Network-based Drivers of Technical and Social Innovations in Integrated Food, Water and Energy (FEW) Systems

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Introduction

Food, energy, and water (FEW) systems are interconnected with one another in ways that have become critical to the services they provide. At the same time, these interconnections potentially pose vulnerabilities given that failures in any one of them can cascade to the others as well as to other infrastructures that support them. Interconnections can increase recovery time given the large number of systems that have to be restored.[1] Disruptions can become more severe the more tightly coupled and complex the interdependencies are.[2] Moreover, many FEW interconnections are often not identified or known to those who manage the individual systems, only to be discovered once a disruption occurs. Previous conceptual modelling has been done to portray these interconnections.[3] Many kinds of models are used to characterize interdependencies in general.[4] These can serve as a foundation to understand FEW linkages explicitly in the context of social and technological conditions that shape the connections. These relationships vary by condition, location, time, and the type and severity of external events. The term interconnections is used here to encompass two different kinds of relationships: dependencies which imply that one system affects another and interdependencies which imply multi-directional effects.[5]

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[1] Rae Zimmerman, "Implications of Combined Infrastructure Concentration and Interdependency for Extreme Event Recovery," in *Safety, Reliability, Risk, Resilience and Sustainability of Structures and Infrastructure*, Proceedings of the 12th International Conference on Structural Safety & Reliability (ICOSSAR 2017), eds. Christian Bucher, Bruce.R. Ellingwood and Dan M. Frangopol (Vienna, Austria, 2017), 2122-2131.
[2] Liz Varga and Jim Harris, "Adaptation and Resilience of Interdependent Infrastructure Systems: a Complex Systems Perspective," in *International Symposium for Next Generation Infrastructure* Conference Proceedings: 30 September - 1 October 2014, eds. T. Dolan and B. Collins (Vienna, Austria: International Institute of Applied Systems Analysis (IIASA), 2015), 132, 135.
[3] Rae Zimmerman, Quanyan Zhu, and Caroline Dimitri, "Promoting resilience for food, energy, and water interdependencies," *Journal of Environmental Studies and Sciences* 6 (2016): 50–61; Rae Zimmerman, Quanyan Zhu, and Caroline Dimitri, "A Network Framework for Dynamic Models of Urban Food, Energy and Water Systems (FEWS)," *Journal of Environmental Progress & Sustainable Energy* 37, no. 1 (2018): 122-131.
[4] For a summary of these see: Min Ouyang, "Review on Modeling and Simulation of Interdependent Critical Infrastructure Systems," *Reliab. Syst. Saf*. 121 (2014): 43 –60.
[5] Steven M. Rinaldi, James P. Peerenboom, and Terrence K. Kelly, "Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies," *IEEE Control Systems Magazine*, 21, no. 6 (2001): 12; Frederic Petit, Duane Verner, David Brannegan, William Buehring, David Dickinson, Karen Guziel, Rebecca Haffenden, Julia Phillips, and James Peerenboom, "Analysis of Critical Infrastructure Dependencies and Interdependencies" (Lemont: Argonne National Laboratory, 2015), 7-12; Rae Zimmerman, "Critical Infrastructure and Interdependency

The use of the term interconnections has been used before for these kinds of infrastructure relationships as well as the related concept of infrastructure concentration.[6]

In this paper FEW interconnectivity is identified and analyzed in general and then in the context of the COVID-19 pandemic. First, generic FEW relationships are presented in the introduction based on networks emphasizing the type and direction of connections drawn primarily from the literature. These relationships are combined with and developed further in the context of distortions created by extreme conditions, using the COVID-19 pandemic that emerged in late 2019 to exemplify extreme conditions and how they have shaped and continue to shape FEW relationships. Second, characteristics of and trends in the individual sectors, i.e., food, energy and water are then emphasized in the context of the pandemic. Third, combinations of water and energy first and then those two combined with food systems are presented. Finally, in conclusion, the frameworks and the scenarios are discussed that alter components in integrated, interconnected FEW systems that provide innovative ways for decision-makers to identify how changes in food, energy, and water options either under their control or not are a way to manage these systems, communicate them to constituencies and make investments accordingly to mitigate adverse effects of extreme perturbations.

Network-based Perspectives for FEW Systems

Networks are common approaches to develop and portray frameworks and concepts for interconnections. Networks have the benefit of scaling relationships at many geographic levels. Linkages within the food supply chain are constantly changing even under unperturbed conditions so defining a steady-state or "normal" state is often difficult. Different scenarios portray these variations in terms of (1) socially-driven consumer styles, preferences, and perceptions about safety, security, availability, aesthetics, and ability and willingness to pay (2) technical resource availability and practices for food production, storage, water, and transport (resource type, quantities, capacity, etc.) and (3) combinations of social and technical alternatives to define gaps in social and technical expectations. Another component of the social-technological linkage is ecological, which with respect to food relates to ecological and environmental conditions and changes related to social and technical components. While the emphasis is upon energy and water, FEW systems are also influenced by other infrastructures, particularly transportation and communications, that support those systems.

COVID-19 Impacts on FEW Systems

New sensitivities and vulnerabilities encountered by FEW systems have emerged from the catastrophic pandemic effects of COVID-19 that dramatically transform and distort food supply chains. These impacts have in turn cascaded into the water and energy systems to which they are connected. Interrelationships among individual systems escalate the impacts by increasing in network terms the number of nodes and paths affected. Many of the distortions shape and are also driven by human behavior in reaction to new conditions, and human behavior is a

Revisited," in *The McGraw-Hill Homeland Security Handbook* – 2nd edition, ed. David G. Kamien (New York, NY: The McGraw-Hill Companies, Inc., 2012), 443-445.

[6] Rae Zimmerman, "The Interdependencies of Infrastructure," in *Urban Infrastructure: Interdisciplinary Perspectives from History and the Social Sciences*, eds. Jonathan Soffer, Joseph Heathcott, and Rae Zimmerman (Pittsburgh, PA: University of Pittsburgh Press, forthcoming).

common driver of how people consume food and use infrastructure-related services.[7] First, consumers fearing shortages resort to panic buying. This behavior can then increase shortages in certain food sectors at least temporally until supply chains can adjust. Second, stay at home orders are often altering human food preparation and consumption behavior, such as increasing home meal preparation. Home-centered food activities have shifted food products consumed and how they are transported. One of the basic challenges of the food industry and associated infrastructures upon which it relies is coping with the instability in consumption patterns.

Consumption depends upon many factors often distinct from yet affected by an extreme event such as COVID-19. For example, Leiserowitz et al. have related income to the ability of people to access certain kinds of foods.[8] The types of foods people eat vary by gender.[9] Dietary and style trends impose yet another layer on consumption patterns. Dietary shifts to fresh foods and vegetables away from processed foods will result in larger water consumption as well as increasing the amount of organic waste at the end of the chain.[10]

Characteristics of Individual FEW Components

Food Systems and Distortions Created by the COVID-19 Pandemic

Food systems consist of numerous components broadly categorized as type of product, preparation, packaging, transport and distribution, and disposition of residuals at every stage. Steiner et al. defines food systems as "a complex web of activities involving production, processing, transport, and consumption."[11] Energy and water are used throughout each of these stages.[12] Each of these is described below and ways the COVID-19 pandemic actually or potentially changed the nature of water and energy use, though it is too early to identify changes in those nodes and links in the network.

Type and diversity of products

The number of variations on any given product can be vast. Likewise, a large number of producers offer these products at any given time. Given more intense demand some producers are resorting to horizontal integration in the form of contracting or outsourcing production functions. General Mills for example reported increasing its use of third party food-production

[7] Rae Zimmerman, "Human Behavioral Factors that Shape Urban Physical Infrastructure Services," in *Proceedings from EDRA 50: Sustainable urban environments*, eds A. Beth, R. Wener, B. Yoon, R. A. Rae, and J. Morris (Brooklyn, NY: Environmental Design Research Association, 2019).
[8] Anthony Leiserowitz, Matthew Ballew, Seth Rosenthal, & Jillian Semaan, *Climate Change and the American Diet* (New Haven, CT: Yale University and Earth Day Network, Yale Program on Climate Change Communication, 2020), 4.
[9] Leiserowitz et al. *Climate Change and the American Diet*.
[10] Zimmerman, Zhu and Dimitri, "A Network Framework," 126.
[11] A. Steiner, G. Aguilar, K. Bomba, J.P. Bonilla, A. Campbell, R. Echeverria, R. Gandhi, C. Hedegaard, D. Holdorf, N. Ishii, K. Quinn, B. Ruter, I. Sunga, P. Sukhdev, S. Verghese, J. Voegele, P. Winters, B. Campbell, D. Dinesh, S. Huyer, A. Jarvis, A. M. Loboguerrero Rodriguez, A. Millan, P. Thornton, L. Wollenberg, S. Zebiak, *Actions to Transform Food Systems Under Climate Change* (Wageningen, The Netherlands: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), 2020), 13.
[12] Zimmerman, Zhu and Dimitri, "A Network Framework," 125.

entities.[13] Alterations in the location of production relative to consumers have been going on for some time. A notable example is the use of indoor spaces to grow foods such as vertical gardens which may have originated for environmental purposes to cleanse the air or water.[14] In addition to type of product is the diversity of offerings, which has declined over the course of the pandemic.[15]

Preparation and processing

Ways in which foods are prepared or processed at production or intermediate handling facilities prior to packaging include no change (natural), mixing and chopping or cutting, baking, freezing, freeze-dried, vacuum sealing, washing and other cleaning. The energy implications of different types of processing can be substantial. For example, freezing is considered to have the highest energy usage and baking is second.[16] Energy usage where freezing is not involved is estimated to range from a quarter to three-quarters of the energy usage in processing.[17] Building systems such as lighting, HVAC and pumps also consume large amounts of energy. As people stayed at home more, baking increased in popularity, which would contribute to the shift of energy usage to the residential sector. Apparently related to the surge in baking was a growing scarcity of flour and bread ingredients such as yeast however, in mid-July 2020 the scarcity resided.[18]

Packaging (which is related to preparation)

Packaging operations consist of a wide range of materials and processes. Materials in common use include metal, synthetic material, glass, plastic, paper, and cardboard. Distributors can vertically integrate by assuming packaging functions. Large chain store retailing distributors recently began packaging milk for example by running their own bottling plants responding to increased milk consumption accompanying stay at home restrictions.[19] Producers of cereals have assumed packaging functions.[20] Packaging materials can become limiting factors in food production. For example, as the popularity of certain soup brands increased, a shortage of cans used to package them occurred, a condition that the pharmaceuticals industry faced also.[21] In

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[13] Mark Maurer, “General Mills Adds More Outsourcing Partners as It Aims to Meet Packaged-Food Demand,” *Wall Street Journal*, July 27, 2020, https://www.wsj.com/articles/general-mills-adds-more-outsourcing-partners-as-it-aims-to-meet-packaged-food-demand-11595842200?mod=searchresults&page=1&pos=4

[14] Dickson Despommier, “Vertical Farms Fill a Tall Order,” *Wall Street Journal*, July 25, 2020, https://www.wsj.com/articles/vertical-farms-fill-a-tall-order-11595649662?mod=searchresults&page=1&pos=1

[15] Annie Gasparro and Jaewon Kang, “From Flour to Canned Soup, Coronavirus Surge Pressures Food Supplies,” *The Wall Street Journal*, July 12, 2020, https://www.wsj.com/articles/coronavirus-surge-challenges-struggling-food-supply-chains-11594546200?mod=searchresults&page=1&pos=1

[16] Zimmerman, Zhu and Dimitri, “A Network Framework,” 125, citing E. Masanet, P. Therkelsen, and E. Worrett, Energy Efficiency Improvement and Cost Saving Opportunities for the Baking Industry (Berkeley, CA: Ernest Orlando Lawrence Berkeley National Laboratory, 2012), LBNL-6112E, 5.
https://www.energystar.gov/sites/default/files/buildings/tools/Baking_
Guide.pdf

[17] Masanet, Therkelsen and Worrett, 5.

[18] Gasparro and Kang, July 12, 2020.

[19] Cary Docter, “Walmart, Kroger Bottle Their Own Milk and Shake Up American Dairy Industry,” *Microsoft News,* July 27, 2020. https://www.msn.com/en-us/news/local/walmart-kroger-bottle-their-own-milk-and-shake-up-american-dairy-industry/ar-BB17hACd

[20] Maurer, July 28, 2020.

[21] Scott Tong, “New Supply-Chain Crisis During Pandemic: Not Enough Cans for Food,” *Marketplace*, July 24, 2020, https://www.marketplace.org/2020/07/24/new-supply-chain-crisis-during-pandemic-not-enough-cans-for-food/

addition to packaging materials, packaging technology also became a limiting factor to the distribution of certain foods. For example, in England, flour distributors were limited in their ability to directly send goods to households by the need to scale down the size of the packages from industrial or commercial sizes.[22] Contents of packaging are typically very complex. The U.S. Office of Technology Assessment analyzed the profile of a typical chip bag, identifying multiple layers of different materials and coatings.

Transport and distribution

Although the FEW concept does not directly include transportation, indirectly transportation has a considerable effect on the energy and water systems linked to food and vice versa. First, stay at home orders and quarantining have increased deliveries for restaurants and grocery stores.[23] In both sparsely populated and dense areas conventional carriers such as the United States Postal Service (USPS), Federal Express and the United Parcel Service (UPS) have seen dramatic increases in service. Sometimes producers will vertically integrate by assuming the transport function directly. In denser inner city areas transport additionally involves motorized delivery via micro-transit to bring food to the consumer or alternatively having consumers use curb side pickup. The proliferation of multiple modes of travel reflects this condition. Directly related to food production are the trends in selected transportation modes that affect workers. The dramatic decline in mass transit has compromised the ability of many workers to reach work destinations.

Disposition of residuals

The UN and USDA estimate that about a third of the food supply is wasted globally or in the U.S. respectively.[24] Food residual processing prior to disposal and transport to disposal sites requires water and energy. Patterns of food disposal can vary considerably by population characteristics of the consumers and the place of consumption.

<u>The Energy Sector</u>

Energy systems have their own individual characteristics independent of the relationship with food yet act as contexts or constraints on food systems.

As the pandemic expanded, energy demand showed dramatic shifts in the magnitude and distribution of demand across consumption sectors. The residential sector's consumption increased due to stay at home and work at home practices. Industrial and commercial sector consumption declined due to business declines. Demand also shifted over the course of a day generally starting and ending later in the day. The vast electric power network that supports distribution such as electric power plants and transformers has had to adapt quickly. Where the system is overloaded the outcomes are underground fires and outages. With an increased spread in the pandemic, the U.S. Energy Information Administration in July 2020 tracked changes in electric power demand nationwide and the factors contributing to it. For electricity

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[22] Geneva Abdul, "Pandemic-Baking Britain Has an 'Obscene' Need for Flour," *The New York Times,* May 20, 2020, https://www.nytimes.com/2020/05/20/business/britain-flour-mills-baking.html?searchResultPosition=4

[23] Nina Trentmann and Mark Maurer, "Fast-Food Chains See Shifts Made During Pandemic Paying Off," *The Wall Street Journal*, July 29, 2020.
https://www.wsj.com/articles/fast-food-chains-see-shifts-made-during-pandemic-paying-off-11596032316?mod=searchresults&page=1&pos=1

[24] Leiserowitz, et al., 2020, 17.

consumption, U.S. Energy Information Administration estimated a 4.2% decline from 2019-2020, a 7.6% decline in the commercial sector, 5.6% in the industrial sector, and about the same in the residential sector.[25] However, in NYC, Meinrenken et al. found for 400 apartment buildings that weekday electricity demand increased particularly in the residential sector by 7% after the stay-at-home-order.[26] For New York City, changes in electric power demand for both weather extremes and other conditions are reported by the New York State Independent System Operator (ISO) and traced by others. The New York State ISO has pointed to declines in energy use in the early spring probably reflecting changes in the large industrial and commercial sector users.[27] As the summer of 2020 approached, further increases in energy usage were expected given increased residential uses of electricity for cooling due to expected increases in temperature.[28] Patterns of energy use are strongly affected by user behavior.[29]

At the same time energy suppliers are struggling to adjust supplies to meet the shifts in demand, there is also continued support for renewable energy that had been an increasing share of the energy sector. Columbia University's Energy Policy Tracker shows that 39% of public funds for energy are for clean energy and 51% for fossil fuels.[30]

<u>The Water Sector</u>

Water impacts food and energy infrastructure at many levels especially in the context of extreme events. First, the infrastructure providing water ranges from large storage systems to finely distributed conveyance structures. Second, flooding can overwhelm the functioning of many of these water system components, particular for storage and treatment. Third, different economic sectors vary in water usage rates. For example, the IPCC noted that agriculture among other factors has contributed substantially to the increased rate of both land and water use, and in particular with "agriculture currently accounting for ca. 70% of global fresh-water use (medium confidence)."[31] Further down the food chain, water is used for cleaning food products, and production areas and freezing where applicable.[32]

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[25] U.S. Department of Energy, Energy Information Administration, *Short-Term Energy Outlook*, 2020 (July 2020): 3. https://www.eia.gov/outlooks/steo/pdf/steo_full.pdf.
[26] C. Meinrenken, V. Modi, K. R. McKeown and P.J. Culligan, "New Data Suggest COVID-19 Is Shifting the Burden of Energy Costs to Households," (New York, NY: Columbia University Earth Institute, April 21, 2020).
[27] New York State Independent Operator (NYS ISO). 2017a. 2017 Load & capacity data "gold book." https://www.nyiso.com/documents/20142/2226333/2017-Load-Capacity-Data-Report-Gold-Book.pdf/8f9d56cc-dc20-0705-ca19-52e35a535b44; NYS ISO. 2017b. Power trends report 2017. https://www.nyiso.com/documents/20142/2223020/2017-Power-Trends.pdf/7baea2ba-cdca-93a6-2e45-4d948383ccbd.
[28] Meinrenken et al., 2020.
[29] Johan Schot, Laur Kanger, and Geert Berbong, "The Roles of Users in Shaping Transitions to New Energy Systems," *Nat. Energy*, 1, no. 5 (2016): 1-7.
[30] Columbia University, Center on Global Energy Policy and 13 expert organizations (2020) Energy Policy Tracker database.
[31] Intergovernmental Panel on Climate Change (IPCC). *An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Summary for Policymakers*, (Geneva: Intergovernmental Panel on Climate Change (IPCC), 2019), 5.
[32] See references in Zimmerman, Zhu, and Dimitri (2016, 2018).

Connectivity

Water-Energy Connections

Energy and water inputs to one another occur in several ways: unit inputs of energy for water production, unit water inputs for energy, and unit water and energy inputs for selected food consumption levels. The U.S. Department of Energy has quantified water-energy inputs.[33] Zimmerman et al. (2016, 2018) and Canning et al. (2010) and various references within those articles are an important foundation for understanding the networks and the nature and intensity of the interconnections.[34] Zimmerman et al. (2017) summarized selected U.S. DOE (2014) and Meldrum et al. (2013) relationships for water and energy as unit levels of water consumption (in terms of gallons per MWh) for coal, natural gas and nuclear fuels across the production functions of extraction, processing and transport.[35] As one might expect, the unit values varied dramatically with nuclear exceeding other fuels in unit water consumption and processing ranking high among the other functions in water use.

Water use requires energy to run equipment, e.g., to operate pumps and other equipment.[36] Energy in turn requires water for production. In Hurricane Irene, a survey conducted by the Cadmus Group (2012) identified power outages as the most significant factor in the inability of water systems to function.[37] Both water and energy are required throughout the food system by transportation systems to move components from one production stage to another.

Food, Water and Energy Connections

Given the vast, rapid, and often unstable transformations occurring in the food system under typical conditions, it is difficult to anticipate how energy and water usage is affected by the food system changes as a result of the COVID-19 pandemic. Some examples are noteworthy that were introduced earlier.[38] If more home cooking occurs then water usage in the residential sector can increase. If food distribution points shift to doing food packaging and production, then water and energy usage could increase at those points. Water and energy usage can shift to residences if there is an increase in fresh food consumption by residences. Where more processed foods are used then water and energy usage would increase at food processing sites. A first step is understanding how these relationships exist under general conditions in the absence of extreme events, as has been described above.

Conclusions

Lessons from many extreme events have shown that the structure of FEW relationships is sensitive to the hazards these events pose. Networks are an important foundation for understanding these relationships and impacts on them. The COVID-19 pandemic is presenting unusual stresses on FEW connections and an important question is how similar these are to

[33] U.S. Department of Energy, *The Water-Energy Nexus: Challenges and Opportunities* (Washington, D.C.: U.S. DOE, 2014).
[34] Zimmerman et al. 2016, 2018; P. Canning, C.A. Huang, K.R. Polenske, *Waters, Energy Use in the US food System*. (Washington, DC: US Department of Agriculture, Economic Research Service, 2010).
[35] Zimmerman et al. (2017): Table 2
[36] Zimmerman et al. (2018), 126.
[37] The Cadmus Group, Inc. "Report on the Operational and Economic Impacts of Hurricane Irene on Drinking Water Systems" (Denver, CO: Water Research Foundation, September 2012).
[38] See Zimmerman, Zhu, Dimitri (2016, 2018).

those experienced from other hazards and whether or not the adaptations and mitigations are similar. Dramatic gyrations in the demand for different food products is likely to produce substantial changes in the energy and water sectors that support them. Although some of the changes in those sectors individually are becoming apparent, the connection to changes in the food system are yet to be seen. Nevertheless, it is important to explicitly think about the connections in order to protect the vital energy and water resources upon which food systems depend for resilience and sustainability. The decline in energy usage and the shifts in energy usage toward the residential sector is probably reflecting the increase in the home bound population, and much of the activity is related to food preparation. Planning for such flexibility may be a critical part of future energy planning, including supporting what has already emerged as a trend in the direction of increased use of renewables.[39] Similarly, water usage all along the food chain will likely change as the food supply chains shift in terms of types of food products consumed.

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[39] Columbia University, Center on Global Energy Policy and 13 expert organizations (2020) Energy Policy Tracker database.