Trade-offs and Decision Support Tools

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I- ABSTRACT

At the time where decisions for addressing goals within water, energy, and food systems are becoming more tightly interconnected, given the wide spectrum of stakeholders with varying preferences, a greater need emerges for tools which assess the trade-offs among possible future trends. Through the use of integrated resource analytics, such tools would produce trade-off assessments which play a role in catalyzing dialogue among those decision makers. A large number of assessment tools which address specific angles of the WEF Nexus exist. Nevertheless, various challenges exist including matching the appropriate tool, or set of tools, with the different nexus hotspots, the ability to customize existing tools to fit local specificities, compatibility of collected data with the needs of integrative nexus assessment tools, and evaluating these assessments through incorporating stakeholder input and providing guidance forward for solution implementation.

KEYWORDS: trade-offs, integrative assessments, decision making, resource allocation and planning, sustainability evaluation, dialogue

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II- INTRODUCTION

The FEW nexus will face many intertwined social, engineering, and economic considerations, that cut across the three, highly heterogeneous landscapes of energy, food, and water. Within this heterogeneous landscape, there is a need for new analytical tools that can be used to model, analyze, and optimize the decision making processes of stakeholders, as well as the overall operation of the nexus nodes, in terms of resource allocation, system optimization, and resilience.

The following are examples of sample critical questions at different scales:

National Scale

- What is the impact of increased food subsidies on national water security?

Global Scale

- What is the extent of impact of allocating corn for ethanol production in major corn producing countries, on food prices globally?

Urban City Scale

- What are the implications of promoting water reuse for urban agriculture on food security?

Farm Scale

- How would policies set to incentivize farmers to produce more food impact water quality?

Business/Industry Scale

- What are the implications of investing in water efficient technologies on the long term sustainability of the business operations?

This review will specifically:

1) Address the key challenges and major research questions associated with improving our understanding of the nature of needed assessments and the current state of the science
2) Identify data and knowledge gaps which need to be addressed by the scientific community
3) Identify potential transformative technological, community based, and policy solutions for this field of research
4) Highlight the impact of further expansion of such research on science and society

III- KEY CHALLENGES/RESEARCH QUESTIONS

The growing need for integrative assessments resulting from a greater acknowledgement to the tight interconnectedness between water, energy, and food challenges, has led to the development of a large number of WEF Nexus tools.
Critical questions addressing different WEF Nexus hotspots vary across scales, and across various stakeholders within the same scale. Different tools address different questions at specific scales. Those questions could be at a national, regional, global, city, farm, or business/industry level.
At the national scale, different stakeholders would include ministries of agriculture, water, energy, economics, and environment, for example. All of those would need to be considered while studying a new national water strategy. Decision made at a farm scale, would include farmers,

water utility companies, environmental protection agencies, and land commissioner, as another example.
While there is a need to identify the proper analytics to address a water-energy-food nexus hotspot, a key challenge lies in identifying the criteria upon which resulting assessments are evaluated and communicated with stakeholders, in order to catalyze a dialogue over trade-offs.

In the following are some thoughts of such questions and overall challenges:
Overall Research Questions
- At what scale and complexity do we need to model? What is the appropriate resolution in which assessments could be effectively communicated with different decision makers?
- What analytical and trade-off tools need to be used for simulating and evaluating different scenarios of resource allocation, climate change, population growth, drought, different water sources and technology choices?
- How could approaches for resource allocation assessments be evaluated?
- How could stakeholders' input be incorporated as part of the criteria for scenario evaluation?
- What are ways to address the lack of coherence, or competition, between different decision making entities across sectors and scales? How could that be factored into the assessment of scenarios being evaluated?

In this context, there exists a number of key decision making challenges that cut across the various scales identified in Section II:
- **At a national scale**, governmental agencies must interact and work together in an effort to provide subsidies, improve FEW resource security, and bring together stakeholders across food, energy, and water.
- **At a global scale**, there is a need to understand how global policies (e.g., environmental policies) can in fact impact the national scale policies and subsidies, as well as the efforts to create national-scale FEW nexuses.
- **At an urban city scale**, beyond policy making decisions that occur within the city, there is a need to understand how resources can be allocated across water, energy, and food systems, while being cognizant of the upper-scale policies and decisions. impact global
- **At a farm scale**, tools are needed to analyze how farmers can or might react to the higher-level decisions done at national and city scale, while also investigating the impact of such decisions on the actual production of the farms.
- **At the business/industry scale**, there is a need to analyze the economic decision making processes of the players, in an effort to study the new market opportunities that arise from the FEW nexus vision, as well as how those markets can be affected by the decisions at the various other scales.

IV-DATA/KNOWLEDGE GAPS

Some of the most common data gaps and challenges within the water-energy-food nexus modeling community include the following:
- Lack of interlinkages data. The majority of available data is disciplinary. Data at the interface between different disciplines is still not as developed.

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- Data within private sector/within specific industries could be more challenging than others for the research community to have access to; energy data for example.
- Incompatibility of collected disciplinary data with nexus tool needs, and the lack of coherence and compatibility of data across different scales
- Lack of sufficiently "nexus trained" professionals (lack of institutional capacity) to work with nexus assessment tools.

V-POTENTIAL TRANSFORMATIVE SOLUTIONS NEEDING MORE RESEARCH

By inspecting the aforementioned challenges, from a decision making perspective, one can identify one common denominator – large-scale interdependencies between the decision making processes that exist within each scale and across scales. Such interdependent decisions must be mathematically analyzed, so as to organize the seemingly chaotic and complex environment that arises from the FEW nexus. To this end, game theory [1] provides a formal analytical framework with a set of mathematical tools to study the complex interactions among rational decision makers whose goals, actions, and objectives are interdependent. Throughout the past decades, game theory has made revolutionary impact on a large number of disciplines ranging from engineering, economics, political science, philosophy, or even psychology [1]. More recently, game-theoretic tools have become prevalent in the analysis of engineering systems, such as wireless networks [2] and smart energy systems [3]. Within the FEW nexus, game-theoretic tools can be used to analyze decision making at two key levels: technology and policy governance, as follows:

- **Technology:** From a technology perspective, game-theoretic tools can be used to model how resources can be efficiently allocated across the FEW nexus. In such games, the players will be individual nodes at the production, distribution, and consumption levels of a nexus and the actions will essentially pertain to the amount of resources a node requires, distributes, or produces. Both non-cooperative and cooperative game models are applicable in this context. Non-cooperative solutions would better model scenarios in which individual system nodes have no means of coordinating their strategies, while cooperative models can be suitable to analyze how one can pool resources across interdependent nodes that have a means to coordinate their system parameters. Another promising framework for resource allocation is that of matching theory [4]. Matching theory is a Nobel-prize winning theory that allows understanding how to match resources across two sets of distinct players. Within the FEW nexus, matching games can be used to match resource production to resource consumption, in a stable and efficient manner. Overall, from a FEW nexus technology perspective, game-theoretic frameworks will provide analytical approaches that can shed light on how distributed resource allocation can efficiently occur in the FEW nexus across possibly heterogeneous types of actors/nodes. In addition, such game-theoretic solutions can be useful to enhance the resilience of the resources allocation processes of the nexus and their response to potential failures.

- **Policy/governance:** Game theory is a natural framework to model interactions between stakeholders. Within the FEW nexus, such interactions can occur at multiple scales, as previously mentioned. The key objectives here are to: a) identify economic, political, and regulatory actors, their interactions, and their cumulative effects on the overall FEW nexus system, b) understand what type of subsidies can be provided at different scales to bring together FEW stakeholder (an example on the use of game-theoretic approaches for analyzing subsidies can be found in [5]), c) design incentive mechanisms that can promote cooperation between stakeholders and that can positively impact the technological landscape of the nexus, and d) provide policy recommendations that can render the FEW nexus more efficient, resilient, and environmentally sensitive.

VI-IMPACT ON SCIENCE AND SOCIETY

Improving the developed nexus analytics and trade-off assessment tools, would allow us to be better prepared for addressing interconnected resource challenges. It would allow policy makers to have the information needed to make informed decisions and put incentives in place to push towards sustainable future resource allocation. Realizing the need for use of such tools and analysis would also create a push toward building scientific and institutional capacities for professionals who could need to carry forward those assessments and communicate them with different stakeholders. It would also further create a more pressing need for collecting different kinds of interlinkages data that are currently not being collected.

While game theory has a broad range of tools that can address the aforementioned problems, a number of key challenges must be addressed:

- **Utility design:** Game-theoretic constructs typically rely on individual utility/objective functions that are defined per player. Within the FEW nexus, such utility designs must directly stem from practical considerations of the FEW nexus as well as from the data. To design such realistic, data-driven utility functions, one must overcome the data gaps identified in Section IV.

- **Multi-scale and dynamic nature of the nexus:** As outlined previously, the FEW nexus will have agents interacting at multiple scales and the system will dynamically evolve over space and time. As such, there is a need for new game-theoretic models that can inherently integrate multiple timescales in the decision making processes. Here, notions of stochastic games [1] can be useful to capture the spatio-temporal FEW dynamics that can evolve over time. Moreover, to practically capture decisions at multiple timescales, such stochastic game constructs can be merged with emerging game-theoretic frameworks such as multi-game solutions [6] and multi-resolution games [7], which enable the analysis of the co-existence of multiple, interdependent games, at different scales.

- **Models of spatio-temporal interdependencies:** To create realistic game-theoretic decision making models, there is a need to properly model the spatio-temporal interdependencies across the FEW nexus. Such interdependencies can be technological (e.g., dependence between infrastructure nodes) or policy-oriented (e.g., which actors truly impact each other). Here, one can combine game theory with tools from graph theory, such as the notion of temporal network analysis [8], that can help identify interdependencies across time and space, which can then be fed into game-theoretic constructs for analysis of the decision making processes.

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VII- CONCLUSIONS

No one tool is able to address the complexities of the different nexus challenges across scales and stakeholders. Based on an identified critical questions and stakeholders associated with it, a tool or suite of tools could be prescribed or customized to perform the required assessments. A better understanding and quantification of the interconnections between different resource systems, as well as the interactions among various involved players, would improve the value of the developed assessments and proposed solutions. Moving forward, there needs to be a push for collecting data that is in sync with the assessment needs and the tools needed for those. There also needs to be further incentivisation for building capacity in the quantifying, analysis, modeling, and communicating the water-energy-food nexus challenges among both the scientific and policy making communities.

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