Chapter 2
Systems Science

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2.1 Introduction to Systems Science

A system is a set of things connected in a way that creates some unified whole. The nature of a system is, to some degree, simple, complicated, or complex. This distinction between "complicated" and "complex" is important and subtle and is addressed below (Sect. 1.4.2).

Simple systems typically have a small number of parts with usually linear "cause–effect" interactions between the parts. For example, imagine a system of pulleys connected by a rope where a force pulling on the rope turns one pulley and then additional pulleys in a linear succession through the simple application of force imparted through friction between the rope and the pulleys. As an output, one of the pulleys is attached to a weight and lifts that weight. If the pulleys are suitably arranged, an applied input force moving the rope a considerable distance can result in a much larger force moving the weight a much shorter distance. This simple system operates under the application of physics to a small number of parts. There is an independent variable X (or a small number of independent variables), a dependent variable Y, and changes in X explain changes in Y through some function $Y = f(X)$. Simple systems have clear boundaries and are fundamentally predictable without much effort (if you know the calculus).

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A food, energy, or water system might be defined by the set of sources, movements, uses, and sinks that constitute a way of understanding the unified whole in the context of a particular place and time. There are many parts, and the interactions between them are by no means simple; the relationships may be

For example:

- Nonlinear (e.g., water withdrawals may have thresholds beyond which significant changes in ecosystem function occur or where certain uses are prohibited).
- Multivariate (e.g., changes in energy demand depend on weather conditions, the rate economic growth, building size and location, demographic changes, and other factors).
- Multiscalar (e.g., food production occurs at the local level; domestic markets at a regional level; and trade at an international level; with each affected by factors at that level).

Further, a system's boundaries may be multifaceted (e.g., a food–energy–water system may have boundaries associated with an agricultural region, a regional electric grid; a watershed; and several political jurisdictions).

Studying such systems requires the careful use of science and much effort, but complicated systems are still fundamentally predictable in principle.

As the number of simply interacting subsystems within a system increases, the number of interactions increases geometrically, and systems become complicated very quickly. For example, a water system in isolation might have N interactions, an energy–water system might have $2N + 2$ interactions (energy and water separately, plus each of their effects on the other), and a food–energy–water system might have $3N + 6$ interactions following the same pattern. Water systems are determined by processes of supply and demand for water, water balances, and water quality, but when energy is included, every change to the water system cascades to affect the demand for energy to produce water and the demand for water to produce energy.

Complicated systems are predictable in practice if you can afford the workforce, data collection, and computing power necessary. Engineers are specialists in designing and managing complicated systems—like the space shuttle, the power grid, a fuel refinery, or a computer.

Complex systems are different because although they may have many parts or only two, they are fundamentally unpredictable to some degree, and chaotic because feedback renders the traditional idea of cause and effect meaningless. "Interaction" is a general term for all kinds of connections, correlations, feedbacks, and cause-effect relationships—both biophysical and human. Forcings or controls are interactions by which one subsystem causes effects in another subsystem. Feedback involves loops of causes and effects. For example, when increased demand for water increases demand for energy to produce water which reduces the supply of water and increases the cost of both the energy and the water. More broadly, weather conditions, policy decisions, ecological impacts, and economic activities are all difficult to predict and have two-way dependencies and impacts on the demand and production of FEW commodities over different timeframes.

The principles or processes in a complicated system might include the application of physics, chemistry, botany, hydrology, engineering, and many other physical and life sciences, as well as the application of social sciences applied to human beings, social organizations, and societies which operate under various economic, political, and sociocultural rules.

For FEW systems, these principles and processes of "system science" are applied to the sources, movements, transformations, uses, and sinks of food, energy, and water—a combination of the functioning of the biophysical world and the demands and impacts of the social world.

Engineering, in particular, is the discipline that focuses on the quantitative analysis, optimization, and control of real-world systems, including the infrastructure underlying FEW systems. Historically, engineering has focused on complicated systems, not complex systems, but this is changing presently.

Applied areas within the social sciences (psychology, economics, political science, sociology, anthropology) focus on the analysis, optimization, and management of real-world human-based systems.

System science is the scientific study of a unified whole composed of many parts:

1. It is defined by some unifying identity or macroscopic framework (e.g., food, energy, or water).
2. It exists within certain **boundaries** of space, time, or institution.
3. It relates to **external or exogenous factors** or "forcings" (e.g., sources and sinks of matter or energy and drivers) that may be parts of other systems (e.g., the climate system interacting with a water system).
4. It has **structural relationships** or "networks of relationships" among its parts (e.g., the relationship of water flows between rainfall, reservoirs, aqueducts, and consumers) and between its parts and external systems. **Structure** establishes the potential for function and the pathways of functional interaction.
5. It has internal or endogenous **functional relationships** between the parts which are governed by natural and anthropogenic principles or processes (laws of thermodynamics, economics, engineering of infrastructure, public policy, etc.). Function is distinct from, and constrained by, structure. Function is what matters, but structure enables function. Infrastructure is structure while commodity flow is function.
6. It often involves **agents** that are not entirely rational or predictable.
7. It changes **dynamically** in response to external and **internal interactions**.
8. It may be described over space and time by mathematical **models** which attempt to recognize and incorporate all crucial factors.

The objective of system science is to understand the entire system holistically, and with as much precision as needed for purposes of analysis and decision-making (i.e., excess detail can be ignored). At the very least, system science is needed to establish the nature of the system (simple, complicated, complex) so that the limits of its predictability can be clearly understood.

How a system is defined and studied is usually shaped by balancing important human dimensions, e.g., the scale and boundary of the decision-making process or institution, such as a farm, or a political jurisdiction, such as a city (Chap. 18) with consideration of physical scales and boundaries, e.g., an environmental boundary like a watershed (Chap. 19), or the boundaries of important material or energy inputs and outputs. These boundaries are not just defined by space but also time (e.g., growing seasons or political cycles). This is a **Coupled Natural-Human System** (CNH).

The application of system science is to predict system behavior in order to (1) design systems and (2) guide decision-making to maximize benefits and minimize adverse impacts.

Models of systems (Chap. 15) are often considered in two ways: "bottom-up" and "top-down."

Bottom-up models start by experimentally isolating and understanding the individual components of a system and then adding them together (or linking them) to construct the system. For FEW systems, bottom-up models tend to emphasize the environmental and technological aspects of a system. The challenge with bottom-up models is that the whole is greater than the sum of the parts; that is, the isolated parts do not add up to explain the whole, due to the complex interactions between the parts. For example, efforts to model how water moves through the system may capture environmental factors like precipitation (snow, rain), movement of water through the hydrologic cycle, and even the built environment like dams and networks of water distribution, but miss the legal and policy structures that also control water flows.

The main problem with bottom-up models is, therefore, that they are never complete or detailed enough to understand the system's behavior as a whole—although they may be very accurate for one subsystem or component.

A secondary problem with bottom-up models is that their representation of the whole system's behavior may be poor despite a good representation of the behavior of the subsystems. For example, a weather model of a hurricane could get the energy of the ocean surface precisely correct, and also its rainfall totals, but still fail to accurately predict the trajectory of the hurricane as a whole.

Top-down models "deconstruct" a whole system into a few essential components, and then proceed to disaggregate each of the components into a hierarchy of finer subsystems. For FEW systems, top-down models tend to emphasize economic and policy aspects of a system and global or national processes. The problem with top-down models is their limited predictability because of complicated and complex systems where the large-scale pattern emerges from the interactions of many atomic (small) parts; this yields surprises. For example, a top-down model of regional water stress might be based on demographics and prosperity, which motivate financing and policy, which leads to infrastructure, and withdrawals. This approach might accurately project long-term water shortages and economic problems of a water-scarce arid region by evaluating aggregated supply and demand for water. However, this model could not tell you much about whether any individual city or family is going to run out of water. One city might be in serious trouble, and another immune to the water stress, based on details that are only available at a finer level of

disaggregation. Such an approach also has limited ability to identify and quantify ecological impacts and environmental trade-offs.

The pros and cons of different approaches to modeling systems are addressed later in the book (especially Chap. 15).

2.2 Complex Systems

Complex systems have attributes that distinguish them from simpler systems; including:

- **Heterogeneity**: The many parts of the system are diverse (heterogeneous) in their characteristics and modes of operation. In the systems that we are considering, there can be both many distinct biophysical and human elements operating in diverse ways. Subsystems are of many types; operate at many scales; can process mass, energy, or information; and can be quantified with many different units. For example, the biophysical aspects of food production are quite different to the financial and policy aspects. A second example is that electrical power production typically occurs at a few large generation facilities of a few types, but food production is widely distributed across the landscape and takes on near-infinite forms.
- **Interconnections**: Components (subsystems) of the system are interdependent. That is, the behavior of subsystems is dependent on the behavior of other subsystems. Components can act on each other directly and indirectly through other parts of the system. There can be interactions operating under the laws of nature and interactions operating under the influence of cultural norms, governmental laws, human motivations, and economic principles as applied by independent decision-makers. Physical and human elements are interrelated because of the way they impact each other and depend on each other (recognizing that natural ecosystems could function without human intervention while human activities shape how many ecosystems function). For example, policies and laws governing natural water bodies are connected to food consumption through a series of interconnections; water law > water body > water use by farmers > food availability and price > food retail > food consumer.

  Often interconnections can be described by a set of mathematical expressions. This can allow systems to be described by a computational model where many mathematically described interactions between subsystems are calculated simultaneously and influence the next set of projected interactions between subsystems. These types of models are referred to as **Process Networks**.

  Process Networks are typically represented by graphs of nodes (representing subsystems) connected by "edges" (lines representing interactions) and studied within a field of mathematics called "Network Theory." Social networks, communication systems, and FEW infrastructures are subtypes of process networks.

  An electric grid is an excellent example of a process network because generation and demand must be kept in balance at all times to the grid to function. As a result, an extensive network of technology measure conditions at a large number of nodes on the grid and provide feedback to electricity sources (e.g., power plants or energy storage devices) to increase or decrease generation to match demand. The application of electric sensors and internet communication to the grid constitutes the so-called "smart grid." As the diversity of energy sources increases along with more distributed variable generation sources, more energy storage devices, and demand management tools, the need for ever more sophistical tools to ensure a reliable and resilient electric grid.

The critical need for balancing supply and demand for all FEW commodities and the existence of nodes where commodities flow in and out on a continuous basis mean that process networks are a very useful tool for FEW systems.

Network theory provides many tools for the analysis of complex systems; most network theory applies to simple networks like internet-based social networks, but more sophisticated network methods are being developed to address the more complicated types of real-world Process Networks found in FEW systems. Scientists and engineers have done the most science on communication and computer networks, so the fields of **Information Theory** and computer science are particularly valuable sources of methods for Process Network study.

- **Distributed Natural and Distributed Human Controls**: The combination of the complex interactions between different parts of a system, and changes to individual elements, causes changes to ripple through the entire system. A complex system is not controlled by one force or by one component but by multiple forces and components that are distributed throughout the system. Ecosystems and the laws of nature provide a number of controls on how systems operate. Distributed natural controls for FEW systems include such factors as soil conditions, annual climate cycles, seasonal precipitation, and wind speed.

  Similarly, human systems usually have many independent decision-makers and actors (**agents**) who have different priorities and objectives and frequently work toward different (and often conflicting) outcomes. For example, the individual choices of billions of people determine the demand for food products, which in turn drives production patterns and natural resource consumption. However, control is not equitable. Hierarchies and hubs for control exist; there is a net flow of information from "controlling" to "controlled" parts of the system, even when both parts are exerting some control.

  Distributed human controls for FEW systems include such factors as fertilizer application by farmers and government agricultural policies for food; drilling of new oil wells and wholesale electricity markets for energy; groundwater pumping rates and water pricing for water; and for all aspects of FEW systems, consumers, investors, distributors, and regulators in diverse locations.
- **Hierarchy**: Complex systems still have hierarchies of scale, importance, and control. Despite their heterogeneity, interdependency, and emergent properties, some parts of the system exert more control than others, and some scales are more important than others. Complex systems have distributed control, but there are centers and hubs of control. At the same time, a more complete understanding of a complex system includes recognition of the free parameters of

smaller-scale elements. For example, farming systems operate with regional agricultural ecosystems that define what types of farming are practical, and agricultural ecosystems exist within larger economic systems, which operate within sociopolitical systems that shape investment and policy drivers. A second example is the U.S. Power Grid, which has three physical "interconnections" (Eastern, Western, and Texas), but within each interconnection, there are various "balancing regions" that govern power quality, and within those multiple power utilities produce and distribute the power.

- **Emergence**: The characteristics of the whole system cannot be adequately understood from the separate study of individual parts and the bottom-up **aggregation** of the properties of disconnected components. Instead, characteristics of the entire system "emerge" from the interconnections between the fine-scale parts of the system. For example, epidemics that destroy food crops or livestock emerge from a combination of bad luck and bad management practices at individual farms and processing facilities and then spread widely only if enough facilities follow bad management practices.

  A simple way to visualize emergent properties is to consider how the features of a building are distinct from the separate properties of the various elements of construction, such as the joists, bricks, windows, doors, wiring, and paint. One might say that the properties of the building, its rooms, its controlled environment, and so forth emerge from how the building elements interact with each other.

  Food, energy, and water markets, where they exist, are emergent properties that result from the interaction between consumers, policymakers, energy producers, and the technologies and infrastructure required to produce, move, and utilize the various forms of food, energy, and water.
- **Feedback (Coevolution, Synchronization)**: As one part of the system changes or "evolves" over time, other parts of the system will change or evolve as a result. That change will influence the change of the first part, a phenomenon known as "feedback." As a result, parts of the system "coevolve" based on their interactions with each other, yielding synchronized or partially synchronized subsystem states. In the presence of feedback, "cause" and "effect" lose their classical or original simplistic meaning. Complex systems may exhibit forms of relative stability or equilibrium even as they include dynamic processes. However, slow or small changes may lead to rapid or abrupt changes, which can sometimes occur at "tipping points" where nonlinear change can "cascade" through a system.

  For example, food production coevolves with energy and water systems because of the importance of water for irrigation and energy for fertilizers and machinery. In a second example, decreased electrical power demand decreases demand for water to generate power and then decreases the demand for power to pump the water.
- **Self-organized criticality**: The dynamics of complex systems often grow toward one or more critical limits where "catastrophe" (rapid and large-scale change) is just a small step away, and where a small disturbance to push them over that edge into a new system state. Forest fires, earthquakes, and avalanches are examples

in natural systems, but in human systems, we see "trigger events" that mobilize action and fundamentally shift the landscape. Trigger events can include, for instance, major disasters, "viral" cultural moments, key elections, successful terrorist attacks, the opening of a new communication or transportation route, or the introduction of disruptive technology. For example, a 5-year drought in Syria is thought to be a trigger event that led, in part, to the Syrian Civil War (see Chap. 20). The dramatic shifts in the energy systems of many countries as a result of the energy crisis of 1973 is another example.

- **Sensitivity to Initial Conditions**: How a system evolves is dependent on the starting conditions of a system. In many cases, the evolution of a system is dramatically different based on small changes in the initial state. The widely known "butterfly effect" illustrates this point, but is commonly misunderstood. The classic "butterfly effect" is the best example of the importance of initial conditions—and of chaos in systems; when a butterfly flaps its wings in China, the tiny alteration in the system's condition can produce dramatically different weather in the USA—through a series of amplifying feedback loops and processes in the atmosphere.

  In practice, most chaotic systems tend to fall into one or more relatively stable states regardless of their initial conditions. The precise state of these systems cannot be predicted or controlled, but the general "ballpark" state of the system (the attractor) can be predicted and controlled. The important difference between projections and predictions was noted above (Sect. 1.5.3). Estimates of future outcomes (projections or forecasts) are based on specified **assumptions** relevant to a question and decision option.
- **Complex Adaptive Systems**: Inherent in human decision-making, natural evolutionary processes, especially ecosystems, physics, and recently AI-based **machine learning** is the ability of complex systems to learn from experience, experimentation, observation, and study, and to adjust system structure and control to achieve a more preferred or optimal outcome. Often these changes are thought to occur in pursuit of some optimality principle, such as maximization of information. Thus, complex systems that connect human and natural biophysical elements, including many that will be examined in this book, have the additional attribute of being adaptive. Adaptive systems sense, anticipate, learn, and act; complex adaptive systems must do these things rapidly and skillfully because they change so frequently and unpredictably.

  The deployment of new technology in all sectors results in a period of learning and adaptation. Changes in how consumers understand FEW commodities also results in adaptation. For example, a better understanding of the nutritional value of food products, or household energy consumption, or the environmental consequences of certain products or practices frequently results in changes in consumer behavior and adaptations to FEW systems.
- **Sentience**: Human beings and social organizations are particularly adept at the invention of new ideas, memes, and values. Sentient behavior can include the pursuit of idea-based and value-based objectives that appear to be maladaptive but which nevertheless have a rationale. With sentient agents controlling a system,

its behavior is not necessarily predictable, because the principles and values guiding the system's function can change rapidly, unlike, for instance, the Law of Gravity which is stable over time. For example, while people may be concerned about the impacts of climate change may understand the contribution of driving large fuel-inefficient vehicles or having a diet heavy in meat consumption, only some will change their driving or eating behavior and then only modestly. However, when such concern becomes widely shared in a society, cultural shifts can occur, leading to larger changes in perception and behavior.

2.3 Food Systems

In the narrow sense used in this book, food systems bring together the components of the "food chain" or food supply chain path from production to processing, distribution, and consumption of nutritional substances that humans and their household animal pets eat and drink. Generally, this is understood to include feed for agricultural animals. With the recent expansion of biofuels, and because our subject is the FEW nexus, we include in food systems the production of plant ethanol and biodiesel. Because natural fibers are produced by the same plants and animals that produce foodstuffs, as part of the same farming operations, food systems are considered to produce fiber also. In a broader sense, food systems integrate all of the inputs, processes, conversions, infrastructure, outputs, uses, wastes, allocations, and *impacts* of food, feed, fuel, and fiber. For example:

1. Food **production** affects what foods are produced, how they are produced, and where. Food production (including seafood harvesting and aquaculture) integrates soils; land-use; ecosystem functioning; water movements and use; seeds and animal **stocks**; fertilizers, herbicides, and pesticides; climate; nutrient cycles; energy use; agricultural practices and economics; labor relations; agricultural and food processing machinery; farm management and operations; production wastes and pollutants; manufacturing and processing corporations; public agricultural policies and food policies; farmer and consumer organizations; processing systems; and environmental policies and consequences.
2. Food **distribution** affects how certain foods are moved to where, who gains access to them, and who benefits from the distribution. Food distribution includes the economics and social organization and cultures of actors from farmers to retailers and institutional food services; roads, rail; ports, refrigerated rail cars and trucks, and other forms of transportation infrastructure; food marketing and food service corporations and institutional food services; trade policies; and other issues which shape how certain foods are moved and where to, who gains access, who benefits, and how much.
3. Food **consumption** affects who gains access to what foods and the associated nutrition. Food consumption includes issues of types of nutritional needs based on **demography** and public health; food quality and preservation; affordability

and issues impacting access to food; culture and social equity; food preservation, preparation and homemaking roles; food policies; food waste; and recycling.

With the exception of seafood harvesting and some aquaculture, and emergent vertical farming (including hydroponics and aquaponics), most contemporary food production is land-based. Because of the foundation of most contemporary food production in land-use, including soils and ecosystem functions and decisions related to them, some scholars prefer land-energy–water integration to food–energy–water integration. While such an approach does have some benefits from a food perspective, it can obscure, or de-emphasize non-food aspects of land use and ecosystems, and all of the non-land aspects of food, as well as aquatic food systems such as fisheries.

Food production, distribution, and consumption each raise important issues about where to define the **boundaries** of food systems and how to address **external factors**. A consideration of the global food system requires explicit recognition of the geochemical cycles of water and nutrients like nitrogen and phosphorus and the operations of transnational food corporations. At smaller scales, considerations lead toward local flows of water and nutrients and pesticides and labor and farm operator decisions as inputs and outputs, sometimes resulting in imbalanced conditions. For example, importation of feed from the Midwestern region of the USA results in a nutrient imbalance in the Chesapeake Bay.

Food systems studied at various scales are explored in different parts of this book. Here it suffices to note that boundaries for studies of food systems can include subparts of larger systems such as the following:

- Individual production facilities (e.g., gardens, greenhouses fields, farms, hydroponic and aquaponic systems);
- Facilities that process or convert raw agricultural products into food products;
- Food processing and manufacturing corporations;
- Storage and stockpiling systems for food including refrigeration;
- Landscape systems encompassing many farms or agricultural communities;
- Crop systems which look a particular crop or set of crops across multiple regions or nations;
- “Foodsheds” that serve a particular population;
- Both raw agricultural products and food products (because the differences can be subtle);
- Market and nonmarket economics of trade and exchange of food;
- Restaurants, grocery stores, and food markets;
- Wholesale, warehouse, and retail supply chains for a particular food product or location;
- National and international government agencies for food policy and regulation;
- National and international producers and consumers civil society organizations, and
- Local, state/provincial, national, and international food policy systems.

Food systems include some significant complications as compared with water and energy systems. For example, there is an immense variety of food product types, brands, and qualities, each with its nutritional attributes, some of which are commoditized and some not, while water and energy feature a smallish and relatively well-defined set of types and properties and (especially in the global north) are heavily commoditized.

There are multiple conversion processes from agricultural commodities to food commodities that require careful attention. These can be simple like the conversion of wheat into flour, or the use of one product like corn as a feedstock for a secondary product like beef, or the combination of products into a process to produce an output like a frozen dinner.

These complexities lead to a diversity of **structural relationships** between different parts of food systems, with some structural arrangements more dominated by anthropogenic factors like agricultural practices, economics, industrial labor relations, and diet choices than others, which orient more toward biological, chemical, and environmental factors. These different structural relations lead to various **internal interactions** between the parts of the food system and a wide range of approaches to **modeling**. Figure 2.1 shows an illustrative example of an integrated model of a farm system with select flows and interactions.

Modern approaches to food systems are typically oriented toward efficiency, standardization, and quantity of production and/or delivery, such as how to maximize outputs (tonnage, **calories**, nutritional value, delivered products, etc.) while minimizing inputs (seed, land, fertilizers, herbicides, pesticides, irrigation, processing, preservation requirements, etc.) and achieving a consistent and regulation-compliant quality (if not high quality) product, to maximize profit and marketability of the food.

A common metric for modern food systems is the price per unit of foodstuffs paid to the farmer by the food processor; or the price paid by the retailer or the consumer, all of which are frequently impacted by subsidies and other forms of public policy. This is a “value chain” economic model for food that adds value and price at

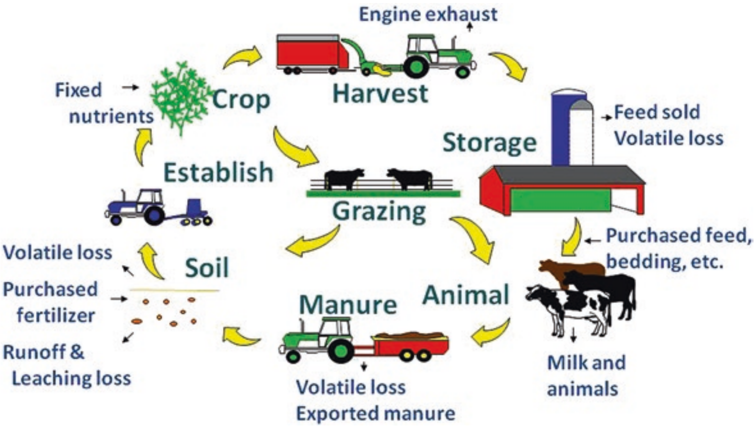


Fig. 2.1 Integrated farm system model. (Source: USA Department of Agriculture Integrated Farm System Model website)

each step, much like the factory model for industrial goods. To some degree, price entrains attributes of cost, perceived value, quality, and regulatory compliance, along with the timing of delivery. Thus, many food system models, especially those in the global north, address the system from an economic perspective using **econometric** models that use statistics and economic data to understand human system behavior.

However, alternative metrics for food systems emphasize non-economic factors such as environmental and social concerns or food quality. Examples include: "local food" systems which seek to minimize transportation and develop food community; organic food systems which seek to minimize synthetic chemical inputs; approaches which emphasize the nutritional qualities of the food; "fair trade" systems which seek to maximize compensation to farmers in poor or disadvantaged regions of the world; "slavery-free" systems which seek to ensure humane and equitable relations of production; farm animal welfare systems that seek to ensure the humane treatment of farm animals; and "footprint" or "life cycle" metrics that measure environmental impacts.

One notable challenge to the study of food systems is that they are often profoundly integrated into both particular aspects of local and regional and national geography, such as land availability and climate, as well as culture which strongly influence what foodstuffs can be produced and in what ways, what foodstuffs can be marketed profitably, and what types of foods are desired locally and regionally and globally (e.g., vegetables versus meats).

The emergence of affordable long-distance transportation and storage of foodstuffs aided by refrigeration has reduced the "distance from production" issue to some degree, allowing ever more urbanized consumers to become ever more separated from food production which can occur in different parts of the world, even as they enjoy the increased convenience and diversity and year-round availability of food options in their stores and restaurants and food service institutions. The same trend raises issues of equity as people local to production can lose (1) control over, and access to, traditional food supplies, and (2) market share as they increasingly have to compete with producers in different societies around the world. In some cities, urban agriculture and innovative programs integrating FEW elements at the city scale have been used as strategies to address the disconnect between low-income communities and local food access (see Sect. 18.5 for illustrative case studies in cities). Further, as food production is concentrated in fewer areas, there is increased vulnerability to problems impacting those areas such as climate change.

As societies develop, cultural attitudes toward food also change. Perhaps the most notable change is the growing desire for protein, especially meat protein, in societies emerging from relative poverty and transitioning to relative prosperity. Because meat protein is produced one step higher on the value chain and food web than vegetable protein, its costs, and environmental impacts tend to be an order of magnitude higher.

The effect of development on food systems is often treated in a straightforward three-phase evolution from traditional to intermediate to modern.

- Traditional food systems describe the approach of indigenous people to produce foods locally or gather them based on local environmental conditions, including locally available animal power, surface water or rainwater, and natural fertilizer inputs, and to consume them in accordance with local cultural customs and local seasons. Subsistence and hunter-gatherer models are forms of traditional food systems, alongside traditional "city-hinterland" agrarian models. Traditional systems do not require much capital intensive or specialized machinery, chemicals, GMO (genetically modified organism) seeds, imported technology, or non-animal energy inputs. Traditional food systems are highly local, yielding extremely diverse system types. While traditional food systems are commonly viewed as "sustainable" due to their modest ecological impacts, scaling up production to feed large urban populations can be challenging, and localized droughts and disasters easily propagate to cause local famine due to a lack of access to food from other regions. Note, however, that some ancient societies used surprisingly modern food systems, with the massive irrigation projects of ancient Egypt, Mesopotamia, or China as examples.
- Modern food systems are a complex network of industrial-scale food production occurring in diverse environments with significant chemical and engineering inputs, processed in a variety of ways and transported over vast distances to consumers. Modern food systems are marked by "industrial" characteristics of high levels of inputs, economies of scale, specialization of producers, branding of products, both "just in time" production and large-scale storage, corporate ownership and management, separation of (mostly rural) producers from (mostly urban) consumers, separation of the local growing season from the timing of consumption, and increasing global homogeneity of crops, agricultural practices, policies, and diets emphasizing the most commercially successful, profitable, and efficient types. Efficiency is typically defined in terms of cost, volume, or mass and (usually) not in terms of nutritional values and environmental costs.
- Intermediate food systems combine local production with a connection to larger systems.

The simplistic application of these categories lends itself to ideological, rather than practical, thinking. In the real world, food systems tend to fall into a grey area blending these categories in ways that reflect subtle contextual trade-offs and constraints. Much of this book is oriented toward recognizing and engaging with the complications of systems in a manner that promotes nuanced decision-making about trade-offs and integrates food, energy, and water aspects in a balanced way without idealizing one component or model over others.

Food systems change dynamically as a result of varying soil conditions, environments, climate and weather, crop decisions, agricultural practices and innovations, availability of inputs, population, changes in diet and culture, political and economic conditions, the market power of food corporations, and numerous other factors. **Climate variability**, seasonality, and disturbances from extreme events are natural sources of dynamics, but technological and policy change, market changes, consumption habits, and conflicts also drive dynamics.

Water and energy are often considered as inputs to food system models reflecting the demands that food production makes on water and energy and subject to possible supply constraints. Examples of how food systems place demands on water have already been given. Examples of how food systems place demands on energy include:

- Energy embedded "virtually" in the life cycle of agricultural inputs such as fertilizers, pesticides, and irrigation water.
- Energy demand (fuels) for operating agriculture equipment, transportation, and distribution, and (electricity and natural gas) for the processing and preservation of food products.
- Energy demand for agricultural labor.

Food systems are extremely nutrient-intensive because of the need for Nitrogen (N) and Phosphorous (P) fertilizers on crops and because of the transportation of nutrients and carbon embodied within food products. N and P limitations may become critical for some food systems in the twenty-first century. N and P helped create the "Green Revolution" in food production, but they are not unlimited resources (especially P), and they contribute dramatically to freshwater pollution via **"nonpoint source" pollution** of waterways and "dead zones" where oxygen has been depleted from waters by oxygen-eating microorganisms feeding on N and P, so fish cannot live.

In studies of food systems, the use of food crops as feedstocks for biofuels brings competing demands for water with food production for human consumption. In the USA, a large fraction of corn is used for ethanol production; Brazil is also a leader in biofuel production from corn and sugar cane. Biofuel production is controversial because "first generation" biofuels like corn ethanol compete with human food for land and water resources. This is in contrast to "second generation" advanced biofuels-based crops like algae, willow, switchgrass, and other woody products. See Sect. 8.2.2 for more on biofuels.

Changes in land use and ecosystem functioning because of water- and energy-related uses of land (e.g., mining, reservoirs, wind farms, pipelines, solar farms) may or may not raise food production issues. The addition of solar and wind production has allowed landowners to "produce" renewable energy as a crop and maintain their other crop productions as well. At the same time, dams on rivers provide both hydroelectric generation and supplies of water for agriculture.

Major considerations for modern food systems include the following:

- Concerns over genetic modification, pesticides and herbicides, and industrial-scale food systems.
- Local food movements and farmer-to-consumer linkages.
- Organic food movements.
- Food cultures that emphasize authenticity or specific diets.
- Food self-sufficiency as national policy, with its consequences for water demand in dry regions.
- The right to food as a local and national policy.

- **“Virtual” water**-embedded crops and products that are traded.
- Drought and famine in low development status countries and subsistence farming economies.
- Access to out-of-season food via trade and long-distance transportation.
- Food waste as a major inefficiency (over 30% is wasted).
- Government policies of overproduction and subsidy.
- Transitions (and declines) of farm communities.
- Smart agriculture technology.
- Bioengineering for higher yields (the green revolution).
- Nutrient and energy input management, including extra use of fertilizer as “**insurance**.”
- Nonpoint source farm pollution, oxygen depletion (hypoxia), and aquatic ecosystems.
- Industrial-scale food supply chains and food safety.
- Changing the nutritional content of foods as a result of breeding and/or heavy processing.
- Changing diet and its health implications in high development status countries.
- Growing meat consumption and its footprint implications.
- Refrigeration and its fragility and electrical demands.
- Humans as the largest users of the terrestrial land surface.
- Volatility in water supplies from both drought and flood (sometimes in proximity).
- Volatility of food prices in low development status countries.
- Land competition between crops for first-generation biofuels and other agricultural products.
- Land use for crops that are exported from less developed countries to more developed countries.
- Impact of global markets and trade.

2.4 Energy Systems

Energy systems, at the largest scale, integrate into a whole the various components of energy resources, including their form (solid, liquid, gas, etc.), production, conversion processes (and efficiencies), long-distance transmission, short-distance distribution, end-use, and wastes. Conversion processes include such actions as the refining of gasoline and the generation of electricity and the conversion of biomass into biofuels.

Decision-making defined by political borders, energy processes, or end-user communities typically defines the boundaries of energy system studies and leads to a demarcation between external factors and internal interactions, and to the identification of the structural or functional relationships between different parts of the system being considered. For example, electrical power grids have no internal physical boundaries, but the wires cross many different corporate, State, National, and regulatory jurisdiction boundaries. This is especially significant because some aspects of energy systems are highly regulated (e.g., electric power) and/or dominated by large public and private corporations (e.g., integrated oil and gas companies).

In the USA, generation, local distribution, and retail sales of electricity have historically been regulated at a state level. Thus, until the 1990s, vertically integrated electric utilities generated, transmitted, distributed, and sold electricity to retail customers within states (see Sect. 10.3.5) at rates set by each state. Each state would decide what power plants would be constructed by which utility, with (nuclear power plants excepted) modest oversight from the federal government. However, the US power system has become more distributed, utilizing power generated at a distance, especially wind and solar farms built in locations best suited to them, with more wholesale power crossing state lines regulated by the federal government. The outcome has been a restructuring of electricity markets in most locations. In 2018, two-thirds of Americans received their electricity via competitive, usually multistate, wholesale markets. The restructuring of US electricity markets is an ongoing process.

The decision-making perspective also leads to a choice about taking a bottom-up (i.e., starting with individual components) or a top-down (i.e., beginning with a whole system) approach to viewing energy systems. Bottom-up approaches to energy start with specific technologies of energy production, conversion, or use with internal interactions dominated by physical, environmental, engineering, subcultural, and microeconomic factors. Top-down approaches are dominated by macroeconomic and policy and cultural considerations. They may also be dominated by decisions made in **arbitration** unseen to most of society. For example, after the Fukushima earthquake and tsunami that impacted one of Japan's major nuclear facilities, Germany decided to phase out nuclear power, thus ending contracts early and subjecting it to major arbitration cases. In the example of US electricity markets described above, historically, states have top-down projected demand and approved new power plant construction and what type of plants are constructed, with costs inserted into electricity rates charged to customers. Restructured electricity markets are far more open to bottom-up power plant decisions by independent actors. Chapter 20 includes many examples of decision-making processes and tools to address conflicts that arise.

Energy systems can be studied at the scale of the following:

- Individual devices and machines.
- Buildings.
- Facilities ranging from a power plant to an industrial facility like a refinery or a factory.
- Human communities such as cities or metropolitan regions (see Sect. 18.2).
- Regional transmission systems that connect multiple states or regions together.
- Particular energy resources, fuels, and energy products (e.g., electricity systems).
- National and international multi- and total-energy systems.

Notable examples of tools to explore large-scale energy systems that will be addressed in Chap. 15 (Modeling) include the following:

- MARKAL (derived from "Market Allocation") developed by the International Energy Agency is a model widely applied at many scales to project the evolution of energy systems over 40–50 years under certain assumptions. This is a bottom-up model that allows the assessment of different techno-economic assumptions about the future.
- TIMES (The Integrated MARKAL-EFOM System) is a successor to MARKEL (Fig. 2.2).
- National Energy Modeling System (NEMS) developed by the U.S. Energy Information Administration to project the future of the U.S. energy system and support an "Annual Energy Outlook."
- Model for Energy Supply Strategy Alternatives and their General Environmental Impact (**MESSAGE**) developed by the International Institute for Applied Systems Analysis (IIASA) used to explore energy scenarios related to several large-scale analyses including the Intergovernmental Panel on Climate Change (IPCC).

An interesting tool worth mentioning in the same context is the Long-Range Energy Alternatives Planning System (**LEAP**) developed by the Stockholm Environment Institute to explore scenarios of energy use (in all sectors) with emissions of greenhouse gases.

The ability of many primary energy sources to be converted to electricity and the significance of electricity as an end-use energy source (nearly 40% of global

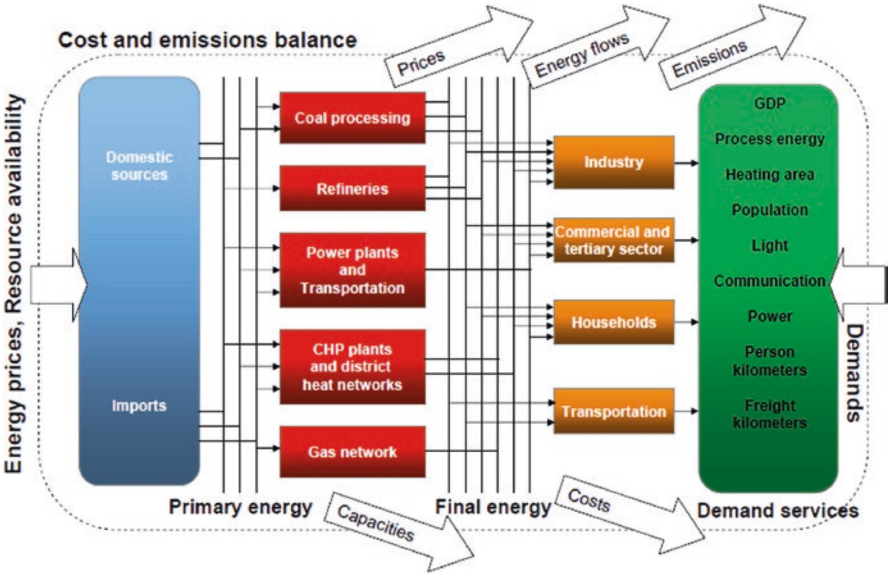


Fig. 2.2 Schematic of TIMES energy system model inputs and outputs. (Source: Remme et al. 2001)

Total Primary Energy consumption) has resulted in many studies of energy systems looking just at the electricity sector, so the knock-on impacts of electricity on water use, on other energy sources, and on the environment were often ignored. Similarly, the dominance of **petroleum** as the primary input for transportation leads to designs and models of transportation that ignored the availability of electricity, which is the transportation fuel of the future. CO_2 and greenhouse gas emissions were not considered during the design of the modern energy system, and this has turned out to be a serious problem.

As should be expected, water and food should be considered when developing models of energy systems, and vice versa.

The water demands of energy are significant. Some uses, such a hydroelectric generation, are largely **non-consumptive**, in that the water is returned after use (except for the increased evaporation from the impoundment). Other uses, such as thermo electric power plants (41% of all the water withdrawal in the USA in 2015), irrigation (38%), and public water supplies (12%) are **consumptive** users of water (USGS 2018). Although much of the water withdrawn for thermo electric power is returned to the water body, significant evaporation occurs, and the returned water is a higher temperature than the withdrawal. After 2007, a major shift in US electricity generation away from coal to natural gas and renewables dramatically reduced power plant water consumption. This has been offset somewhat by the increased use of water in hydraulic fracturing for unconventional oil and gas production.

Conversely, the energy demands of water are also significant. Power is used to pump water, move it, clean it for use, heat and cool it, and, to clean wastewater before return to the environment. In a move toward recognizing the value of integrating water and energy systems, the considerable energy use to heat water has led the State of California to prioritize the efficient use of heated water during a recent drought because of its added benefits for energy efficiency. Some cities have created hot water districts around thermo-electric plants, and some hydroponic and aquaponic facilities are co-locating with thermo-electric plants.

Similarly, energy use for food production is primarily a focus of food system studies and is merely one more demand for energy use. However, significant energy is used in agricultural operations and for creating inputs such as fertilizers and pesticides. Energy is required to preserve, move, process, and distribute food products, as well as address waste by-products. Refrigeration to preserve foodstuffs is a significant part of energy use in the commercial and residential sectors.

Some key considerations for modern energy systems include:

- greenhouse gas emissions, treaties, and climate change (Chap. 11);
- rapid advancement in renewable energy technology and economics (solar, wind, etc.);
- access to electricity and other modern forms of energy;
- aspirational development of renewable biofuels;
- the transition to electrical power from other energy sources;
- increasing use of geothermal energy for residential heating;
- rapid evolution and reliability problems of the massive and complex electrical power grid (Chap. 10);

- managing power grid peak demands, including with battery technologies;
- power grid peak demands driven by urban air conditioning;
- energy independence, dependence, and geopolitics, especially in oil and natural gas, but increasingly with wind and solar siting;
- vehicle fuel efficiency increases and vehicle electrification;
- energy for mass transportation;
- air pollution and health from fossil fuel burning, including power plants, and vehicles;
- air pollution and health from biomass and charcoal burning for cooking fires and residential heating;
- the problems with establishing safe and agreeable disposal of wastes from nuclear energy;
- the Faustian bargain of “normal accidents” with nuclear energy;
- aging energy infrastructure;
- falling energy prices and disincentives for developing new cleaner technologies; and
- economic and technological approaches for increasing energy efficiency.

2.5 Water Systems

The water system most familiar to many readers is the hydrologic/water cycle of the earth, defined with planetary boundaries between the upper atmosphere and subsurface water tables. The water cycle of the planet is also one of many geochemical cycles that are studied at a planetary level, including oxygen, carbon, phosphorus, and nitrogen (Fig. 2.3).

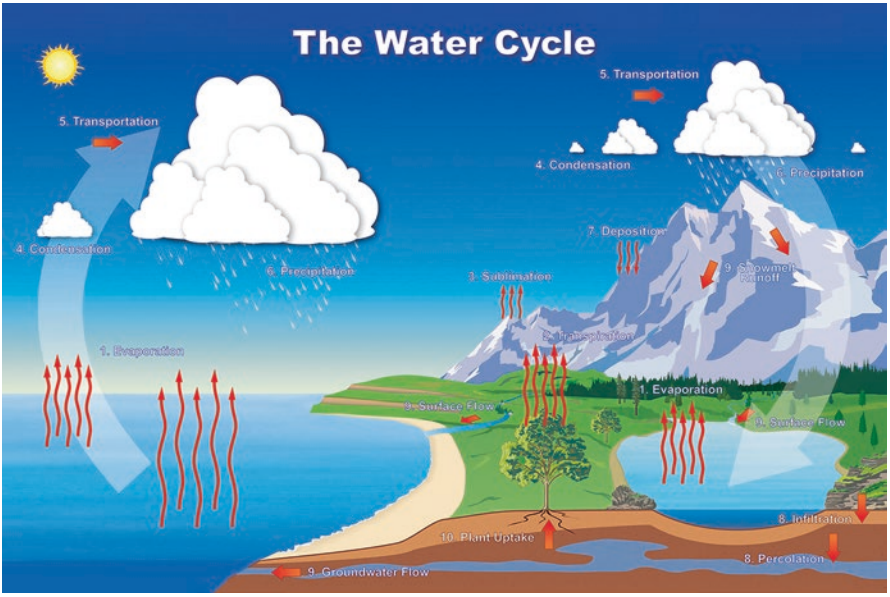


Fig. 2.3 Schematic of the water cycle. (Source: NOAA)

The energy provided by the sun is the most significant external factor impacting the system, although the earth's gravitation force also operates as an external force. There are structural relationships between the water contained in oceans, ice, groundwater, soils, lakes, atmosphere, swamps, rivers, and biology.

Internal interactions between these parts of the system are mediated by the laws of nature governing the hydrosphere and further mediated through the climate system, oceans, the biosphere (the living parts of the earth systems), and the **cryosphere** (the frozen water part of the Earth system) and manifest them as more straightforward processes such as evaporation, condensation, precipitation, transpiration, sublimation, surface and subsurface flows, percolation, and plant uptake.

Human actions include the creation of reservoirs, irrigation, and multiple types of consumption that have more or less impact on the larger natural process in different locations. The water cycle changes dynamically on many time scales from hours (storm intensity) to years (seasonal changes) to hundreds of thousands of years (ice age cycles).

Modeling the earth's water cycle with Global Hydrological Models (GHMs) is a major scientific discipline in its own right and is a significant part of efforts to understand the climate system through Global Circulation Models (GCMs) or the earth system as a whole through "Earth System Models" (ESMs). In this book, we will be looking at FEW systems integrations primarily at smaller scales.

The famous image of the entire earth taken from the Apollo 17 spacecraft in 1972 (page 1) has given rise to the view of the earth as the "water planet," the "blue planet," and the "blue marble." However, from a human perspective, it is 1% of the planet's water that is fresh and accessible, which is most important. Thus, water systems at sub-planetary scales tend to focus on the freshwater systems that can meet human needs, their capture/extraction, distribution, pretreatment, use or consumption, post-use treatment, and disposal. Examples of traditionally studied water systems at various scales include the following:

- Hydroponic systems where water acts as a medium for transporting nutrients to plants.
- Water facilities such as pre- and post-use treatment facilities, hydroelectric power plants, thermoelectric power plant cooling, and a wide variety of industrial facilities in which water flows have a critical function.
- Irrigation systems which can range from a single field to a farm to an entire agricultural region.
- Human communities including cities and metro regions (see Sect. 18.2) which have defined boundaries for water collection, distribution, use, and disposal.
- Groundwater systems which drive the evolution of aquifers or the movement of pollutants.
- Aquatic ecosystems where water quality, quantity, and movement impact an essential natural resource.
- Watersheds, water **basins**, drainage basins, and catchment areas where the water flows in a given area go to a common outlet such as a reservoir or a bay.

The spatial and temporal scale of these types of water systems is primarily driven by human decision-making processes and conflicting demands on limited supplies of available water. These conflicts are often rooted in, quantified by, and sometimes resolved by infrastructure and economic considerations that are incorporated into models (see Chap. 15). Such systems often depend on assumptions of what the hydrologic cycle has been versus what it is projected to be.

The decision-making process will often suggest an important metric that may be simple such as the volume of production or consumption, or a more complex metric such as the efficiency of use, or intensity of water demand, or a metric of a side effect such as the greenhouse gas emissions related to the water flows. The decision-making process will usually suggest a timescale for the parameter. Metrics will be explored in depth in Chap. 13.

Food and energy are often considered when developing models of water systems. Traditionally, the consideration is where food and energy are two types of demands on water.

Food demand on water includes the following:

- Agricultural production uses of water such as crop irrigation, water for animals, and water for farming practices.
- Impacts of runoff from agricultural fields and production.
- Production of agricultural inputs such as fertilizers.
- Food processing water use.
- Changes in land use and ecosystem functioning from agricultural practices impacting water flows.

Energy demand on water includes the following:

- Production processes such as hydroelectric power, oil and gas drilling (especially hydraulic fracturing), and irrigation of biomass crops.
- Energy transformation processes such as thermoelectric power plant cooling systems and biofuels production.
- Changes in land use and ecosystem functioning from energy production such as the creation of reservoirs, adding heat to rivers with water used for cooling.
- Impacts on the water cycle, such as through the release of greenhouse gases.

Other demands on water are also considered, such as demographics and human consumption, ecosystems, industrial uses, and non-consumption uses for human recreation. There is also a movement to ensure that rivers have a right to water as well.

Thoughtful approaches to water systems also recognize the land and energy needs of water, including the following:

- Land required for water capture and storage diverted from agricultural use.
- Energy use to pumping groundwater, transport and distribute water.
- Energy use to treat water before and after use and for the heating and cooling of water.

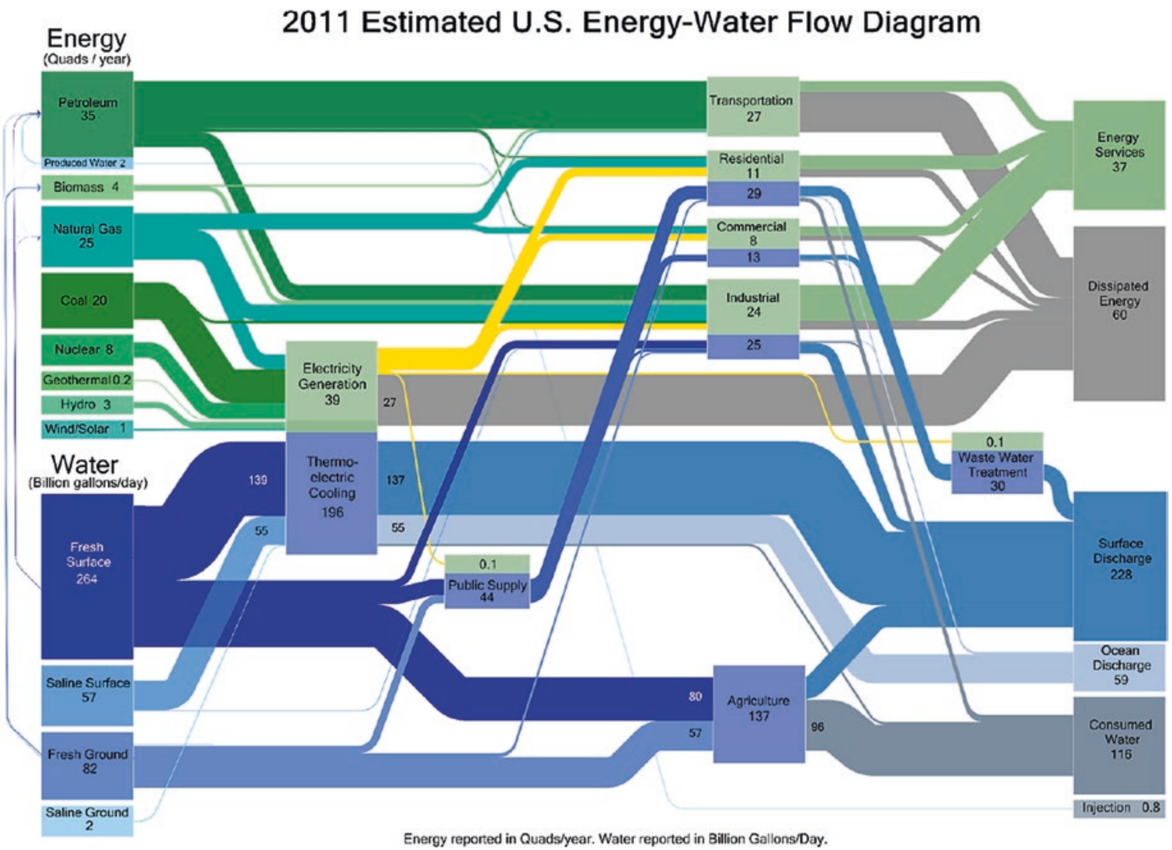
However, disciplinary hydrology and water resource (HWR) studies of water systems typically focus on the impacts on the water system rather than the effects of water's land and energy use. When your tool is a water balance equation, your analysis tends to ignore factors that do not appear directly in that equation. The commitment to core methods, concepts, and theories is both the greatest strength and greatest weakness of the traditional disciplinary approach; it is a weakness for systems work.

Some key considerations of the modern water system include the following:

- Massively centralized infrastructure dependency (Chap. 10);
- Growing global demand for water, especially for irrigated agriculture;
- Growing importance of managing life cycle water use and water footprints;
- The growth of human populations and economies in desert regions;
- The transition from a water-abundant world to a water-scarce world;
- Regional and planetary boundaries and carrying capacities for water;
- The conflict between environmental flow requirements and human demands;
- Humans as a major, or dominant, part of the water cycle;
- Groundwater mining and depletion;
- Outsourcing of water-intensive food production via virtual water (see Sect. 7.5);
- Informal water systems and water quality problems in low development status countries;
- Water pollution and water quality;
- The impact of both floods and droughts, often in proximity;
- The impact of existing and new hydropower development.

A study by the U.S. Department of Energy (DOE 2014) represented the estimated US energy and water flows in 2011 (Fig. 2.4). This study illustrates the connections and trade-offs that come with the interactions between food, energy, and water systems, using a Sankey flow diagram. The energy flows into the transportation, industrial, residential, and commercial sectors include energy for water and food systems. The water flows into thermoelectric cooling, and agriculture are very large.

It is important to note the difference between **water consumption** and **water withdrawal**. Consumption is different between water withdrawn from the immediate aquatic environment as compared with the quantity of water that is returned (discharged) to the same immediate environment at a similar time, place, and quality. Generally, water consumption is due to evaporation and evapotranspiration or its embodiment in some products (e.g., food). However, the water returned to a watershed may be altered by its use. For example, water use for cooling in a thermoelectric power plant typically raised the temperature of the water. In another example, water use in agriculture may result in the addition of nutrients. Both of these examples can result in significant ecological impact when non-consumed water is returned to a watershed, via thermal or chemical pollution.



Energy reported in Quads/year. Water reported in Billion Gallons/Day.

Fig. 2.4 2011 estimated U.S. energy–water flow diagram. (Source: DOE 2017)

It is also important to note that much (most?) energy does not go into providing energy services but is dissipated as heat before its use. This is especially true in thermal power plants using turbines and internal combustion engines.

Also note that the flow diagram in Fig. 2.4 is not a model, but rather data that is visualized using a specific type of visualization method (the Sankey diagram). While Fig. 2.4 represents how energy and water flows go to different sectors and how much is consumed and discarded, it does not explain the intention of the flows, embody scientific and engineering concepts, show interactions and causation, or allow the user to experiment with changes to inputs and interactions to see what outcomes result. This diagram is descriptive and is based on empirical data.

2.6 From Separate Systems to an Integrated System of Systems

2.6.1 Science

In the previous sections, we have seen how food, energy, and water each play a part in careful studies of systems of the other two components. As such systems become ever more comprehensive, the treatment of the other elements become ever more detailed, until those systems become subsystems embedded in a more extensive system. Advanced studies of food systems, for example, will include many water and energy interactions, both direct and indirect. Where sets of those interactions are connected, they begin to be recognized as components of the food system with internal attributes of a system—mini-systems. Thus, advances in the study of food, energy, and water systems separately (**separated FEW systems**) lead to considerations of an integrated “system of systems.”

2.6.2 Sustainability

There is also a sustainability path to the same outcome. Societies have thought about how to sustainably provide themselves with essential food, energy, and water services for millennia. The conflicts between efforts to provide the three critical consumables have also been long recognized. The environmental consequences of meeting the rapidly expanding demand for each of the three came to the fore in the 1960s and received serious attention in 1972, at the United Nations Conference on the Human Environment in Stockholm, Sweden, now referred to as the Stockholm Conference (The UN is explored in see Sect. 6.2.2).

Later, the United Nations World Commission on Environment and Development, chaired by former Norwegian Prime Minister Gro Harlem Brundtland, famously define sustainable development in its 1987 report, Our Common Future, as follows:

> Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

While the Brundtland Report, as Our Common Future is now commonly referred to, contains the most widely known definition of sustainable development, there are many others.

The U.S. Environmental Protection Agency states that

> Sustainability is based on a simple principle: Everything that we need for our survival and well-being depends, either directly or indirectly, on our natural environment. To pursue sustainability is to create and maintain the conditions under which humans and nature can exist in productive harmony to support present and future generations.

Such general definitions of sustainability are, unsurprisingly, subject to debate, and challenge. Regardless of the definition of sustainability, the core question of sustainability is how to provide essential services to human societies without causing long-term (decades or centuries) degradation to natural ecosystems and the services that they provide to human communities.

As a scholarly field, sustainability science has come to broadly encompass the study of interactions between the natural environment and human societies, classified as “human-environment systems” or “**social-ecological systems**,” and recognized as “coupled systems.”

One core scientific challenge is how to measure sustainability. This vital issue, in the context of FEW systems, will be addressed in detail in Chap. 13 (Metrics).

One core practical challenge is how to address sustainability when human societies vary dramatically in their resources, population growth, social and economic development, and values.

Studies of food, energy, and water systems have helped bring into focus the scientific and practical challenges of sustainability.

With growing demands for food, energy, and water-related to both population growth and economic prosperity, political and policy conflicts between different claims and demands on food, energy, and water resources have become ever more frequent. As a result, for some policy-makers, the question of how to provide constituents with food, energy, and water in a manner that can be sustained for decades to come is the practical definition of sustainability. While environmental conditions are not explicit in such a question, large-scale ecological degradation makes an answer to such a question impossible and places environmental considerations at the core. Such questions can also be critical in bringing disparate parties together to find solutions (see Chap. 20).

While sustainability is much broader than sustainable food, energy, and water systems, the necessity of simultaneously providing all three critical consumables has provided a human- and ecosystem-focused impulse for integrating FEW systems as an essential practical application of sustainability.

2.6.3 Principles of a System of Systems

Studying an integrated "system of systems" utilizes the similar principles of system science described above in Sect. 1.4 and of the emerging field of sustainability science. The attributes of a system of systems include:

2.6.3.1 A Question (or Problem) as a Macroscope Which Defines Boundaries and Scales

If we are integrating three components, what is the unifying identity (or macroscope) by which we perceive the system of systems? In practical situations, the unifying identity is the question (or problem) that is being addressed: "how do we manage a system in a certain context in which food, energy, and water are critical components to achieve desirable outcomes?"

The keyword and phrase in such a question are "context" and "desirable outcomes." The question will also define issues of spatial and temporal scale (defining its boundaries and external factors) metrics, data, modeling, and computing.

The issue of defining or framing the question will be addressed in Chap. 12; its relationship to metrics, data, modeling, and computing will be explored in Chaps. 13–16; and the application of science to practical questions addressed in Chap. 17.

2.6.3.2 Heterogeneous Parts Which Have Mutual Relationships

While in FEW systems, the parts include food, energy, and water elements; there are usually other parts like population, economics, infrastructure, ecosystem services, and biodiversity to include.

Interactions are both direct and indirect and usually operating in both directions, so that we can think of elements of an integrated system having complex interactions embodied in mutual relationships. Further, when one element changes, the interactions with other parts of the system result in additional interactions on the first element, that is, reciprocal relationships usually include **feedback interactions**.

Direct, or first-order, interactions are the influence on a system by another system; for example, the demands on water by the energy system and on energy by the water system. Many examples of this type of interaction were given above in our consideration of water, food and energy systems separately.

Indirect interactions include the impacts of one element on another to which it is not in direct contact. Rather the impact is mediated through other intermediate parts of the system or factors external to the system. Here are three examples where there is one step mediating the indirect interaction:

- Energy use of crops for biofuels makes demands on water because of the irrigation needs of those crops.

- Particular crops can alter ecosystem functioning and the change the percentage of rainfall that accumulates in groundwater or flows in streams and leaves a certain area.
- Energy used to heat water can lead to emissions of greenhouse gases that alter the climate, which in turn impacts the growth of food crops in a variety of ways.

Where there is one step to mediating the interaction, we can call this a “second order” interaction. If two steps are mediating an indirect interaction, we can have “third order” interaction. If more steps are mediating the interaction, we have “higher order” interactions. Each additional indirect step in an interaction makes a system more complex to study.

Indirect interactions are frequently folded into direct bilateral interactions or a two-way mutual relationship. For our three examples, this might be done in the following manner:

- The water demands of crops for biofuels are considered within the bilateral or mutual relationship of agricultural water use.
- The impacts of particular crops on groundwater storage are regarded within the bilateral relationship of land use/cover and water.
- The effects of water energy use on crops are considered within the reciprocal relationship between climate and crops.

2.6.3.3 Structural Arrangements

The parts of an integrated system are usually grouped into a system of dynamic “components” or “modules” based on strong interactions rooted in biophysical and societal relationships (e.g., resource flows, a shared decision-making process, or a robust economic relationship).

Parts usually reflect distributed control of a system, indicating opportunities or change their operation and management. Parts can sometimes also be seen as the units of coevolution.

In the most straightforward approach to this, we might think of food, energy, and water components managed to achieve the desired outcome. However, in practice, integrated systems are far more complicated.

Models describing structural arrangements must address the systems simultaneously and their mutual relationships consistently (both biophysical and societal.) An integrated energy–water system model must recognize the direct interactions of the demands on water by the energy system and on energy by the water system. It must also acknowledge the indirect interactions mediated through the food system, land use, climate, ecosystems, economics, and social changes.

2.6.3.4 Emergence

The purpose of studying an integrated system of systems is to identify patterns and find solutions to severe problems that “emerge” from understanding the complex interactions between the parts of the subsystems.

2.6.4 System of Systems and Models

Given this evolution of individual food, energy, and water systems towards an integrated analysis via a system-of-systems approach, one emerging area of challenge is modeling tools to go along with this approach. Modeling of food, energy, and water systems is the subject of ample literature, including textbooks. However, when modeling these systems individually, typically the other two are assumed to be unchanged or unimpacted. This simplifies the analysis and enables solutions to problems in each of these systems to be found, and to some extent, these solutions may work, at least under some constrained conditions that satisfy this assumption. But in a more general sense, and particularly when these systems are intensely stressed (e.g., by human activity such as urbanization, and expansion of services in food, energy, and water sectors), it is intuitively easy to understand that these systems will interact and be dependent upon each other (nexus). This interacting **coupling** is illustrated in Fig. 2.5. We explore this system of systems approach in more detail from a modeling perspective in Chap. 15.

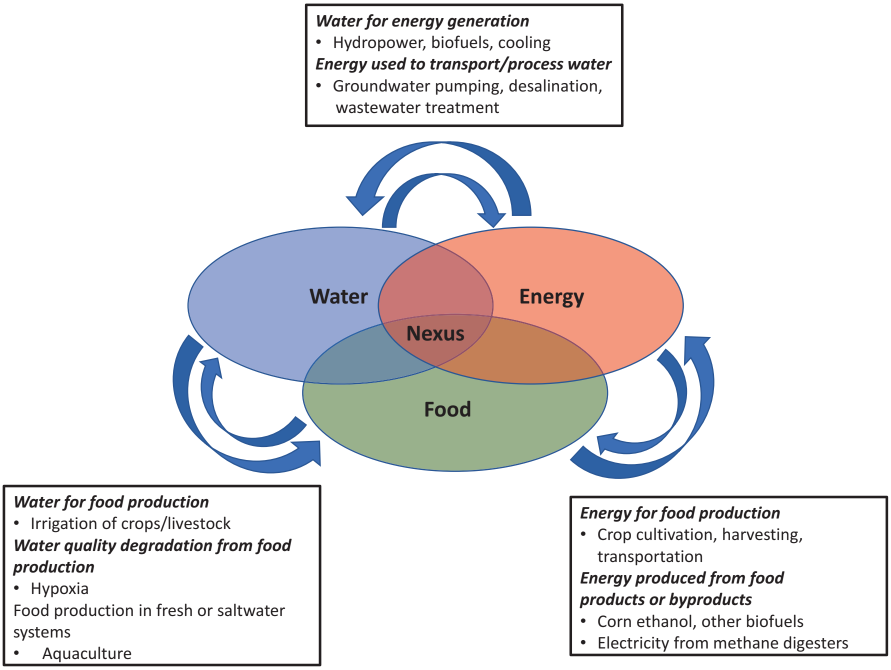


Fig. 2.5 Examples of modeling interactions and feedbacks among the FEWS nexus. (Source: Fernando R. Miralles-Wilhelm)

Key Points

- Systems describe a whole composed of many interacting parts with a unifying framework; boundaries in space and time; external forcing factors; structural arrangements; functions; change and variability; and humans as both forcings and participants in the system.
- Complex systems have heterogeneous parts with complex interactions that make them interdependent, coevolving, and subject to distributed control. The characteristics of the whole system emerge from the interactions between the components of the system giving rise to stability and changes that are often hard to predict and sensitive to initial conditions.
- Because complex systems are influenced by external factors such as human actions, models of complex systems make projections based upon certain assumptions rather than predictions about actual future outcomes.

Discussion Points and Exercises

1. The FEW system is an excellent example of all four system-of-systems attributes. Now that you have read this chapter, describe how this is so.
2. Discuss what makes a system complex, and why the FEW system IS or IS NOT complex.
3. Describe a food system as a process network.
4. Describe heterogeneity in a FEW system at the local, regional, and national levels.
5. Describe hierarchy in an energy system.
6. Describe three emergent properties in a: (a) food system; (b) energy system; (c) water system; (d) FEW system
7. Develop a Process Network of a (a) food system; (b) energy in transportation system; (c) water system; (d) farm system including FEW components; (e) household system including FEW components.
8. Describe a Complex Adaptive System in: (a) the agricultural sector; (b) the electricity sector; (c) a urban FEWs context; (d) a rural FEW context.

   For Exercises 9–17, consider modeling a system. Describe the following:

   (a) The boundaries of the system;
   (b) The main components;
   (c) The structural arrangement of the components;
   (d) The most significant functional interactions between components;
   (e) External factors and their interactions with the system;
   (f) The most significant (distributed) controls on the system including human actions;
   (g) Issues that might alter the stability of the system; and
   (h) An emergent property of the system.

9. The water system for a city. Specify the location of the city and think about geographic variation.
10. The water system for a farm growing an irrigated crop.
11. The food system of a landscape encompassing many farms or agricultural communities.

12. The food system of a facility that processes or converts food products.
13. The energy system of a building.
14. The energy system of a coal-fired power plant.
15. The integrated food, energy, and water systems of a house.
16. The integrated food, energy, and water systems of a college campus.
17. The potential differences between a food, energy, and water system in the USA, India, Ghana, and an island country like Trinidad and Tobago.

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