, energy, and water, especially in fast-growing countries. At the same time, not only is scarcity in either water, energy, or food caused by physical factors but there are also social, political, and economic issues at play that affect the allocation, availability, and use of these resources.

Population and economic growth are expected to continue to increase demand for food, energy, and water. Yet, approximately 800 million and 2.5 billion people remain without water and sanitation, respectively. Stresses such as rapid urbanization and climate change are growing on all water uses. Cities in developing countries will face meeting the demand of 70 million more people each year over the next 20 years. By 2030, 45 % more water will be needed just to meet human food needs. Further, over 1.3 billion people are still without access to electricity worldwide and closing the energy gap has implications on water, such as for fuel extraction, cooling water, and hydropower.

In the case of water, scarcity is on the rise. About 2.8 billion people live in areas of high water stress and 1.2 billion live in areas of physical scarcity. It is estimated that by 2030, nearly half of the world's population will be living in areas of high water stress affecting energy and food security (WWAP 2012). Climate variability and related extreme weather are already causing major floods and droughts, putting

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populations, livelihoods, and assets in danger. This variability is likely to worsen under current trends; the number of people affected by climate-related disasters doubled every decade in the last 40 years. Decreasing water quality also impacts growth as it degrades ecosystems; causes health-related diseases; constrains economic activities such as agriculture, energy generation, industrial production, and tourism; impacts the value of property and assets; and increases wastewater treatment costs.

Demand for energy for electricity generation will grow as population and economic activity expand (Shah et al. 2009; Voinov and Cardwell 2009; WWAP 2012; Schornagel, et. al. 2012). Emerging economies like China, India, and Brazil will double their energy consumption in the next 40 years. By 2050, Africa's electricity generation will be seven times as high as its electricity generation nowadays. In Asia, by 2050, primary energy production will almost double, and electricity generation will more than triple. In Latin America, increased production will come from non-conventional oil, thermal, and gas sources and the amount of electricity generated is expected to increase fivefold in the next 40 years; the amount of water needed will triple (World Energy Council 2010).

Water is needed in almost all energy generation processes, and energy is needed to extract, treat, and distribute water and to clean the used and polluted water. Water is required for hydropower generation and for cooling purposes in all thermal power plants. Moreover, water is used to extract or process fuels (oil, coal, gas, uranium) and hydraulic fracturing processes are expanding rapidly, consuming significant quantities of water. Both energy and water are used in the production of crops, and some crops are used to generate energy through biofuels. Water supplies in turn will be put under increased stress due to the impacts of increased withdrawals for other water uses, population increase, and climate change.

Thermoelectric power plants account for 39 % of the freshwater withdrawn every year in the USA (USGS 2015; see Fig. 1) and for 43 % in Europe (Rubbelke 2011), almost just as much as the agricultural irrigation use. Although most of the water is not consumed and is returned to the water source, the amounts of water withdrawn by the power and food production sectors have an impact on the ecosystem and on the water resources of a region.

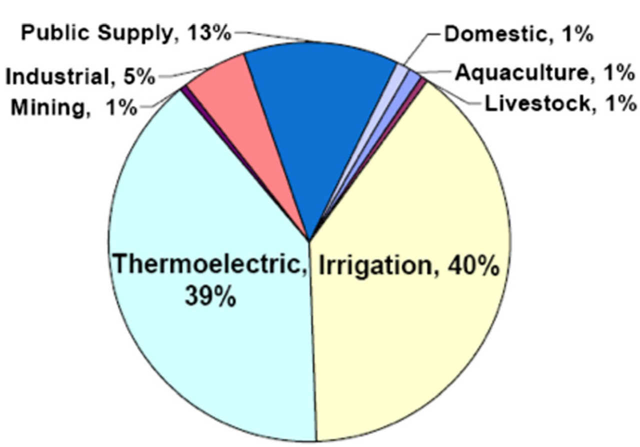

Fig. 1 Freshwater withdrawals in the USA (USGS 2015)

Climate change will have a range of impacts in different parts of the world, including impacts on the supply and demand for energy and water. Impacts on water supply will vary and are likely to include increases or decreases in average precipitation, surface runoff, and stream flow; increases or decreases in rainfall variability; and increases in the probability of extreme events, such as intense storms and floods, and droughts. Reduced runoff from climate change trends in precipitation and evapotranspiration are anticipated in, among other places, southern Africa, the Mediterranean basin, Central America, and the southwest regions of the USA and Australia (FAO 2008). This is likely to increase competition for water across sectors, e.g., agriculture, energy, water supply, and the environment. In some areas, the combined effects of population growth, climate change, and increasing hydrological variability will result in increased reliance on relatively energy-intensive water supply options, such as water transport or desalinization plants to supplement urban water supply. Moreover, as temperatures rise, more water will be needed by the energy sector to meet both its own demand for water for cooling per unit of energy produced and then to meet increased energy demands for the cooling of houses, offices, and factories. Climate change will also impact the energy sector through changes in energy demand and through the need to transition to energy supply options involving low or zero greenhouse gas emissions.

These ongoing examples around the world suggest a pressing need for integrated planning of FEW resource development and use, to avoid unwanted and unsustainable scenarios in the coming years. Although the FEW nexus is fairly evident, these three sectors have historically been regulated and managed separately, and despite growing concern over these trends, decision-makers often remain ill informed about their drivers and ill equipped to deal with possible outcomes. The simultaneous realization of climate change effects on FEW resources provides a window of opportunity to materialize such integrated planning.

The research agenda set out in this paper is directed at institutions, agencies, and other organizations that have a stake at reaping benefits of integrated analysis of food, energy, and water systems. In the USA, NSF has recently launched the Innovations at the Nexus of Food, Energy and Water Systems (INFEWS) Program, while other agencies such as the DOE, USDA, NOAA, and EPA have been pounding research programs at the nexus for quite some time, e.g., DOE's long-standing water-energy nexus work (http://www.energy.gov/downloads/water-energy-nexus-challenges-and-opportunities). This paper places particular emphasis on the FEW nexus globally, and specifically within the context of international development, as many countries around the world are struggling with similar issues of food, energy, and water security, which are major drivers of the integrated approach that is at the core of these nexus efforts. Because of this, another list of FEW nexus stakeholders is composed of international development organizations such as USAID, the World Bank, regional development banks (e.g., IADB, AfDB, ADB), non-governmental organizations, and many others.

In addition to focusing on the FEW nexus in the international arena, this paper makes an effort to highlight the need for analytical tools, encompassing conceptual and mathematical models that are based on data and/or physical processes, which would enable integrated analysis of the FEW nexus. Furthermore, the focus of this tool development would be to support "upstream planning" of FEW systems, allowing the quantification of trade-offs and benefits/costs of different food, energy, and water system configurations at a given spatial (e.g., city, state, country, regional) and temporal (near, medium, and long terms) scales, simultaneously meeting desired FEW objectives. This integrated approach at the same time differs and poses a natural evolution from existing and traditional sector-based approaches such as integrated water resources management (IWRM), energy systems planning, and analysis of food production systems, which are amply documented in the literature and have formed the core of tools used in sector-focused planning globally for a long time.

Materials and methods

Limitations in existing FEW nexus analytical (modeling) tools

A number of modeling platforms have been developed to support assessment of energy sector development under different economic and environmental policy conditions and to support integrated resource development in the water sector. The water models include consideration of water utilization for hydroelectricity expansion versus other uses, and some energy models include calculations of water requirements for different technology investments. Typically, however, the models are designed for different purposes and linkages between energy and water sector development are limited. Moreover, the level of technical detail and complexity in the models can preclude their application for upstream sector strategy development, a crucial analytical need in development planning. The converse is also true for the needs at river basin or sub-basin level, when models are too general and do not include the necessary level of detail.

Recent reviews of existing integrated resource assessment and modeling literature focused on FEW systems (e.g., NSF 2014; World Bank 2013; Asian Development Bank 2013; Cambridge Econometrics 2010) have shown that the analysis of individual systems (such as energy or water systems) is undertaken routinely but is often focused only on a single resource or has often been applied on an aggregated scale for use at regional or global levels and, typically, over long time periods. Likewise, the analytical tools used to support decision-making are equally fragmented. Examples of existing tools used for energy system analysis include the MESSAGE, MARKAL, and LEAP models. A commonly used model for water system planning is the Water Evaluation and Planning (WEAP) system, and for water scarcity and food security planning, the Global Policy Dialogue Model (PODIUM) is well established.

However, these and other models, in one way or another, lack the data and methodological components required to conduct an integrated policy assessment especially where these may be needed in a country/state/local policy context. Generally, they focus on one resource and ignore the interconnections with other resources, have overly simplified spatial representations, are grand policy "research" rather than short-term applied "policy"/decision support models, or analyze scenarios which are impractically long term.

Conceptual approaches to integrated analysis of the FEW nexus

In the growing economies of the world, the need to understand the interactions between water, energy, and food is increasing, and in addition, planning and development challenges involve land use, urbanization, demographics, and environmental protection. These challenges and complexities can no longer be addressed in the conventional way, with each sector taking decisions independently, with separate regulations and different goals. The complexity of the system requires a more systematic approach taking into account all the existing interactions and dependencies between sectors.

Figures 2 and 3 provide examples of the components that need to be integrated and analyzed simultaneously in the planning stages of FEW systems. What these examples have in common is that food, energy, and water "resource spheres" are analyzed in a coupled fashion, with explicit endogenous interactions and feedbacks among them, while other variables are included as exogenous to the FEW system. For instance, Fig. 2 shows that although food, energy, and water are clearly interconnected, many other external factors drive these interactions. FEW nexus planning and development challenges are likely to involve other factors such as land use, urbanization, demographics, and environmental protection. A number of data and modeling platforms have been developed to support assessment of FEW sector development under different economic and environmental policy conditions and to support integrated resource development in the different sectors. Typically, however, these data and modeling tools are designed for different purposes and linkages between food,

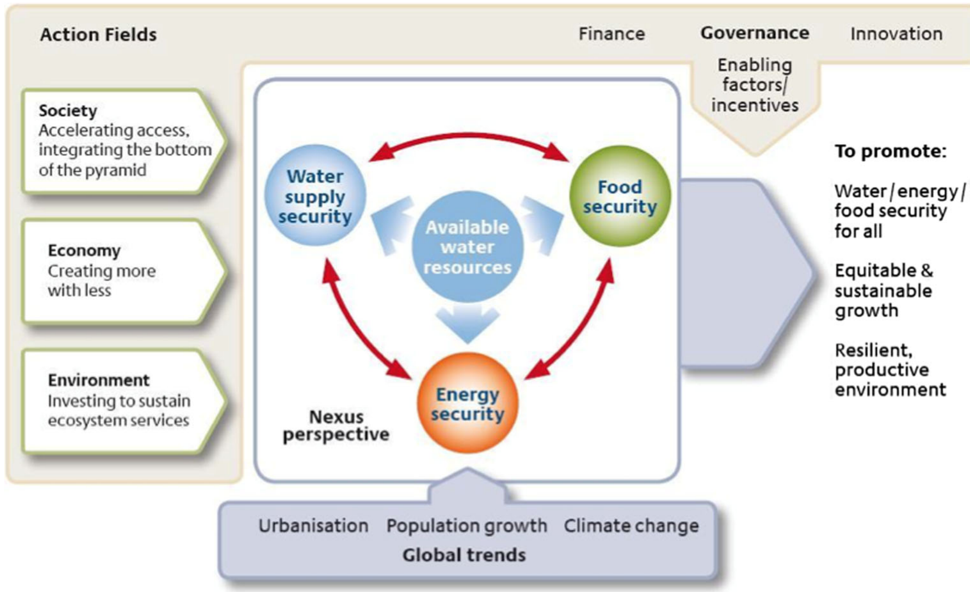

Fig. 2 The FEW Nexus Framework (adapted from Stockholm Environment Institute 2011)

energy, and water sector development are limited. Moreover, the level of technical detail and complexity in the models can preclude their application for upstream sector strategy development, a crucial analytical need in development planning.

Another important consideration is that the approach to analysis of the FEW nexus normally depends on the perspective of the policy maker (Harris 2002). If a water perspective is adopted, then food and energy systems are users of the resource (see, e.g., Hellegers and Zilberman 2008); from a food perspective, energy and water are inputs (see, e.g., Mushtaq et al. 2009; UN-DESA 2011; Khan and Hanjra 2009,); from an energy perspective, water as well as bioresources (e.g., biomass in the form of energy crops) is generally an input or resource requirement and food is generally the output (e.g., Asian Development Bank 2013; World Bank 2013). Food and water supply as well as wastewater treatment require significant amounts of energy. Of course, areas such as food as fuels (i.e., biofuels) tend to blur these descriptions (see, e.g., Nonhebel 2005) due to additional impacts associated with land use, land use change, and use of the available biomass resource. In any case, the perspective taken will affect the policy design. This is due to the specific priorities of the

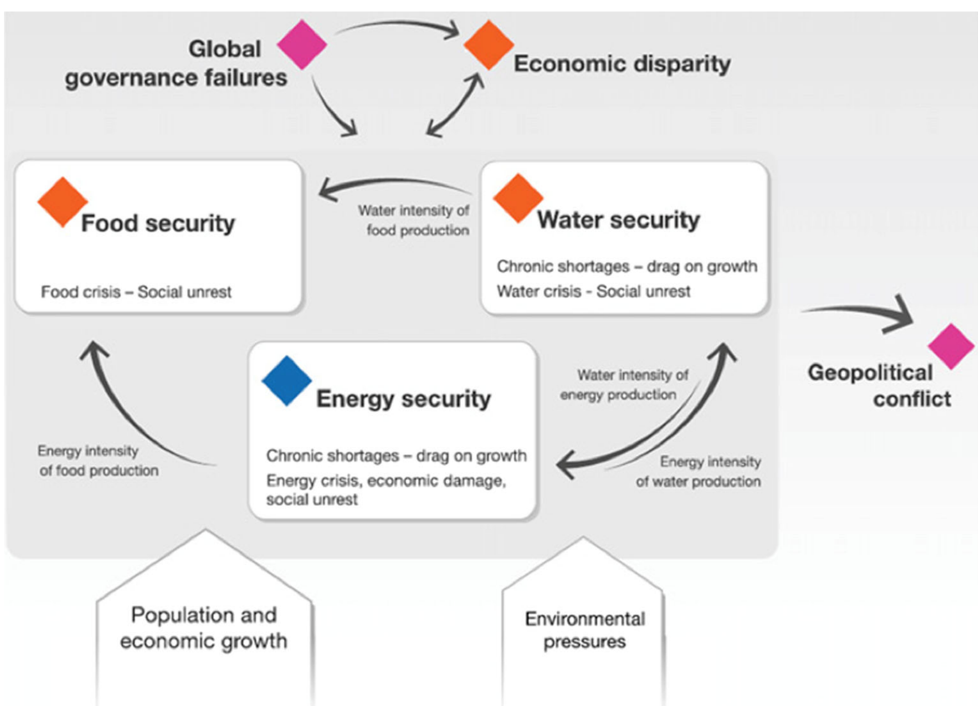

Fig. 3 Nexus schematic with a FEW security focus (Bazilian et al. 2011)

institution or ministry, as well as the data, knowledge, and analytic breadth of the tools of the associated experts and support staff.

Although this perspective bias may not be directly addressed through improved data/modeling tools, one role that such tools can play is to provide information to sectoral-based policy makers on the implications of potential choices on other sectors. These implications are likely not difficult to translate as food, energy, and water systems have many characteristics that are common.

- All three areas have many billions of people without access (quantity or quality or both).
- All have rapidly growing global demand.
- All have resource constraints.
- All are "global goods" and involve international trade and have global implications.
- All have different regional availability and variations in supply and demand.
- All have strong interdependencies with climate change and the environment.
- All have deep security issues as they are fundamental to the functioning of society.
- All operate in heavily regulated markets.
- All require the explicit identification and treatment of risks.

It is clear that each of the three resource spheres affects the other in substantive ways. Ignoring effects in one can have significant impacts on another. As Lee and Ellinas (2010) note, "The anticipated bottlenecks and constraints – in energy, water and other critical natural resources and infrastructure – are bringing new political and economic challenges, as well as new and hard-to- manage instabilities." Thus, the need for a systematic, coordinated planning approach is obvious.

Research objective and questions

The main objective of the proposed research agenda on analytical tools for the FEW nexus is to contribute to sustainable management and development of the food, energy, and water sectors by increasing awareness and building capacity on integrated planning of investments, identifying and evaluating trade-offs and synergies. This agenda can be achieved by developing innovative approaches and evidence-based operational tools to assess the economic and social trade-offs of constraints in water, energy, and food security, particularly as constrained by climate change. Developed tools will focus on upstream sector planning in order to identify primary opportunities and constraints to water, energy, and food development, as well as evaluating opportunities to curb demand growth without compromising quality of service, thus indicating priorities for more detailed analysis as well as providing characterization of alternative sequences of investment in each sector. Economic tools can be employed to quantify the impact on sector investments and the economy as a whole of economic scarcity of water, energy, and food as indicated by measures of their opportunity costs. This will also be an important step toward improved understanding of economic and social trade-offs among competing uses (i.e., water for energy production versus food production, industrial and municipal uses, and environmental benefits of in situ water). The results of this research thus aim at helping stakeholders move in the direction of integrated FEW system planning and of prioritization of investments.

This fundamental research objective can be approached through the following research questions:

> What are the synergistic opportunities and constraints posed by the mutual interaction and interdependency of food, energy, and water?
>
> The proposed analytical tool development should focus on upstream sector planning in order to identify primary opportunities and constraints to water, energy, and food security, as well as evaluating opportunities to curb demand growth without compromising quality of service, thus indicating priorities for more detailed analysis as well as providing characterization of alternative sequences of investment in each sector.
>
> What are the impacts of the FEW nexus interactions on policy and decision-making, particularly with respect to development investments?
>
> Economic analysis can be employed to quantify the impact on sector investments and the economy as a whole of economic scarcity of water, energy, and food as indicated by measures of their opportunity costs. This should also be an important step toward improved understanding of economic and social trade-offs among competing uses (i.e., water for energy production versus food production, industrial and municipal uses, and environmental benefits of in situ water). The results of this research thus aim at helping stakeholders move in the direction of integrated FEW nexus planning and of prioritization of investments.
>
> What are the threats and opportunities posed by climate change on the FEW nexus at several temporal (short, medium, and long terms) and spatial (local, national, regional, global) scales?
>
> Although understanding of climate change impacts on the food, energy, and water sectors has advanced significantly in recent years, little research has been done on the impacts of climate change on the interacting FEW nexus. Potentially, impacts can be compounded or offset each other, posing threats and opportunities, respectively. The proposed research should use climate and socioeconomic development scenarios and projections to identify and quantify these impacts.

What are the institutional barriers for the utilization of FEW nexus integrated planning tools?

The food, energy, and water sectors are planned today without much integration, e.g., water is allocated without considering energy constraints, energy generation is planned without much consideration for water sources and costs, and food production is planned without considering energy and water requirements for the most part. The case needs to be made that planning tools and institutional procedures in place need to evolve toward integrated planning approaches in order to realize synergies and manage threats identified through this research.

Discussion

Toward building FEW nexus interdisciplinary modeling capabilities

An integrated FEW nexus modeling system needs to address the shared needs of food, energy, and water producers; resource managers; regulators; and decision-makers at the country, state, and local levels. Ideally, the system should provide an interactive environment to explore trade-offs, explore potential synergies, and evaluate alternatives among a broad list of food/energy/water options and objectives. In particular, the modeling system needs to be flexible in order to facilitate tailored analyses over different geographical regions and scales (e.g., national, state, county, watershed, interconnected regions).

This integrative modeling approach can be implemented through specific research topics such as:

- Analyze and assess the water balances for the basin/system in question, quantifying the existing water allocation for energy generation and food production, and assess the existing model's handling of basins/regions
- Analyze the future demand for water, energy, and food, and different scenarios for FEW supply in the system, based on existing strategies and plans, as well as climate change scenarios (as locally available)
- Analyze the future demand for water (including water for power and water for food production) by overlapping existing and future power plants/coal mining/shale gas areas, irrigation, and production of meat and other food products, focusing on those geographical areas where the energy generation and food production activities are located
- Identify the basins where potential conflicts might arise in the future and quantify potential FEW deficits
- Incorporate climate change impacts on water availability, energy demands, and food production outputs
- Analyze opportunities to decrease these conflicts, by looking at different FEW management schemes and different technologies to reduce water and energy use (such as dry cooling, energy efficiency of waste stream treatments) and looking at opportunities to curb both energy and water demand growth through demand-side actions
- Quantify the costs and benefits (through partial or general equilibrium frameworks) of different solutions and synergies
- Analyze the impacts of changes in FEW prices/tariffs to the water, energy, and food demand and planning

The results of this research agenda research can support FEW nexus multi-sector dialog. In particular, this research can generate knowledge (in the form of analytical tools) that may be used for policy advice regarding the integrated planning (management of sources, production, and distribution) of food, energy, and water resources. This research can also contribute to the identification of investments that can support FEW needs as well as specific FEW nexus policies at the different scales.

FEW nexus modeling tools should be able to support the following capabilities:

- Decision-making: A well-formulated integrated modeling tool would help decision- and policy makers assess their options in terms of their likely effects on the broad energy-water system. The toolkit should be able to transparently evaluate the trade-offs reflected in different options.
- Policy assessments: Given limited resources, it is important for policy makers to ensure that policies are as cost-effective as possible. If multiple objectives can be achieved by a single policy, it may advance development more than policies focused separately on single objectives. The toolkit should therefore provide a more complete, multi-system policy assessment.
- Facilitating policy harmonization and integration: There are instances of very contradictory policies, e.g., electricity subsidies that accelerate aquifer depletion—that in turn lead to greater electricity use and subsidy requirements. The toolkit should help harmonize potentially conflicting policies.
- Technology assessments: Some technology options can affect multiple resources, e.g., nuclear power could reduce GHG emissions and exposure to volatile fossil fuel markets but may increase water withdrawals and use. As with other policies, the toolkit should allow a more inclusive assessment of technological options.
- Scenario development: Another goal is to identify consistent scenarios of possible socioeconomic development trajectories with the purpose of identifying future development opportunities as well as of understanding the implications of different policies. This is important for exploring

possible alternative development scenarios and the kinds of technology improvements that might significantly change development trajectories.

Outputs and products: Integrated System Modeling Hubs, testbeds

This research agenda should review existing and in-development *Integrated System Modeling Hubs* (ISMHs) for FEW nexus analysis, and link them to integrated assessment models and trade-off analysis methods and tools. *Testbeds* should be proposed and showcased to demonstrate and apply these new tools to integrated FEW planning processes. These ISMH testbeds should be documented to define scientific, engineering, and data challenges in understanding the FEW system.

ISMH for individual FEW processes These *modular ISMHs* should result in a library of components, annotated with requirements, metrics, and design variables, to serve as modules of more complex distributed systems across the FEW nexus. Research to be pursued includes new powerful architectural systems models that allow the integration of multi-physics models; optimization and trade-off analysis tools, sensing, and control algorithms; treating geometry at all scales as a design variable; treating material selection as a design variable; and easy aggregation and detailed evaluations and validation of designs across space and time scales.

ISMH for distributed FEW systems ISMHs can be linked to integrated assessment models (IAMs, e.g., Wise et al. 2009; Clarke et al. 2008; Edmonds et al. 2007; Kyle et al. 2013). In this area, research should focus on extending the analysis of individual systems, currently emphasizing only a single resource or applied only on an aggregated scale for use at regional or global levels, and integrate current fragmented analytical tools used to support decision-making. Examples of existing tools used for integrated FEW system analysis include GCAM (Kyle et al. 2011; Davies et al. 2013). Climate-hydrology components of Earth systems models include CWRF (e.g., Yuan and Liang 2011) with modules for water resources management, water quality, and agricultural crop dynamics. For instance, GCAM has already been linked to a model for water system planning (Voisin et al. 2013; Hejazi et al. 2013), and for water scarcity and food security planning, to the Environmental Policy Integrated Climate (EPIC) model (Kyle et al. 2011). The emphasis should be on linking models of economic and environmental policy, food demand and supply, energy demand and supply, water demand and supply, financial and cost, and social and behavioral variables. Modeling results should include system designs, dynamic control and scheduling of resources, policies, and investment decisions.

Knowledge dissemination, capacity building, and COP

As this research agenda unfolds, it should involve a large number of stakeholders such as technical experts responsible for the design and implementation of lending instruments, sector planners, academia, high-level policy decision-makers, and the private sector; a strategy to keep these audiences engaged throughout the process is imperative. Conducting stakeholder consultations, widely disseminating outputs and sharing knowledge, and developing messages and products to reach global audiences through appropriate communications platforms will all be crucial to support this agenda.

Moreover, the research agenda's dissemination strategy should aim to broaden the platform of implementation of the modeling tools by encouraging exchanges between scientists and policy and decision-makers within the context of creating a *community of practice* (COP).

The FEW nexus highlights the interdependences between different sectoral institutions and the importance of integrated planning. Hence, it will be important to create an interdisciplinary mentality in such institutions and to foster cooperation and knowledge sharing between them. This research agenda should aim to adopt more creative and cost-efficient approaches to share knowledge; audience-appropriate mechanisms should be used to share this information, such as (i) web-based social media tools, (ii) interactive web-based tools, (iii) learning events/workshops/meetings, and (iv) cooperation with other global learning platforms.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

References

Asian Development Bank (2013) Thinking about water differently: managing the water, energy and food nexus

Bazilian et al (2011) Considering the energy, water and food nexus: towards an integrated modelling approach. Energy Policy 39: 7896–7906

Cambridge Econometrics (CE) and Sustainable Europe Research Institute (SERI) (2010) A scoping study on the macroeconomic view of sustainability—final report for the European Commission, DG Environment

Clarke LE, Weyant J, Edmonds JA (2008) On the sources of technological change: what do the models assume. Energy Econ 30(2):409–424

Davies E, Kyle P, Edmonds J (2013) Adv Water Resour 52:296–313

Edmonds JA, Wise MA, Dooley JJ, Kim SH, Smith SJ, Clarke LE, Malone EL, Stokes GM (2007) Global energy technology strategy: addressing climate change phase 2 findings from an international public-private sponsored research program. Battelle Mem. Inst, College Park, MD

Food and Agricultural Organization (FAO) (2008) Climate change, water and food security. Technical background document from the expert consultation. FAO, Rome, February 26-28, 2008

Harris G (2002) Energy, water, and food scenarios. Best Partners

Hejazi M, Edmonds JA, Clarke L, Kyle P, Davies E, Chaturvedi V, Wise M, Patel P, Eom J, Calvin K, Moss R, Kim S (2013) Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework. Technol Forecast Soc Chang. doi:10.1016/j.techfore.2013.05.006

Hellegers P, Zilberman D (2008) Interactions between water, energy, food and environment: evolving perspectives and policy issues. Water Policy 10(S1):1–10

Khan S, Hanjra MA (2009) Footprints of water and energy inputs in food production—global perspectives. Food Policy 34:130–140

Kyle P, Clarke LE, Rong F, Smith SJ (2011) Climate policy and the long-term evolution of the U.S. buildings sector. Energy J 31(2):145–172

Kyle P, Davies E, Dooley J, Smith S, Clark LE, Clarke, Edmonds JA, Hejazi M (2013) Influence of climate change mitigation technology on global demands of water for electricity generation. Int J Greenhouse Gas Control 13:112–123

Lee B, Ellinas L (2010) Water and energy security in tackling the world water crisis: reshaping the future of foreign policy. The Foreign Policy Centre and Nestle

Mushtaq S, Maraseni TN, Maroulis J, Hafeez M (2009) Energy and water tradeoffs in enhancing food security: a selective international assessment. Energy Policy 37:3635–3644

National Science Foundation (NSF) (2014) Food, energy and water: transformative research opportunities in the mathematical and physical sciences

Nonhebel S (2005) Renewable energy and food supply: will there be enough land? Renew Sust Energ Rev 9:191–201

Rubbelke D, Vogele S (2011) Impacts of climate change on European critical infrastructures: the case of the power sector. Environ Sci Pol 14:53–63

Schornagel J, Niele F, Worrell E, Boggermann M (2012) Water accounting for (agro) industrial operations and its application to energy pathways. Resour Conserv Recycl 61(2012):1–15

Shah T, Gulati A, Hemant P, Shreedhar G, Jain RC (2009) Secret of Gujarat's agrarian miracle after 2000. Econ Polit Wkly XLIV 52: 45–55

Stockholm Environment Institute (SEI) (2011) Understanding the nexus: background paper for the Bonn2011 Nexus Conference. The water, energy and food security nexus, solutions for the green economy, 16–18 November 2011

UN-DESA (2011) World economic and social survey, New York

United States Geological Service (USGS) (2015) Estimated use of water in the United States in 2015

Voinov A, Cardwell H (2009) The energy-water nexus: why should we care? Universities Council on Water Resources Journal of Contemporary Water Research & Education. Issue 143, pp. 17-29, December 2009

Voisin N, Liu L, Hejazi M, Tesfa T, Huang M, Liu Y, Leung R (2013) Hydrol Earth Syst Sci Discuss 10:6359–6406

Wise MA, Calvin KV, Thomson AM, Clarke LE, Bond-Lamberty B, Sands RD, Smith SJ, Janetos AC, Edmonds JA (2009) The implications of limiting CO2 concentrations for agriculture, land use, land-use change emissions and bioenergy, PNNL-18341

World Bank (2013) Thirsty energy, water papers, water partnership program

World Energy Council (2010) Water for energy. World Energy Council, London, UK

World Water Assessment Program (WWAP) (2012) The United Nations world water development report 4. UNESCO, Paris

Yuan X, Liang X (2011) Evaluation of a conjunctive surface–subsurface process model (CSSP) over the contiguous United States at regional–local scales. J Hydrometeor 12:579–599