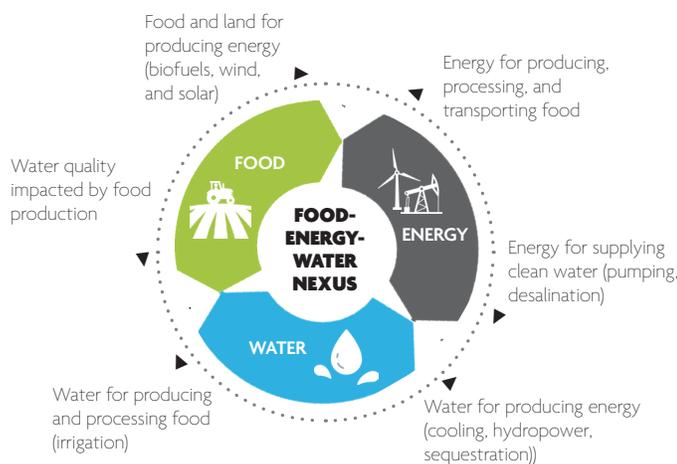


# ALLOCATING SCARCE RESOURCES

## MODELING TO SUPPORT FOOD-ENERGY-WATER SUSTAINABILITY

Global freshwater supplies are increasingly under stress due to the combined effects of population growth, increasing urbanization and industrialization, and climate change. Water resources must be managed and allocated in ways that are economically efficient and that account for interdependencies between food production, energy generation, and water provision, often referred to as the food-energy-water nexus. Mathematical modeling provides the means to anticipate what might happen in the future based on certain conditions, allowing decision-makers to optimize water use across sectors while taking into account uncertainties over future water availability.

Food, energy, and water are central to sustainable development, yet in many parts of the world, food and energy compete for water. Agriculture is the largest consumer of the world's freshwater resources, and the food sector currently accounts for roughly 30 percent of global energy consumption. Too often, these domains are managed in silos, undermining security in the other domains, and jeopardizing human well-being and economic growth. The intertwined nature of food production, energy generation, and water networks — known as the Food-Energy-Water Nexus — calls for an integrated approach to management and decision making. By holistically managing this nexus, decision-makers can better manage trade-offs and mitigate uncertainty and risks.



To advance sustainable management of food-energy-water nexus systems, scientists develop computer models that analyze alternative system configurations, such as combinations

### KEY MESSAGES

- ✓ An integrated approach to food-energy-water nexus management ensures solutions that are more favorable to sustainability than those made in silos. In the face of huge increases in demand for food, energy, and water over the next decades, nexus management will be more efficient across sectors and regions and will enable optimal use of limited resources.
- ✓ Future water availability is highly uncertain as it depends on weather variability and climate change. Ignoring uncertainty can increase both costs and risks. Uncertainty should be taken into account in decisions to invest in new technologies and solutions with a longer time horizon for return.
- ✓ Mathematical modeling offers options for optimizing upfront investments in water-saving technologies and water use to ensure the desired level of domestic food and energy security given the uncertainties.

of technologies that can be deployed in energy and agriculture, types of crops that can be grown, and the use of fertilizers. Typically a model implements a certain management goal, for example, minimizing costs or maximizing profits. A model's solution is a system configuration that achieves the desired goal given food, energy, and water demand targets and supply constraints.

### CHALLENGES OF UNCERTAINTY

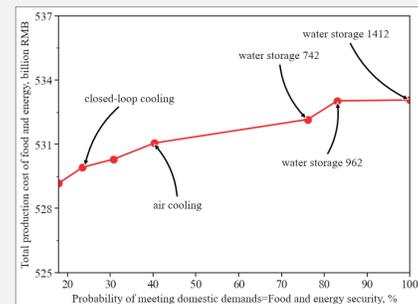
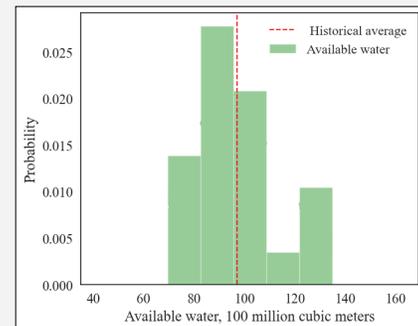
Food-energy-water systems are affected in significant but uncertain ways by a number of complex external drivers, including financial markets, human preferences and behavior, and, increasingly, weather variability and climate change. Both precipitation and evaporation influence patterns of water availability, and climate change is making corresponding weather conditions more severe and less predictable. Crop choices and other crop management decisions are particularly challenging when little is known about future drought risk or water demand. This is especially true in developing countries whose economies are often highly dependent upon agricultural production and export.

Traditional food-energy-water decision-support models rely on average parameter values derived from historical data. However, this approach is not without risk. For example, in years with below-average water, solutions may require more

## CASE STUDY: SHANXI, CHINA

Water scarcity is a pervasive problem across much of China. Population growth, rising food demand and disrupted patterns of rain and snowfall due to climate change further compound the problem. The coal industry is responsible for more than 22 percent of the nation's total water withdrawal, second only to irrigated agriculture at over 60 percent. Shanxi, China's top coal-producing province, is one of the most water-scarce provinces in the northern part of the country. Decades of mining have damaged underground water tables and contaminated groundwater supplies. Residents are forced to draw on groundwater, which is often pumped faster than it can be recharged. Dry years can cause reservoirs and rivers to dry up and groundwater levels to subside, further limiting drinking water supplies.

A team of scientists used stochastic, chance-constrained programming models to ensure food and energy security in the region through water-use efficiency in coal production. Higher levels of food and energy security require greater investments in water-saving technologies that allow water to be used more efficiently and therefore ensure that domestic production can meet demand even when the water supplies are low. As finances are limited, the model offered solutions that prioritize the introduction of water-saving technologies over time, starting with those that deliver higher-security dividends at a lower cost. Both closed-loop cooling and air cooling technologies reduce water use in coal-fired power plants compared to the widely-used open-loop cooling. Transitioning to these water-saving technologies could free up water for irrigated agriculture. Deploying closed-loop cooling in all of Shanxi's coal-fired power plants would support meeting domestic food and energy demands with a probability of 24%. The deployment of air cooling would increase this probability up to 40%.



water than is available. Decision-makers would have to either reduce production targets and run the risk of food and energy under-supply; prioritize production and take water away from private households; or exploit the water system beyond sustainable levels. Any of these measures alone or in combination would ultimately reduce human wellbeing.

## OPTIMIZING UNDER UNCERTAINTY

Stochastic programming is an increasingly popular mathematical tool for modeling problems that involve uncertainty. When model parameters are unknown or uncertain, modelers turn to probability distributions — a function that shows the relationship between the outcome of a plausible event and its frequency of occurrence. To maximize a set of benefits while minimizing risks, these models can include 'chance' constraints, which ensure that the probability of meeting a certain constraint is above a certain level. At the food-energy-water nexus, chance-constrained optimization would allow decision-makers to set up food and energy security goals based on the target probabilities for which the domestic supplies of food and energy would meet the domestic demand. These approaches have been especially important in engineering and finance, where uncertainties in price, demand, supply, and currency exchange rate are common. More recently, it's been used to manage

water resources and agricultural supply chains and optimize renewable energy portfolio requirements.

## CONCLUSIONS

Chance constrained stochastic programming is an effective and convenient approach to control risk in decision-making under uncertainty. It improves the realism of model recommendations as it avoids the fallacy of relying on averages. Sustainability transitions rely on processes that involve numerous uncertainties, and these must be addressed in models used to inform such transitions. Unique mathematical approaches allow the inclusion of probabilities to meet desired objectives, giving decision-makers additional space to maneuver in reaching sustainability goals.

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