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The need for universal metrics in the energy-water-food nexus

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Abstract The ability for a new food-energy-water (FEW) initiative or program to thrive and prove valuable at a local, national, or international scale is often critically dependent not on the power or impressiveness of its technical innovation, but the ability for that innovation to be introduced, and subsequently welcomed, into a society. As the global population expands, there is an inevitable increase in competition for vital resources. The interaction of these resources—namely, food-energy-water—is referred to as the FEW Nexus. Water is the key resource that is in limited supply, and as the demand grows for energy and food dependent on it, so does global inequality and suffering. It is only through technical and socially aware innovations that these allocation issues can be addressed. Universal metrics, though flawed, are needed to help compare and contrast new FEW Nexus projects and technologies for those that need to plan and implement interventions to improve access to these vital resources. Social stickiness, or society's willingness and ability to adopt and apply FEW Nexus interventions, is a vital component of these universal metrics. Social stickiness measures the ability of innovations to be successfully transferred from "science lab" to "social life" in order to educate and improve the global quality of existence through widespread and educated user adoption. Existing FEW program/technology metrics usually define an output per unit input (e.g., kWh/m^3) and are limited to two areas the FEW Nexus with an obvious, but undefined association to the third (e.g., less water for agriculture). All technical metrics appear to treat the FEW Nexus as a static problem with no social or cultural context. Consequently, universal metrics should include a social measure of the target population as well as the traditional output/input measurements. The United Nations' inequality-adjusted human development index (IHDI) could be a way to quickly include a social component to assess an innovation's usability and improvement in the global community. The FEW needs and constraints found in developed and developing countries vary drastically, meaning that any universal metric that is created will not account for the complexity of the international situation, but would still be a useful tool to compare and contrast different innovations for local non-experts seeking to implement them.

Keywords Food-energy-water · Metrics · Nexus · Social stickiness · Innovation

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Introduction

There are nearly 7.3 billion people in the world today, and as this number grows, enormous strain is placed on critical resources, namely food-energy-water (FEW). These three resources are inextricably connected, and this interdependence is known as the FEW Nexus. Water is "central to energy production" as well as a "critical limiting factor for food"

(SAB Miller and WWF 2014). It is therefore extremely problematic that there is simply less usable freshwater available. The freshwater that remains is also at higher average temperatures, leading to greater degrees of evaporation, biome change, and reduced cooling efficiency. Ultimately, this induces water strain across all climates.

The interactions and constraints within the FEW Nexus give rise to a plethora of problems given the number of interrelationships. Some are obvious, such as reduced agricultural output from extended drought. Others are less obvious, such as the closure of nuclear power plants in temperate climates because the usable water temperature is now too high. The interrelationships of the three key areas have led to unforeseen complications and competition between critical resources. These are not new revelations, but the speed of the changes that display the complex interdependencies have pushed FEW issues to the forefront of national attention and policy-making, as demonstrated by the climate change conversations in Paris in November-December 2015. Traditionally, agricultural output was viewed as a commodity, followed by energy availability, but now, in the most recent discussions, water has again become the most critical resource. This interplay, which is presented simplistically above, is the basis of much turmoil now and likely more in the future across countries, economies, and societies. Businesses and communities will take different approaches to combat this turmoil, from improved use efficiency to waste stream reuse. Currently, there is not an easy way to compare the efficacies of the various projects or technologies, nor is there an agreed upon weighting between energy, land, water, food and greenhouse gas emission lifecycle impacts. Establishing universal metrics will allow a standard quantification of these innovations and will allow for easier comparison. Admittedly, a universal yardstick for food-energy-water will always be inadequate for such a complex system, especially as the social metric is included to turn the FEW Nexus conversation into a more holistic and socially focused FEWS Nexus. However, not having any attempt to compare programs is even more of a disservice for such the critical body of work that the FEWS Nexus programs addresses, especially for the non-experts that will need to implement new innovations.

A thought experiment among the authors and their colleagues gave rise to this perspective work. Its origins were a discussion about how to rank different FEWS Nexus technologies for those on the ground, not for researchers but those who are going to actually implement the technologies locally. To give the reader some insight into this discussion, consider the following: assuming access to the technology, for a small community in rural Haiti, would planting genetically engineered plants, that reflect light to reduce water consumption, (Zamft and Conrado 2015) be a better investment than a small hand-powered, water pump (Lifepump 2015)? What about in rural Illinois? The purpose of this paper is to impress the need for universal metrics in order to answer questions such as these, and to suggest a measure of social viability be included in those metrics. The reality is that the field of food-energy-water society is so huge that no one expert can understand all local situations, and those locally may not have an expert on hand to help with a technical decision that has to be made on a complex innovation. A uniform technical-social yardstick, though flawed, could allow different communities in need to wisely pick between different FEWS Nexus systems with a good sense of which may be most useful for their needs and cultural integration. And it is likely that a small handful of people will be responsible for a new concept being pushing into greater use.

Results

Existing metrics for FEW

There are a wide variety of metrics that are related to the FEW Nexus; however, almost all of them are based on the combination of two areas, from energy-water-food, and a time period of measure. Table 1 below summarizes the majority of the metrics that have been used and a few more specific metrics as illustrative examples. This sampling of metrics was obtained by performing an extensive literature search through which the authors obtained energy-water-food metrics currently used in research pertaining to the FEW Nexus. Several metrics occurred in a majority of the works, and these are shown below in Table 1. More specific metrics were included as well as illustrative examples.

Almost all of the metrics for food-energy-water are some measure of the input per unit output, varied across a large scale (e.g., kWh to MWh to GJ). The variance of the different metrics is reflective of the diversity of the FEW issues, from water consumption during energy generation to the energy cost of agriculture. A metric that looks at biomass production as a function of incident light (kg/m^2-year) is a perfect illustration of a precisely defined measurement that would be disserved by a single, universal metric.

Existing social metrics for FEW

As evidenced by the works cited above, FEW Nexus metrics proliferate in academic research and writing. While there is progress in conceptualizing the tradeoffs between two of these resources at a time, there is a gap in the literature around not only the interplay of all three resources simultaneously but also especially defined social metrics. The mention of social metrics is primarily limited to either a qualitative/holistic descriptive tool used to hone an ultimate FEW-centered metric (i.e., what is the community's most pressing FEW need, and in that time and place to create a weighted value, on which resources should be maximized at what price) or it is a discussion of the price of the FEW metric in a social-economic setting, commonly using the metrics summarized below in Table 2.

Table 1 Sampling of existing metrics associated with the FEW Nexus

Metrics	Details
kWh/m^3	Water use for energy production (NSF 2014)
m^3/MWh	Water use for energy production (Walker et al. 2014)
L/GJ	Water to refine fuel (ADB 2013)
Liters evap/GJ	Evaporation to refine fuel (ADB 2013)
gal/MW	Desalination energy cost (Siddiqi and Anadon 2011)
kWh/m^3	Energy for wastewater treatment (Siddiqi and Anadon 2011)
gal/million BTU	Energy for material recovery (Finley and Seiber 2014)
kg/m^2-year	Biomass production per light incidence-year (Murphy and Allen 2011)
MJ/m^2	Upstream energy cost per m^2 (Murphy and Allen 2011)
kg/kWh	Grain production energy cost (Khan, Khan, Hanjra, and Mu 2009)
GJ/ton	Grain production energy cost (Hoff 2011)
MJ/m^2-person year	Biomass energy per person-year (Murphy and Allen 2011)
GJ/ton	Phytomass production (Koning et al. 2008)
GJ/ha	Biomass production per area (Spiertz and Ewert 2009)
kg/m^3	Grain yield per applied water (Khan, Khan, Hanjra, and Mu 2009)
$kcal/m^3$	Grain energy yield per applied water (Hoff 2011)

All of these equations take the form of $/[FEW-resource utilized] or $/[FEW-resource conserved] with differing incorporations of time sensitives and micro- or macroeconomic analysis. While some do a better job than others of indicating not only the financial but also the social costs of an intervention, none of them address the social stickiness issue and how to measure it. While academics continue to debate the best definition of successfully "socially sticky" interventions, for the purpose of this paper, the concept of interventions that are taught in a way that emphasizes interactive learning and stakeholder engagement and ownership is used. This definition was chosen for the evidence in past literature that demonstrates that the *process* of interactive learning results in greater adoption and retention rates by beneficiaries of education programs ranging from elementary scholastic programs to international development programs (for a more detailed conversation of this definition, please see Appendix 1 and Additional citations: Etskowitz (2000); Crocker (2008); Miller (2002); Lundvall (2010)).

Table 2 Sampling of social stickiness metrics

Type	Details
GDPI	How does the conservation of a FEW resource affect a nation's gross domestic income (GDI)?
PV	What does a resource's present value (PV) tell us about the economic impacts of the FEW intervention?
PCI	What affect will the FEW intervention have on the citizens' per capita income (PCI)?
Export/import value flow	What impact will the FEW intervention have on the nation's capability to trade/participate in the global economy?
IHDI	Does the innovation have a broad or specific group that has an increase in their inequality-adjusted human development index?

Discussion

Culturally sensitive and user-specific FEWS Nexus programs will likely achieve much higher rates of success than those solely based on the project or technological novelty, as has been historically seen in a variety of fields (Desowitz 1987; Beshears and Francesca 2015). Existing metrics look at FEW as an engineering process, without social issues, which was mostly true at a time when water was not treated as a commodity. Within creating technical metrics themselves, there are clear needs for multiple metrics to encompass most of the projects that focus on two of the three areas of the FEW Nexus. A single metric encompassing all three areas (food-water-energy) and a social measure would be difficult to create since most issues have one direct relationship and an inferred association.

As explained above, interactive learning was selected from existing social science work as a framework for successful innovation adoption. Specifically, interactive learning can be used to guide and assess the lifecycle of FEWS programs through three steps of analysis: (1) availability and awareness, (2) education and attitude, and (3) long-term adoption. Appendix 1 has more details for non-social scientists that want more information on understanding the social stickiness of their work.

With this three-phased framework in mind, there a few viable social variables that can be considered in creating a FEWS metric that fairly values the social stickiness (i.e., impact and sustainability) of an intervention. The inequality-

adjusted human development index (IHDI) was chosen as the most encompassing and publicly available metric, but potential options include (in alphabetical order):

Beneficiary data In an ideal world, FEWS interventions would follow a uniform existence that originated with innovation and progressed to dissemination through some sort of organized programming. If this were viable, beneficiary data collected through focus groups and interviews could help practitioners rate the community's adoption of such interventions on a standardized scale (i.e., asking beneficiaries to rank their satisfaction/use of the programming on a scale from 1 to 10). This type of targeted surveying would give practitioners an excellent idea of the success of FEW interventions' social stickiness, regardless of the scale of implementation, using a universally employed metric of success. This idealistic scenario has little practical use in the reality of the FEW innovation arena.

Inequality-adjusted human development index As defined by the UN, "*the IHDI takes into account not only the average achievements of a country on health*, *education and income*, *but also how those achievements are distributed among its population by* '*discounting*' *each dimension's average value according to its level of inequality*…." Inequality of life often arises or is exacerbated by unequal access to basic resources, specifically the FEW resources discussed in this paper. For example, children living in poverty, without access to clean water, electricity, or nutritious food will inevitably perform less well than their counterparts when assessed on the dimensions of physical health, good education, and family income. The IHDI could prove especially valuable to our analysis of life expectancy, as longer life is positively correlated with lack of disease, advanced education, and higher socioeconomic status—all of which play a core part in the UN's analysis (Alkire and Foster 2010). Other crucial metrics affecting the FEWS Nexus include population change, government acceptance, and financial support, which are reflected in IHDI.

Life expectancy Although imperfect, this variable also proves well suited to our purposes. Life expectancy data is widely available and well-documented enough to execute many nuanced time series and comparison studies across the globe. Second, as the goal of a FEW metric is to evaluate the efficacy of FEW programs in promoting global justice and improving the global quality of life, we can use greater life expectancy and/or more uniform life expectancies across the globe as a macrolevel indicator of FEW success. On a more microlevel, longer lives can be used as a proxy for measuring individuals' quality of life—as longer life indicates better health made possible by accessing quality resources. Longer life expectancy is also correlated with higher education and better health practices, which in turn gives insight into the second and third components of our interactive learning framework: populations with elder members are more likely to be educated (including in FEW-related innovations) and more apt to live long enough to pass their knowledge onto future generations for long-term adoption. However, life expectancy is also reflected in IHDI.

Recommendations

In considering all the aspects of the FEW Nexus above, certain recommendations were identified for universal metrics that would be helpful to share among those working on the area, be it in government agencies or in the rural developing countries. These metrics can offer simplified frameworks to consider and measure FEW Nexus interventions that would facilitate dialogue between those working in government offices and those working fields.

To achieve universal metrics with a social measure, that are easy to create and understand, the following recommendations include:

1. Identify a specific "first" target population and its IHDI: This allows those outside the R&D to understand the targeted population and the perceived utility of the project. Many projects have obvious global application, but where it first is intended to break ground is a good indicator of its flavor.
2. Implementation scale: The scale of FEWS Nexus projects is where much of the comparison across projects and outcomes breaks down. Simply creating bins that are reflective of global quartiles for energy/per capita, water/per capita, food kcal/per capita would help to place outcomes within relatable bounds.
3. Social stickiness: If it works, why will it benefit the target society (Cheung and Howell 2014)?
4. Estimate readiness: Technology readiness levels are well understood, but for FEW, we recommend simply stating between concept, prototype, and deployable.
5. Applicable universal metric: A calculated measurement from a selection of one or two standardized, universal metrics. What precisely the metrics could be are not presented here, and is the subject of the NCSE workshop this paper is based on.

Conclusions

After discussing the importance of the social metric and exploring how important the user experience is to the adoption and efficacy of FEWS Nexus-related efforts, it is clear that the social stickiness of an intervention should be a central consideration in its creation. Not making an attempt to assess and articulate the social stickiness is a common mistake that can be

avoided by honest attempts to address the target population's perceived benefit and compare it to practitioners' and experts' perceived benefit.

Future studies should focus not only on defining a universally accepted FEWS metrics but also exploring more nuanced variables that could measure FEWS interventions' success on a more nuanced local level.

In conclusion, the hope is that this paper prompts FEW metric evolution to a food-energy-water-society framework. The FEW nexus represents a combination of all important resources whose allocation and use necessitate tradeoffs that lead to economic and quality of life imbalances in the global society. Without social integration and a corresponding FEWS framework to guide scientific and political leaders, FEW projects will largely remain lab-centric or academic experiments because they will go no further than the R&D funding unless they can self-propagate global demand. A FEW-focused intervention that proves a shining example of digital age savvy with no users or social impact is a failure, regardless of its technical "wow" factor.

Appendix 1

Guide for creating social stickiness for food-energy-water programs

To begin, the availability and awareness [REF: An Empirical Test of an Export Adoption Model: Jeen-Su Lim, Thomas W. Sharkey, and Ken I. Kim MIR: Management International Review Vol. 31, No. 1 (1st Quarter, 1991), pp. 51–62] of FEW interventions is paramount to success. For any innovative FEW program to succeed, its beneficiaries must be aware of its availability and interested in learning how to use it properly. Therefore, a successful FEW initiative will not only be flexible and dynamic enough to be made available to a variety of areas suffering from the specific FEW issue, but its contents should be conducive to communicating its appeal to diverse audiences in a culturally sensitive and inviting way. As an example, let us consider an innovative campaign designed to educate beneficiaries on the importance of using clean water to wash their hands before eating. Using this paper's metrics, this campaign would be more successful if it was constructed in such a way that it could be made available and appealing to both schoolchildren and adult caretakers, as opposed to only one type of audience. In other words, the larger the number of beneficiaries aware of the availability of the FEW-related intervention and interested in learning about it, the more successful the effort.

Secondly, the education initiative accompanying the FEW intervention, as well as the educators' attitude [Understanding Technology Adoption: Theory and Future Directions for Informal Learning Evan T. Straub Review of Educational Research Vol. 79, No. 2 (Jun., 2009), pp. 625–649] will be enormously impactful in the intervention's success. While researchers debate the relative importance of the educator and adopter in studying successful innovation strategies, it is clear that the passing of knowledge from instructor to beneficiary sets the tone for subsequent use. While individuals will inevitably bring their own normative and behavioral biases to new practices, the interaction between teacher and student will not only serve to transfer vital content (i.e. information) from one person to another, but also attitudes. For example, past studies have shown time and again that children learn best and learn to prefer, and performer better, in subjects when their instructors promote a hands-on (i.e. interactive), supportive and transparent atmosphere where questions and dialogue are welcomed [Success and Failure on Classroom Tasks: Adaptive Learning and Classroom Teaching Mary Rohrkemper, Lyn CornoThe Elementary School Journal, Vol. 88, No. 3, Special Issue: Schoolwork and Academic Tasks (Jan., 1988), pp. 296–312]. In these cases, failure is viewed not as final but functional - and children are encouraged to learn from their past mistakes and re-engage with the material quickly and robustly. Using this second component of the paper's metric, a FEW-related intervention would be more successful if its educational campaign was conducted in a way that not only transferred key knowledge from instructor to beneficiary in a culturally-sensitive and understandable way, but also created a positive view of the intervention in the community. The combination of successful information- and positive-attitude- transfer will add to the impact and "social stickiness" of the intervention in a way that would be promising for not only present but future use and efficacy. In other words, the most positive the feedback from beneficiaries after their initial training/education on the FEW-related intervention, the more successful the effort.

Finally, the long-term adoption of the innovative FEW programming is critical in gauging its value going forward [Ethics of Global Development: Agency, Capability, and Deliberative Democracy, David Crocker]. While the FEW-nexus has long posed significant challenges to the global population, the specific pain points of its constraints and geographic locations of its complexities are evolving as quickly as our global population grows and diversifies. In order to remain useful in the long-term, successful FEW-related interventions will need to create opportunity for collaborative improvement that will allow beneficiaries and other stakeholders to contribute to its evolution in a democratic and interactive way. In the developed world, the best example of this type of continuous improvement and interactive learning is exemplified in crowdsourced wiki-sites that allow a community of users to share experiences, lessons learned, and best practices with others. However, these types of learning fora are often limited to areas with reliable Internet and plentiful technological supplies. FEW-related interventions, by their very nature, are often most in need of attention where these very

circumstances are absent, making this third criterion a key differentiator in a FEW-focused effort's social success and longevity. Recent research suggests a key tool in solving this dilemma will be the strategic creation and maintenance of public-private partnerships, with public sector actors identifying specific population's needs and private sector counterparts supplying those resources. If these types of partnerships can be encouraged and sustained to support FEW-focused efforts, it will help ensure that the FEW innovations of this day and age are sustainable, far-reaching, and well-funded [Balancing Social innovation in Technology with Social Inclusion: Dan Swinney. "The Bridge." Fall 2015, Volume 45, No. 3]. In other words, the more stakeholders that can contribute to and shape the future of a FEW-related effort in a way that will enhance its longevity and value in a variety of communities, the more successful the effort will be.

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