Final Report of the National Science Foundation Food, Energy, and Water (FEW) Workshop on

FOOD-ENERGY-WATER: NEXUS ISSUES IN ENERGY

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Colorado State University

EXECUTIVE SUMMARY

This document reports on the workshop, **Food-Energy-Water Nexus Issues in Energy**, held in Arlington, Virginia on December 7-8, 2015. The goal of the workshop was to explore and define the underlying science and engineering that must be advanced to facilitate better approaches to sustainable energy. It also sought to explore new technologies that would promote economically viable recovery and recycling of irrigation water and produced water at various points in the energy and food systems. Drs. Kenneth Reardon (Chair), Ashley Anderson, Peter Backlund, Kenneth Carlson, Sonia Kreidenweis, Jeffrey Steiner, and Reagan Waskom, Colorado State University, co-organized the workshop, which was sponsored by the NSF Division of Chemical, Bioengineering, Environmental, and Transport Systems (Award #1541888). The workshop was held in response to the NSF Dear Colleague Letter (NSF 15-040: Dear Colleague Letter: SEES: Interactions of Food Systems with Water and Energy Systems), dated February 2, 2015.

The challenge of providing food, energy, and water (FEW) in the future is characterized by a complex, dynamic network of interactions. Solutions to these nexus problems must therefore evolve from a systems-level understanding. Numerous FEW issues are encountered in energy, including competition for water between food and energy conversion, energy industry impacts on water quality for food production, and competition for resources (land, nutrients, and water) between biofuel and food production. Addressing these nexus issues is essential for moving toward sustainable energy, especially in semi-arid regions. The workshop included expertise and viewpoints from 49 attendees from across the nation, including leading researchers and practitioners (from academia, industry, government, and private non-profit laboratories), students, and government officials. These attendees brought perspectives from the sciences, engineering, and social sciences. Presentations by subject matter experts were followed by focused discussions in three subgroups assessing the state of understanding of the multidimensional FEW challenges in energy. Specific questions posed in the breakout groups were:

- What are the important goals for the next 20 years?
- What is needed to reach those goals? (Models, data, technology, policies, communication…)
- What are the constraints?

The deliberations of these subgroups led to recommendations for near-term and longer-term actions as detailed in this report. Summaries of the key recommendations are:

1. As with any FEW nexus issue, using systems approaches is critical for identifying, quantifying, and solving the resource conflicts that arise in the production of energy. Very often, water is the main resource for which production and processing of energy and food compete. Better models that explicitly incorporate this linkage are needed, including consideration of low-quality waters.
2. Finding solutions to energy issues at the FEW nexus also requires deep collaboration with social scientists. Technical solutions need input from policy makers, decision makers, and the public, who similarly need technical information to understand options.
3. Biofuels have the potential to reduce atmospheric carbon dioxide levels but must be produced in a way that does not draw critical resources from food production. That requires development of biomass feedstocks with reduced water and nutrient inputs, and conversion technologies that use less water. Decision support tools must be developed to find optimal land and resource use.
4. Treated produced water from the production of natural gas by hydraulic fracturing has the potential to offset agricultural water consumption and represents a rare opportunity for synergism between energy and food production. However, this requires research and activities to overcome technical, economic, and social challenges.

Additional recommendations are provided in each section of this report.

A website for the workshop, including speaker presentation materials, can be found at https://vprnet.research.colostate.edu/FEW/nsf-workshop/

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I. INTRODUCTION

Food, energy, and water are primary essential inputs to society. Food, energy, and water (FEW) systems are highly interconnected in many ways, but especially through competition: water is required for both energy and food production, energy is needed for food and water supply, and land can be used to provide both food and energy. These interconnections create a nexus such that problems and solutions impacting one of the triad necessarily involve the others (Perrone and Hornberger 2014, National Intelligence Council 2012). Rapidly increasing climate change and population growth are forces that simultaneously increase demand and limit supply of these three key resources. The challenge of providing food, energy, and water in the future has recently been termed a "trilemma" (Perrone and Hornberger 2014) that is characterized by a complex, dynamic network of interactions. Solutions to these trilemma problems must therefore evolve from a systems-level understanding.

There are numerous challenges in working to address the multitude of problems encompassed in the FEW nexus. Some of these are systematic: the institutions, practitioners, and researchers involved in any one area have generally worked independently of one another, and the regulations and policies that are in place evolved without a holistic view of the larger picture. Other challenges come from the need to involve several disciplines and areas of expertise, and especially to integrate social science perspectives into potential technological solutions (Carrico et al. 2015). Finally, there are challenges that stem from our incomplete understanding of the nature of the problems themselves — of knowing the complex landscape of the trilemma network.

Including both technical and social science perspectives in the discussion of FEW nexus issues is vital because technical solutions are used by and affect people, and because social factors (behavior, policy, and economic) influence what solutions are allowable and how they will be implemented. An aspect of the social-technical interface is that public acceptance of technology in the FEW arena must be considered in the development of solutions. Research indicates members of the general public do not have great knowledge about emerging technologies, nor do they devote significant cognitive resources to them (Scheufele and Nisbet 2007). Instead, when asked to form a decision about an emerging technology, they rely upon cognitive shortcuts to do so (e.g., Brossard and Nisbet 2007). For instance, they might rely upon a frame they encountered in the media, their existing viewpoints about another scientific issue, or their political ideology to guide their perspectives. Trust is one important cognitive shortcut to forming attitudes about emerging technologies, as it helps individuals reduce uncertainty they have around unfamiliar and emerging technologies (Anderson et al. 2012).

One significant facet of the trilemma concerns energy production, the transformation of energy from a primary source (petroleum, solar, etc.) to useful forms that are distributed. A recent DOE report (US DOE 2014) highlighted many ways in which water is used in energy production, including irrigation of biofuel crops, cooling in thermoelectric generation facilities, and various processes in oil and gas production. The use of water for these purposes directly affects the quantity (and often quality) of water available for food production, especially in semi-arid regions such as Colorado and Texas, where both energy and food production are major industries. In some cases, there is the potential for direct linkages between food and energy production. For example, life cycle analyses have shown that biofuels have the potential to reduce greenhouse gas emissions (Sheehan et al. 2014, Duval et al. 2013, Davis et al. 2011, Cherubinia et al. 2009) but there are concerns about the competition for resources (land, nutrients, and water) with those needed for food production (Yaeger et al. 2014). Addressing these nexus issues is essential for moving toward sustainable energy production.

II. WORKSHOP SCOPE, GOALS, AND STRUCTURE

On December 7-8, 2015, a diverse group of scientists and engineers from academia, federal and state government, and industry met in Arlington, Virginia to explore food-energy-water nexus issues related to the production energy. The workshop was sponsored by the Environmental Sustainability Program of the Division of Chemical, Bioengineering, Environmental, and Transport Systems in the Directorate of Engineering (Award #1541888). The Workshop Organizing Committee members were affiliated with Colorado State University:

- Kenneth F. Reardon (PI): Professor and Jud and Pat Harper Endowed Chair of Chemical and Biological Engineering; CSU Site Director of the Colorado Center for Biorefining and Biofuels.
- Ashley Anderson (co-PI): Assistant Professor, Department of Journalism.
- Peter Backlund: Associate Director of the School of Global Environmental Sustainability.
- Kenneth Carlson: Professor, Department of Civil and Environmental Engineering and Director of the Center for Energy Water Sustainability.
- Sonia Kreidenweis (co-PI): University Distinguished Professor of Atmospheric Science and Associate Dean for Research, College of Engineering.
- Jeffrey Steiner (co-PI): Professor and Associate Dean for Research, College of Agricultural Sciences and Deputy Director of the Colorado Agricultural Experiment Station.
- Reagan Waskom (co-PI): Professor of Soil and Crop Sciences and Director of the Colorado Water Institute.

The scope of this workshop was FEW nexus challenges in energy production, with production meaning the transformation of energy from a primary source (e.g., petroleum, solar) to useful forms that are distributed. Issues in the semi-arid Western United States were emphasized because that region has long experienced water constraints, has a diverse agricultural sector, and produces a wide range of fossil and renewable energy. However, the outcomes of this workshop are broadly applicable in the US and elsewhere in the world, especially since more regions will be water-limited in the future.

The workshop scope encompassed the numerous FEW issues that are encountered in the production of useful forms of energy, including competition for water between food and energy production, energy industry impacts on water quality for food production, and competition for resources (land, nutrients, and water) between biofuel and food production. The general topics of systems analysis, data needs, and technology needs, including needs for advanced observational and modeling capabilities, were also covered.

This workshop focused on the needs for new research in the science, engineering, and social science disciplines. The research that is needed will provide data to better understand the challenges, models to synthesize these data for the complex FEW systems related to energy production, and new technologies to provide much needed capabilities for water treatment, drought tolerance, monitoring, among others (NSF MPSAC 2014). The organizers recognized that some aspects of FEW issues in energy production, especially those related to water, require changes in regulations and policies (Waskom et al. 2014), including whether and how water can be reallocated from one sector or another. While important, these issues were considered to be outside the scope of the workshop.

The goals of this workshop were to:

1. Bring together researchers and practitioners with knowledge of FEW nexus issues in energy production, particularly biofuels and unconventional oil and gas production, in order to clearly articulate the current state of knowledge;
2. Foster a meaningful dialog among these experts, elucidating the fundamental science and

engineering research needs and questions in these FEW systems;

3. Bring together experts from different scientific communities, thereby promoting cross-disciplinary linkages that are vital for addressing FEW nexus challenges; and
4. Prepare a white paper for broad dissemination reporting the workshop findings and recommended paths forward.

The workshop included presentations by 17 experts from across the US and engaged subject experts in a focused discussion of the state of understanding of the multidimensional FEW challenges in energy production; current tools derived from physical science, technology, and social science for addressing these challenges; and identification of needed research and development. The workshop participants included basic researchers and those with in-the-field experience, who provided the perspective needed to ensure that the fundamental issues identified are of practical significance. A list of the workshop participants is in Appendix A.

To bring the workshop discussion to a more specific level, discussions began with a look at FEW issues in two key energy sectors — unconventional oil and gas production, and biofuels production. In Session 1 (Focus on FEW Issues in Biofuel Production) and Session 2 (Focus on Synergistic FEW Opportunities during Oil and Gas Production), presentations covered current technologies, FEW nexus issues, potential solutions, the impacts of and on climate change, and social science issues. In Session 3 (Overarching Issues), the agenda broadened to cover social science topics and technologies that are relevant to many aspects of this topic. The second day of the workshop began with Session 4 (Broad Themes for FEW Issues in Energy Production), in which presenters described connections with climate, food, and new technology development. Participants then worked in three groups to develop recommendations for research needs related to FEW issues in energy production. The full workshop program is provided in Appendix B.

III. FEW NEXUS FOCUS TOPICS

This workshop focused on two energy topics that embody many issues at the food-energy-water nexus: biofuels production and the use of water from unconventional oil and gas production for agricultural purposes. Biofuels have been produced at large scale for decades, and many sustainability assessments have been performed to evaluate the water consumption and impacts on food production of different biofuels feedstocks and conversion technologies. In contrast, unconventional technologies for producing oil and gas are newer, especially hydraulic fracturing, and issues of water consumption and wastewater disposal have only recently arisen. Thus, these two topics provided different ways to understand FEW Nexus challenges and research needs.

III-A. BIOFUELS

Background

Over the past 50 years, there have been two periods in which research, development, and commercial production surged: in the late 1970s, following the OPEC oil embargo and other global disruptions to petroleum supplies, and in the late 2000s, when oil prices rose quickly to over USD 140/barrel. In these periods, the driver for biofuel production was need for an alternative supply of liquid transportation fuels. Biofuel production has also been motivated by energy security concerns, with the realization that the US and many other countries import petroleum from a few global producers, which then may exert a large influence over foreign policy. The impact of foreign petroleum purchases on the US trade deficit has similarly brought attention to the benefits of domestic fuel production. More recently, even as global oil prices have fallen to very low levels, there has been recognition of the potential for biofuels to reduce greenhouse gas (GHG) emissions or even to reduce atmospheric carbon dioxide levels (Sanchez et al. 2015). The Renewable Fuel Standard within the 2007 Energy Independence and Security Act recognizes the GHG reduction benefits of biofuels and requires their inclusion in the US transportation fuel supply.

Federal funding levels for biofuel research and development were very low for about 25 years before the recent increase, with the result that the only technologies that were feasible at commercial scale in the 2000s were the production of ethanol by fermentation of starch in corn grain and the production of biodiesel from vegetable oils. Life-cycle assessments have shown that both of these first-generation technologies have favorable energy returns on investment (EROI), but both have large water and nutrient footprints. There are other technologies at different stages of development with better EROIs than first-generation biofuels, but water and nutrient consumption are often overlooked.

Sustainability assessments have been applied to biofuels perhaps more than to any other product or process. Most of these assessments focus on a specific parameter, such as net GHG production or water consumption, and the assessments range in scope from global to local. All of the models used in these assessments consider the entire production chain, from production of the feedstock to the point of fuel distribution. These models are critical tools for evaluation of nexus issues and for identifying points at which new research is needed.

Opportunities and Challenges

In general, the opportunities and challenges for biofuel production span technology, policy, and economic issues. Specifically with regard to the FEW nexus, the development and implementation of biofuel technologies must be linked better with considerations of water as a limited resource and food production as a critical demand with similar resource inputs.

- To date, the production of biofuels is the only potential means by which a fuel can be produced (and used) with concomitant reduction in atmospheric carbon dioxide levels. The concept of "bioenergy with carbon capture and storage" (Sanchez et al. 2015) is nascent and requires further investigation. If it is valid, then efforts to implement this strategy should be increased.
- The most significant challenge to biofuel production, and the development of technologies for more sustainable biofuels pathways, are the current low cost of fossil fuels and the fact that GHG emissions and other environmental impacts of fossil fuel use remain economic externalities. The development of biofuels is also hindered by the lack of awareness of the benefits of biofuels among the public and policy makers, who are more focused on wind and solar energy. Although electric vehicles are increasingly a viable option, there are more than 260 million gasoline and diesel vehicles in the US (http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_01_11.html), and thus there will be a need for liquid transportation fuels for many years.
- Considerable attention has been given to the EROI and GHG emissions from biofuel production (especially for first-generation biofuels), including tools such as the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model from Argonne National Laboratory (https://greet.es.anl.gov) and others (Field et al. 2016). In contrast, there has been limited recognition of the resources used for biofuels. The production of food and biofuels compete for water, nutrients, and land. Recently, ANL has developed the Water Analysis Tool for Energy Resources (http://water.es.anl.gov) and GREET has been modified to include water inputs, but more efforts are needed, including expanded consideration of different water (green, blue, gray) sources. There are thus opportunities to evaluate and quantify the uses of these water and other limited resources, and the challenges are to create biofuel production pathways that consume less water and nutrients and that do not use prime agricultural land. Combined production of food and biofuels feedstocks also represents an opportunity.

Research Needs

In the workshop presentations and discussions, many pressing research needs were identified to improve the sustainability of biofuel production and to identify and mitigate FEW nexus concerns. In the summary below, these research needs are grouped to highlight important themes.

- Biorefineries
  - Biorefineries, whether based on lignocellulosic biomass or algae, must be designed and located to fit a particular landscape. The determinants of this fit are not yet fully understood, and more tools are needed to evaluate how well a biorefinery meets the criteria.
  - New conversion technologies are required that use less water and have higher EROIs, while lowering production costs.
  - To date, biorefineries primarily produce a single product (a fuel), with some waste streams valorized to a small extent (e.g., dry distiller's grains for animal feed). Research is needed to develop biorefineries with several products, some of which should have high margins to improve the economics of biofuel production. The development of biorefineries that can be operated in a flexible manner, readily altering the product profile, would improve efficiency.
- Sustainable feedstock production
  - Continued research is needed to develop biofuel feedstocks that have better water use

efficiencies and nutrient use efficiencies. This is also a need for food agriculture. Recent findings that the phytobiomes of crops can have significant effects on drought tolerance and plant health should be integrated with crop breeding efforts.
    - Technology to more rapidly breed crops with desired traits should be developed. These platforms will integrate hardware and software and use post-genomic knowledge to shorten the time needed to obtain promising cultivars.
    - Biofuel feedstocks that can tolerate marginal lands should be further developed, and their yields with various water and nutrient inputs evaluated. There is a gradient of land capabilities available for biofuel feedstocks, and research is needed to guide decisions about the appropriate feedstock for a given site.
    - Strategies for integrated production of biofuel and food must be developed and evaluated.
    - Since an increase of extreme weather conditions is a predicted aspect of climate change, biofuel feedstock production systems are needed that can withstand these events, and their resilience evaluated over a range of time scales.
    - Research is needed to develop biofuel feedstock production with improved ecosystem services, including the ability to maintain surface water flows, improve water quality, and enhance biodiversity.
- Models and data
    - To minimize competition with food production, strategies for producing biofuel feedstocks should be developed that adopt an integrated/landscape approach.
    - The sustainable production of biofuel feedstocks requires decision support tools (models) that cover a range of physical scales and can be customized for each particular location under consideration. These tools must also couple environmental, economic, and policy issues. Finally, the decision support tools be designed for different users (e.g., farmers, biorefinery operators, and governments) and must enable decisions on crop selection and management practices.
    - Models and data are required to evaluate current and proposed policies and market incentives for landscape change.
    - Databases are needed to organize and make available information on many factors that are critical for biofuel production, including the characteristics (yields, water consumption, nutrient consumption) and variability of new biofuels feedstocks in different conditions over long periods. These data should reflect the location and environmental conditions to enable accurate predictions of crop yields.
    - New sensors to provide data to these models are needed. In particular, sensors for water (surface and ground), nutrients, and soil quality would be highly beneficial.

III-B. PRODUCED WATER RECOVERY AND RECYCLING

Background

The second focus topic explored in this workshop was the potential to cost-effectively treat produced water from oil and gas fields and beneficially reuse the water in agricultural applications. Since most oilfield wastewater is currently disposed of through deep well injection, surface reuse of this resource has the potential to address both water shortages in many agricultural areas that are co-located with oil and gas production and concerns about induced seismicity that has been increasingly experienced in some oil and gas producing states (OK, TX, CO).

Natural gas and oil produced from shale deposits using hydraulic fracturing and horizontal drilling has become an important component in the U.S. energy portfolio. Natural gas is increasingly seen as a bridge fuel between coal and renewables for electricity and as an emerging alternative to oil for transportation. In addition, the application of these technologies (hydraulic fracturing and horizontal drilling) has doubled the U.S. production of crude oil between 2009 and 2014 (4.5m bbls/day to 9.3m bbls/day), a major contributor to the significant reduction in the price of oil and gasoline prices to the consumer. The reduction of gasoline and diesel fuel prices has provided an economic boost to consumers and industries that have significant exposure to fuel prices, including most aspects of agriculture. As these important unconventional resources are aggressively pursued, new systems and approaches need to be developed and employed to minimize the environmental impact and lessen the stress on water supplies for other uses such as agriculture.

Hydraulic fracturing requires large volumes of water (usually greater than 3 million gallons per completion) and even though up to 50% of the water is returned to the surface ("frac flowback") within weeks after injection, the water quality is not suitable for use by agriculture or to augment surface water resources and it is therefore disposed of in deep injection wells. Often, disposal and even reuse results in significant transportation to the location of these activities. This usually involves trucks, and accidents or spills have been on the rise because of these activities. The idea of treating the water on the well pad on which it is collected, followed by transporting it by pipeline to a location where beneficial reuse could occur, has been increasingly accepted by larger oil and gas operators. However, this reuse is usually to frac another well. If the field is completely developed or if the produced water is from conventional drilling and completion, this beneficial reuse option does not exist and the water is disposed of in injection wells.

Presenters and participants in the workshop discussed alternatives to deep-well injection besides use in additional hydraulic fracturing. In particular, the feasibility of beneficially using this water on the surface by transferring it to agriculture or other local industries was considered. Barriers to widespread adoption of the concept, including economic, social acceptance, legal/regulatory and political issues were discussed.

Opportunities and Challenges

- The use of produced water for agriculture is a significant opportunity, particularly in arid areas such as Colorado and Utah. Even if the produced water were used for non-food crops such as biofuel feedstocks, the supply would offset water requirements for food production.
- Produced water contains organic and inorganic compounds that could be used or recovered to provide additional benefits.
- There are numerous technical, economic, and social challenges facing the use of produced water for agriculture. The most prominent technical hurdle is the cost-effective treatment of produced water, especially the removal of salts and organics. Regulatory hurdles exist at various levels that that block use of these waters, even if treated. Finally, there is the challenge of social acceptance of the use of water that was once highly contaminated. Recent experience with public campaigns for re-use of treated domestic wastewater has demonstrated the importance of clear and convincing communication with the public. There are opportunities to use the same approach for agricultural uses of produced water.

Research Needs

- Technology
  - Research is needed on the characterization of produced water, before and after various treatments, and the comparison of those water quality parameters with those for water applied to various crops. Specific contaminants of concern should be the focus of these characterization studies. This will require improved and simplified analytical methods/procedures, especially to identify and quantify emerging contaminants.
  - There are many research needs associated with treatment technologies. Overall, these technologies need to be cost effective, and the treatment systems need to be flexible so that the extent of treatment can be increased or decreased as is appropriate for the intended use. A development goal for these treatment systems is that they should be cost effective even at smaller scales, since local treatment (at the well pad) means less transportation and minimization of both cost and GHG emissions.
  - Specific water treatment technologies of interest include those employing membranes, including ceramic membranes, for both microfiltration and ultrafiltration, as well as new membranes for reverse osmosis.
  - The potential for forward osmosis for treatment of produced water should be evaluated.
  - Biological treatment of produced water, especially post-desalination, should be more thoroughly investigated. Specific questions include the impact of loading rates on biological processes, changes in the characteristics of biosolids and the impacts on biological processes of temperature and frac chemicals.
  - There is a need for a suite of treatment technologies that can treat water to varying levels that are dependent on the ultimate application. A “technology testbed” would be an effective concept for testing new technologies and developing flexible, cost-effective approaches to treatment specific to intended applications.
  - Produced waters often contain minerals (including lithium and rare earth elements), and methods to recover these could improve the economics of the water treatment process.
  - To enable purpose-driven treatment, it is important to understand the impact of residual contaminants on crops and soil. The uptake of many species by plants and soils is not yet well understood.
- Models
  - Process models of treatment systems are required to enable process optimization and to adapt treatment trains to specific applications, especially in situations in which the influent water quality varies with time. Treatment systems also require LCA and technoeconomic models to evaluate environmental and economic sustainability.
  - A decision support system model is required that allows mapping of the treatment system effectiveness and costs. This system-level modeling would include treatment analysis, market structure, matching supplies with user requirements and specific users, and location considerations (having a user located near a supply will reduce transportation costs and thus make the re-use of produced water more economically attractive). Crop selection should also be part of the decision tree; human food crops may have different requirements and different social barriers to acceptance. The tool should monetize the benefits to both agriculture and the oil and gas industry in terms of costs that have been avoided or reduced, including reduced costs for disposal and associated avoided risks (e.g., seismic events linked to disposal activities).

- Social and policy considerations
  - Develop fit-for-purpose collaborative partnerships.
  - There is a need to understand and analyze the regulatory pathways that govern how produced water may be reused, and to then recommend and advocate for improvements that will open up the possibilities of incorporated this water into the FEW cycle. Specific questions that were brought up by the participants included: Where in the process of regulatory approval are the current constraints? What components of produced water need to be evaluated and monitored for various proposed end uses? How can state and federal regulators become engaged in this effort?

IV. CROSS-CUTTING

Many aspects of FEW nexus are independent of the specific energy technology in question. In the workshop, presenters and participants provided insights into three cross-cutting areas. One of these areas — social and political issues — highlights the need to involve social scientists in FEW nexus considerations.

IV-A. LIFE-CYCLE ACCOUNTING OF RESOURCE DEMANDS FOR ENERGY PRODUCTION

Background

Life-cycle assessments (LCAs) are necessary for the evaluation of the sustainability of any product, and are particularly critical to identify and quantify resource demands associated with energy production. As is indicated by the name, a life-cycle assessment considers all inputs and outputs in the production, use, and disposal of a product. Thus, for example, biofuel LCAs begin with the feedstock production, and LCAs of photovoltaic systems must include the resources required to produce the materials and for their disposal. In the context of the FEW nexus, LCAs must specifically focus on water consumption (including water quality issues), nutrient consumption (for biofuels), and land use.

Opportunities and Challenges

- LCAs can provide critical information for decision-making at specific FEW nexuses. While LCA frameworks have advanced considerably over the past 10-20 years and LCAs have been applied to a wide range of products, including energy (especially biofuels), their use to understand resource competition in the FEW nexus is less well developed.
- One of the most challenging aspects of conducting LCAs is to obtain accurate data for the inputs and outputs of the production process.
- Most LCAs have been developed for very large regions, but the inputs, especially water, are highly dependent on the locality. Obtaining data on these smaller scales is challenging.

Research Needs

- LCA frameworks are needed specifically for water, since that is the most important limited resource for both energy and food.
- Integrated LCA-decision support systems are needed to help decision makers evaluate tradeoffs in food and energy production. This requires understanding the types of outputs required by a user, and also requires models that can use data at different physical system scales.
- LCA frameworks that incorporate not only resource inputs but also associated social-cultural dynamics are needed for FEW nexus situations.

IV-B. SOCIAL AND POLITICAL ISSUES

Background

Conflicts over the allocations of natural resources are universal. FEW nexus issues are particularly thorny because there is a tendency to frame the issues in terms such as "fuel versus food", rather than in terms that allow for the possibility of collaboration ("fuel *and* food"). Further, citizens who are impacted positively economically by energy development may be conflicted about the associated environmental issues (e.g., degraded water quality) and frequently do not feel empowered to affect decisions, considering their own stance on these issues.

The factors that influence the ability to find collaborative solutions include:

- Community conditions, including: trust; local knowledge; experience working together; long-term perspectives;
- Institutions, including legal and financial incentives for collaboration;
- The existence of "hurting stalemates": when a long-standing conflict has existed, the possibility of introducing a collaborative solution is enhanced. When locked in a "hurting stalemate", the parties realize that none is making progress toward achieving its goals, and perceive the costs of continuing the conflict to outweigh the benefits, opening the door to collaborative conflict resolution.

The media often provide dissonant messages as conflicts arise and develop. An example reviewed in the workshop showed that media accounts of water quality degradation in Iowa were juxtaposed with messages regarding the importance of agriculture to the state's economy, the importance of meeting environmental goals, and state pride in water resources. Interestingly, studies of the factors shaping public perception have found that the media are not exceptionally influential in affecting citizen opinion or behavior around issues. Rather, interpersonal communication is more influential. Further, individuals need to have a better understanding of how decision makers operate and who exerts influence on them. Tools that enable individuals to see the broader ramification of their own decisions (e.g., land use choices) as well the impacts on their own sphere of influence are helpful.

Opportunities and Challenges

Research indicates that members of the public often have core values that cannot be altered by more technical information / solutions. In fact, increasing the flow of information can cause these values to become more entrenched. For example, the public may have concerns over treating produced water and reusing it for drinking water; information about the safety of the treated water does not necessarily alleviate concerns or cause people to change their views. For their part, despite having data to show the safety of treated water, oil and gas companies are worried about the risk of later lawsuits if produced water is sold or given to end users.

These entrenched perceptions require research on understanding which FEW nexus issues are most amenable to conflict or cooperation:

- Where do the policy values converge or diverge?
- Where does trust exist among key stakeholders?
- Are there venues that can facilitate common solutions?
- How does the political context affect cost-benefit calculations and optimal solutions?

It is also necessary to examine the role of institutions:

- Who has authority and monitoring capacity with respect to FEW issues?
- What information-sharing mechanisms exist?
- What alternative institutions might be more conducive to collaborative problem solving?

Research Needs

Many FEW nexus issues are interdisciplinary, requiring intentionality, clearly-defined frameworks, and a common language. Those needs must be met before additional work can be done. Avenues that may prove fruitful in advancing the social and political aspects of FEW issues include:

- Working with Federal and State regulators to clarify primacy roles and to define rules for allowing / encouraging water re-use
- Evaluating public/private partnership options
- Analysis of liability limitations related to processing, transferring and relinquishing control of product streams
- Engagement in public awareness/advocacy
- Local development of fit-for-purpose projects
- Bridging the gaps between research, industry, and community.
- Developing social and political approaches suitable on a global scale. How can the energy needs of poor countries be addressed without exacerbating FEW nexus issues? How can developing countries grow within the constrained "climate-safe carbon budget"?
- Improved education regarding water issues (both quality and quantity), the local and regional constraints, and the needs for water in the production of energy and food.
- Developing educational resources about the FEW nexus in general. These resources should be targeted not only for K-12 and university students, but also for regulators, decision makers, and policy makers.

IV-C. RELATIONSHIPS AMONG CLIMATE, LAND USE, AND WATER AVAILABILITY

Background

Discussions of Food-Energy-Water Nexus issues must of necessity include how climate change affects the coupled physical systems, as well as its impacts on human dimensions that are integrated into decisions about allocations of resources. The interconnections between Food, Energy, and Water are numerous and evident in projected scenarios, for example, in studies of how drought in one region affects food supplies and how the resulting local impacts have influence on regional and even global scales, depending upon the connections and resiliency that have been built into the coupled system.

The Workshop took place immediately after the 21st Conference of Parties (COP21), held in Paris, and Workshop attendees were briefed by COP21 participant Peter Backlund on some of the issues debated there. Of particular relevance to FEW Nexus issues, a research project entitled "Climate Change, Global Food Security, and the U.S. Food System" emphasized the impacts of expected broad-scale changes in temperature and precipitation, while also noting the ramifications to agriculture: climate forecasts project increases in the numbers of very warm days, but also in the length of very dry periods. The report concluded that, on balance, climate change will reduce yield/acre, even when adaptation steps are undertaken. As a result, the land under cultivation will increase and the cost of food produced will increase.

Increased temperatures in a warmer climate, coincident with growing populations, will in turn increase energy demand. Since water withdrawals are key to thermoelectric power generation, increased water demand for energy generation will certainly arise. Future hot and dry scenarios may shift energy production to other technologies – e.g., photovoltaic – to compensate for reduced water availability.

Biofuel and oil/gas production with water reuse will impact the global water cycle through multiple pathways. Biofuel production will potentially replace low-water use landscapes with high-water requirement crops such as corn or perennial grasses. These biofuel crops may require irrigation, and even without irrigation will modify evaporative/latent heat fluxes, which in turn affect clouds and precipitation. Extraction and use of additional wastewater for oil and gas production will similarly intensify the water cycle, in turn affecting climate, with potential impacts on reduced groundwater supplies, enhanced soil moisture, more evaporation/latent heat flux and enhanced atmospheric humidity and clouds/precipitation.

Central to discussions of how climate change will affect the FEW nexus is the importance of observing and modeling regional and global water cycles, and in particular, development and application of an observing and modeling system that will help monitor and ultimately predict the impacts of such modifications. Over the past several decades, satellite instrumentation and retrieval algorithms have advanced the ability to constrain portions of the water cycle on regional and global scales, but much work remains to be done and new approaches are needed. For example, current polar orbiting satellites have near-global coverage and sophisticated instrumentation, but with a repeat cycle of only 1-2 weeks; further, they observe each location only at certain times of the day, whereas there are recognized diurnal variations in precipitation.

Modeling that is relevant to FEW issues requires an Earth system approach that permits interactions between the atmosphere, land, biosphere, and hydrology. The NASA-Unified Weather Research and Forecasting (NU-WRF) model was described briefly during the workshop, as an example of a regional model that incorporates data assimilation at satellite-resolvable scales. In particular, NU-WRF seeks to improve the representation of regional water cycles through assimilating precipitation-affected microwave radiances from satellites. It is designed to capture the feedbacks and coupling between the land surface and planetary boundary layer, key to understanding how crops interact with regional climate, and to study the impacts of land-surface initialization and hydrological data assimilation on mesoscale weather and regional climate.

Opportunities and Challenges

Understanding how FEW nexus issues evolve in a changing climate requires a comprehensive strategy that includes both observations and modeling. Some recent advances in observing key variables from space have demonstrated the great potential in this approach, especially when coupled with local and regional network observations and when interfaced with an appropriate modeling system capable of assimilating real-time data. Such advances include:

- Crop type: “Greenness” and plant height are currently observable, along with leaf area index, and serve as potential bases for remotely distinguishing between some crop types.
- Irrigation: It is critical to understand where and how irrigation water is being applied. This need also arises in any programs that seek to modify and motivate changes in water use, in turn requiring data to validate the changes that have been implemented. One proposed indirect measurement method is the observed differences between day and night soil temperatures, as these differences respond to irrigation. Other methods are needed to reduce uncertainty in this key variable.
- Soil moisture: An extensive network of soil moisture sensors exists in the U.S., but they are unevenly distributed and thus interpolation and extrapolation are required. Recent work in downscaling soil moisture observations from geostationary platforms shows promise.
- Groundwater depletion: Withdrawal of irrigation water results in depletion of groundwater. New satellite-based instrumentation is enabling space-based estimates of groundwater variability at regional scales.

The development of Earth system models, capable of data assimilation, is a significant advancement. Some examples of recent developments related to the workshop topics include the following:

- Irrigation has indirect, downwind impacts on temperature, convection, and precipitation, since water is being added to the atmosphere; thus regional weather and climate cannot be properly represented without the ability to account for such inputs and their effects. Only coupled models can represent these interactions.
- Biofuels are currently being added to land surface models. Since the characteristics of these plants, including their water use, are so different from other land cover that has been simulated to date, improving their representation is critical to being able to use models to investigate FEW nexus challenges.
- Solar-induced fluorescence in the red and far red can be used to indicate the photosynthetic efficiency of plants. Techniques for exploiting this phenomenon are just now being investigated, but may represent a significant opportunity for passive remote sensing of an important variable that might be assimilated in predictive models.
- Climate change impacts must be assessed from a system viewpoint. For example, simply increasing surface air temperatures by a fixed amount in a modeling sensitivity study ignores feedbacks to atmospheric circulations, precipitation, runoff, and groundwater storage.
- Public perception and acceptance of climate change in Europe is markedly different from that in U.S., and indeed varies across the globe. The current focus in active mitigation of climate change is on reducing greenhouse gas emissions through energy policy and technology, and land use and land cover changes, especially agriculture and forestry.
- Agreements emerging from COP21 will incentivize emission reductions and transitions to renewable energy, likely leading to new production of natural gas and increased development and deployment of biofuels.
- These actions will increase pressure on food systems, and expand the usage of land and water for food production, increasing competition for these resources.
- Media portrayal of issues, e.g. those surrounding biofuels, may be affecting the acceptance and wider implementation of new technologies.

Research Needs

The presentations and group discussions around climate, land use, and water availability revealed some pressing research needs for both observations and modeling. These included the following:

- A better understanding of the adaptive capacity of agriculture against climate change is required, so that future scenarios used for decision making can appropriately include potentials and limits.
- There are shortcomings in the required level of detail that is currently incorporated into land use and crop models, e.g., some crop types are not yet represented adequately.
- Better techniques for discriminating between crop types via remote sensing are needed. For example, can biofuel crops be characterized using lidar remote sensing?
- Satellite and other data must be combined with modeling to develop robust estimates of soil moisture and its variability in space and time.
- Evaporative losses are a key variable in water budget calculations but there are no methods yet developed for independently assessing these. Improvements in modeling are inhibited by the lack of such required observational constraints, e.g., evapotranspiration is deduced from estimated mass balances and hence subject to large uncertainty.
- Detection of changes in groundwater levels is promising; further work is needed to help reduce

uncertainties in this part of the budget.

- More work is needed to establish the accuracy of modeled irrigation water use.
- New geostationary satellite instruments will offer the ability to continuously observe fixed locations, at least on a regional basis. Research is required to develop appropriate data products that can be assimilated into models or that can be used for model validation.
- There is a clear need for modeling of the coupled system and to embed various high-fidelity sub-models into that system. These models must be connected in a way that promotes robust physics between them. In particular, proper feedbacks must be incorporated to generate the corresponding net effects. The use of observational data to build and test these coupled models is essential.

V. SUMMARY OF RECOMMENDATIONS FOR NEEDED RESEARCH

Sustained funding programs and strong university-industry partnerships are needed to fill knowledge gaps and create solutions to the challenges outlined here. Principal recommendations from the Workshop call for research to:

1. Use systems approaches to identify, quantify, and solve the resource conflicts that arise in the production of energy. Very often, water is the main resource for which production and processing of energy and food compete. Better models that explicitly incorporate this linkage are needed, especially ones that consider water of different qualities. These models could incorporate satellite data for more accurate and timely updates of available water.
2. Develop biomass feedstocks with reduced water and nutrient inputs, and understand the role that the phytobiome can play in achieving those goals. New technology to more rapidly breed crops with desired traits should also be created and applied.
3. Develop biomass conversion technologies that use less water and energy to produce biofuels.
4. Develop decision support tools to find optimal land and resource use, beginning with decisions concerning biofuel and food production. These models should also incorporate considerations of resiliency in the face of extreme weather events, and be applicable over a range of physical scales.
5. Find cost-effective water treatment technologies, including treatment trains, that can upgrade water quality to the level required for specific purposes. An important example is that of treating produced water from the production of natural gas via hydraulic fracturing to be useful in agriculture, including the production of biofuel feedstocks.
6. Learn about the fate in agriculture of contaminants in produced and other low quality waters so that the extent of treatment of those waters can be correctly specified.
7. Create frameworks specific to energy issues at the FEW nexus that help technology developers/providers and decision makers understand and address public concerns, and that lead to cooperation rather than conflict.

VI. CONCLUSIONS

This NSF-sponsored workshop on Food-Energy-Water Nexus Issues in Energy benefitted from the active participation of researchers, decision makers, and practitioners from a wide range of science, engineering, and social science fields and representing academia, industry, government, and private non-profit laboratories. Some conclusions from the workshop pertain to any aspect of the FEW nexus: that using systems approaches is critical for identifying, quantifying, and solving conflicts, and that collaborations are vital, not only between technologists and social scientists, but also among researchers, decision makers, policy makers, and the public. There are strong needs for improved system models to support decisions, such as those involving land and resource use between biofuel and food production. These models need inputs from a variety of sources, including sensors, satellites, and databases. The workshop also found that there are opportunities for synergism between energy and food production, such as the potential to use produced water from hydraulic fracturing for agriculture. Using any impaired water will require cost-effective, scalable, and flexible treatment technologies, for which additional research is needed.

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APPENDICES

Appendix A: List of Participants

Erik Anglund	Water Resource Engineer	Anadarko Petroleum
J. Michael Angstadt	PhD Candidate	Colorado State University
Kristen Averyt	Associate Director, Cooperative Institute for Research in Environmental Sciences	University of Colorado, Boulder
Steve Barr	Chemical Engineering Consultant	DuPont
Andrea Blaine	Assistant Director, Center for a Sustainable WE^2ST	Colorado School of Mines
Liz Burrows	AAAS S&T Policy Fellow	AAAS Fellow at NSF
Ken Carlson	Professor, Civil and Environmental Engineering	Colorado State University
Tzahi Cath	Associate Professor, Civil and Environmental Engineering	Colorado School of Mines
Gavin Clingham	Principal	Woodberry Associates
Jill Cooper	Manager of Reporting and Advocacy	Anadarko Petroleum
Kajsa Dalrymple	Assistant Professor	University of Iowa
Ashwin Dhanasekar	Senior Researcher	Colorado State University
Wally Frank	Manager-Water & Chemical Optimization	Devon Energy Corporation
Christopher Freitas	Senior Program Manager, Office of Fossil Energy	US DOE
Bill Goldner	Director, Bioenergy Division	National Institute of Food and Agriculture, USDA
Ben Grunewald	Chief of Operations	Ground Water Protection Council
Bruce Hamilton	Program Director	NSF
Tanya Heikkila	Associate Professor	University of Colorado, Denver
Song-Charng Kong	Program Director	NSF
Sonia Kreidenweis	Professor and Research Associate Dean, College of Engineering	Colorado State University
Kristin Lewis	Science and Technology Policy Fellow	AAAS/NASA
Katie Lewis	Assistant Professor	Texas A&M AgriLife
Jan Mares	Senior policy advisor	Resources for the future
Mark Nechodom	Principal	Nechodom Associates
Liz Neeley	Executive Director	The Story Collider
Brent Nelson	Associate Professor	Northern Arizona University
Robin Newmark	Associate Laboratory Director	National Renewable Anergy Laboratory
Keith Paustian	Professor, Soil and Crop Sciences	Colorado State University
Holly Pearen	Senior Attorney	Environmental Defense Fund
Christa Peters-Lidard	Deputy Director, Hydrospheric and Biospheric Sciences	NASA Goddard Space Flight Center
Patrick Pfaltzgraff	Water Quality Control Division Director	Colorado Department of Public Health and Environment

Chittaranjan Ray	Professor	University of Nebraska
Kenneth F. Reardon	Professor, Chemical and Biological Engineering	Colorado State University
Valerie Reed	Deputy Director/Senior Advisor	DOE/USDA
Alan Rudolph	Vice President for Research	Colorado State University
Peter Saundry	Chief Scientist	National Council for Science, Policy and the Environment
Patrick Schauer	Water Resource Engineer	Noble Energy
Theresa Selfa	Associate Professor	SUNY-ESF
John Sheehan	Senior Research Scientist	Colorado State University
David Smith	Agricultural Economist	USDA-ERS
Seth Snyder	Water Initiative Leader	Argonne National Laboratory
Colby Stoddard	Senior Scientist	DARPA
John Veil	President	Veil Associates
Ethan Warner	Analyst	National Renewable Anergy Laboratory
Reagan Waskom	Director, Colorado Water Institute	Colorado State University
Bryan Willson	Professor and Director of the Energy Institute	Colorado State University
May Wu	Environmental Scientist	Argonne National Laboratory
Tamara Zelikova	AAAS Fellow	DOE
Ariela Zycherman	AAAS Science and Technology Fellow	National Science Foundation

Appendix B: Workshop Program

<u>Monday, December 7</u>

8:00 Arrival, Sign-In, Coffee

8:30 Welcome and Introduction to Workshop and Goals

Alan Rudolph, Colorado State University
Bruce Hamilton, National Science Foundation
Valerie Reed, Department of Energy
Sonny Ramaswamy, Department of Agriculture
Ken Reardon, Colorado State University

9:20 Session 1: Focus on FEW Issues in Biofuel Production

Session Chair: Reagan Waskom, Colorado State University

Current and future issues for biofuel production
Ken Reardon, Colorado State University

Confronting uncertainties in the biofuel – water landscape: assessment and attributes
May Wu, Argonne National Laboratory

Water productivity for hybrid maize under irrigated agriculture
Chittaranjan Ray, University of Nebraska at Lincoln

Agriculture advancements and cellulosic ethanol
Steve Barr, Dupont Pioneer

The good, the bad and the ugly – assessing sustainability of biofuel feedstocks
Keith Paustian, Colorado State University

Social dimensions of bioenergy production: challenges and opportunities
Theresa Selfa, SUNY-Environmental Science and Forestry

12:30 Group lunch

1:00 Session 2: Focus on Synergistic FEW Opportunities during Oil and Gas Production

Session Chair: Bryan Willson, Colorado State University

Current state and future vision for interactions between food, oil and gas production and water systems
Ken Carlson, Colorado State University

What are the primary barriers for reusing produced water for agriculture from industry's perspective?
Erik Anglund, Anadarko Petroleum Corporation

Current state of oilfield wastewater reuse
John Veil, Veil Environmental, LLC

Technologies and methods for treatment of wastewater from O&G exploration and production: limitations, economics, and reuse opportunities
Tzahi Cath, Colorado School of Mines

Growing cotton with treated produced water - lessons learned
Katie Lewis, Texas A&M University

3:35 Break

4:00 Session 3: Overarching Issues
Session Chair: Sonia Kreidenweis, Colorado State University

Management of collaboration and conflict
Tanya Heikkila, University of Colorado-Denver

Understanding perceptions of water resources in the Agricultural Heartland: Who is shaping our attitudes and influencing our behaviors?
Kajsa Dalrymple, University of Iowa

Observing and modeling water cycle changes related to biofuel and oil/gas production
Christa Peters-Lidard, NASA

5:35 Day 1 Wrap up

Tuesday, December 8

8:00 Welcome
JoAnn Lighty, National Science Foundation

8:10 Day 1 Summary

8:30 Session 4: Broad Themes for FEW Issues in Energy Production
Session Chair: Reagan Waskom, Colorado State University

Report from COP21 on nexus issues in energy production
Peter Backlund, Colorado State University

Climate and the energy-water nexus: current and future risks
Kristen Averyt, Cooperative Institute for Research in Environmental Sciences, University of Colorado

Technology, innovation and disruptive R&D for the energy-water nexus
Seth Snyder, Argonne National Laboratory and Ron Faibish, Department of Energy

10:05 Break

10:20 Breakout group discussions to identify knowledge gaps and research needs regarding FEW nexus issues

12:00 Group working lunch

2:00 Workshop summary and next steps