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# The Nexus of Food, Energy, and Water

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**ABSTRACT:** The Earth's population is expected to exceed 9 billion by 2050, posing significant challenges in meeting human needs while minimally affecting the environment. To support this population, we will need secure and safe sources of food, energy, and water. The nexus of food, energy, and water is one of the most complex, yet critical, issues that face society. There is no more land to exploit, and the supply of fresh water in some areas of the world limits the use of land for food. All solutions must also deal with the overlay of global climate change. Meeting current and future populations needs will require security in food, energy, and water supplies. A nexus approach is needed to improve food, energy, and water security integrating the management of the limited resources while transitioning to a more "green" economy, which provides adequate food, energy, and water for the expanding human population.

**KEYWORDS:** *food, energy, water, climate, fracking*

## ■ INTRODUCTION

Interactions among food, energy, and water are complex and inseparable. Water is directly or indirectly used in the generation of energy and the production of food. Agriculture for the production of food and fiber is the largest consumer of water. However, large volumes of water are required for the generation of electricity, extraction of fossil fuels, mining, refining, residue disposal and processing of fossil fuels, and growing feedstocks for biofuels in addition to the water used for agricultural food and fiber production. Energy is required to transport water and to treat it to be suitable for drinking water and clean wastewater for reuse or releases to the environment. Agricultural food and fiber production utilizes about 70% of the fresh water used for human food production. The need to produce food and energy stresses the limited supply of fresh water on the planet. Food systems include the entire gamut of agricultural production and harvesting as well as animal production, aquaculture, and processing, storage, and distribution of food products through the wholesale and retail systems. It also includes seed, land preparation, labor, energy, soil, animals, equipment, and final food preparation of an adequate, nutritious, and safe food supply.[1] The entire food, energy, and water nexus is overshadowed by global warming, which is exacerbated by the excess use of carbon fuels for energy. In this perspective we bring together the interactions of food, energy, and water and make the case that water is the most critical resource for production of food and energy.

## ■ WATER

The water system includes all water utilized for human consumption from surface water or groundwater and the treatment and disposal of wastewater to protect public health and the environment. A watershed is an area that includes surface water and underground water as well as water drainage to other areas independent of political boundaries.[2] The EPA defines 2220 watersheds in the continental United States. Adequate water supplies do not always exist where needed; thus, water frequently must be moved between watersheds to meet agricultural, municipal, industrial, energy, and recreational requirements. For example, much of the water for southern California comes from the Colorado River or the Sacramento Delta, requiring water to be pumped hundreds of miles, sometimes over mountainous terrain. In other areas, much if not all of the water for human consumption comes from underground aquifers.

Regardless of source, when water is withdrawn, some is recovered and some is lost to further use. Water availability refers to water that is diverted from the surface water or groundwater and returned with minimal changes. Consumptive water is water that is no longer available because it is evaporated, transpired by plants, consumed by animals, incorporated into products, or otherwise transformed.[3]

Water is also required for transportation and for wildlife and fisheries. We are in critical need of a comprehensive approach that addresses integrated management of all resources. Particularly, water resources among all sectors of agriculture, energy, food processing, and environmental needs will be required.

Water is required in large quantities in conventional power production, primarily for cooling. It is estimated that nearly half of the fresh and ocean water withdrawals in the United States are for cooling thermoelectric power plants, including nuclear power plants.[4] The fresh water from cooling is frequently used downstream for irrigation and drinking water, whereas the salt water is returned to the source. Thermoelectric power generation constitutes more water use than any other category,

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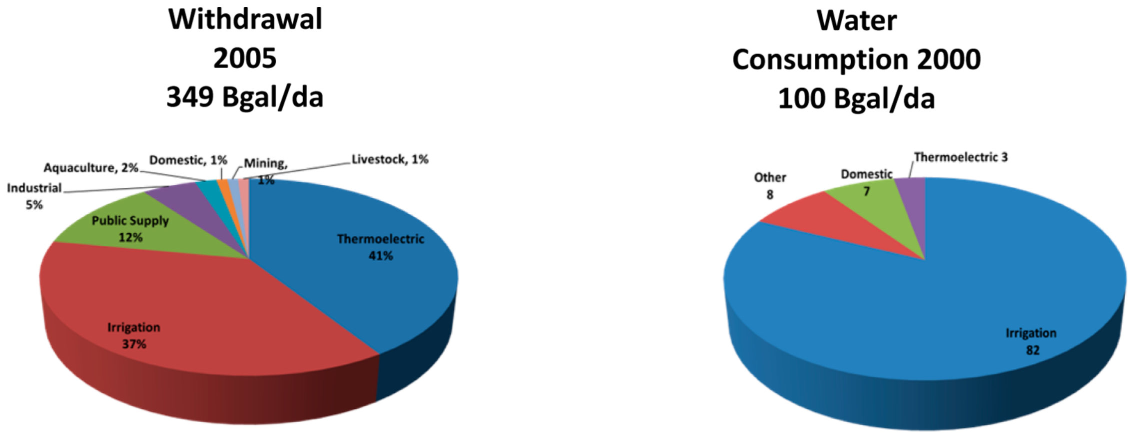


**Figure 1.** Fresh water withdrawals and consumption in the United States. Adapted from Faeth.[5]

**Table 1. Agricultural, Industrial, and Domestic Use of Water Withdrawals in Regions of the World in Cubic Meters per Year Based on 2000 Data[6,10]**

| region | renewable water resources | total water withdrawals | agriculture amount | industry amount | domestic urban | % renewable resources |
|---|---|---|---|---|---|---|
| Africa | 3936 | 217 | 186 | 9 | 22 | 5.5 |
| Asia | 11594 | 2378 | 1939 | 270 | 172 | 20.5 |
| Latin America | 13447 | 252 | 178 | 26 | 47 | 1.9 |
| Caribbean | 93 | 13 | 9 | 1 | 3 | 14 |
| North America | 6253 | 525 | 203 | 252 | 70 | 8.4 |
| Oceana | 1703 | 26 | 18 | 3 | 5 | 1,5 |
| Europe | 6603 | 418 | 132 | 223 | 63 | 6.3 |
| world | 43559 | 3829 | 2663 | 784 | 382 | 8.8 |

including irrigation or public water needs. Much of this water is returned for use in agriculture or municipal uses downstream. For this reason thermoelectric power plants are located near rivers, lakes, or oceans. The power plant needs for water are vulnerable to fluctuating water supplies, and when water is not adequate, there is increased risk of environmental damage or forced shutdown if there is not sufficient water for cooling requirements.

The water demands for food production and processing are enormous. Agricultural crop irrigation accounts of 82% of all water withdrawals in the United States.[5] Irrigation directly competes with water uses such as power-plant cooling, municipal needs, and fossil fuel production and transportation. When we face drought conditions, irrigation restrictions are by state and county governments, which can negatively affect food production. Food production also can have an impact on water quality because of water runoff from agriculture, which contains fertilizers, pesticides, herbicides, and manure from agricultural production and wastewater from food-processing facilities. More efficient use of water, through drip irrigation and other conservation practices, is an ongoing need in agricultural.

Figure 1 illustrates the water withdrawals and water consumption in the United States. Electricity generation and irrigation account for the largest withdrawals of water in the United States. However, electricity generation returns most of the water withdrawn, whereas irrigation does not. This water use is critical for the production of agricultural commodities including both domestic needs and economically important exported agricultural products.[5] Major concerns exist as we see more areas of drought from global climate change (GCC). If we use irrigated biomass for energy production, our already limited water system becomes further strained. GCC estimates are that drier areas will become drier and wetter areas will become wetter. Therefore, water redistribution might be the biggest challenge for the future.

Increases in demand for food and energy have made clear the concerns about sufficient water availability. Renewable water resources throughout the world are used to various degrees for agriculture, industry, and domestic uses. In all cases agriculture is the largest user of water worldwide as summarized in Table 1. It is worth noting that Asia is the largest user of agricultural water, whereas Asia, North America, and Europe use similar amounts of water for industrial purposes. This supports the demand for more efficient use of water in agriculture and the need for plants that require less water for food or biofuel production.

Water is a key component in energy production; it is used in power generation, cooling thermal power plants, and the extraction, transportation, and processing of fuels. Water also is required for irrigation and for processing of biomass crops. Energy is also required for the collection, transport, treatment, and distribution of fresh potable water. Both fresh water and seawater are critically important for transportation of raw materials and products in most parts of the world.[7]

Continuing droughts and demands for irrigation to support food production are requiring greater reliance on underground water aquifers. To meet these needs, water wells must be drilled deeper and deeper. Energy is required for groundwater delivery. As we drill deeper for groundwater sources, more energy is required to bring the water to the surface. The need for current and expanding populations for clean water and sewage treatment will require energy to move water to the needed sites economically and without the addition of more environmental stress.


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If desalination becomes economical, it could provide an important source of water at least in coastal areas. The technology for desalination of seawater and/or brackish water has improved significantly in the past 10 years; as a result, the capacity has grown rapidly. Cost remains a significant figure in desalination. The cost of desalinated water ranges from U.S. $0.50/m$^3$to U.S. $1.00/m$^3$ depending on location. Recent developments including the increase of unit capacity, process design and materials, improved membrane technology, and hybrid systems are offering promise for decreased cost and reduced energy consumption in the desalination processes. The developments of low-energy desalination technologies, such as adsorption desalination, provide promise for low cost and energy demand in the future.[8,9]

The relative amounts of water used in the energy sectors differ among the various sectors. Table 2 provides a comparison of the amounts of water required to produce a million British thermal units (BTU) of energy. The data provide interesting comparisons of the amounts of water required for enhanced recovery techniques. It also must be kept in mind that currently it is difficult to recycle that water. The biofuels comparisons are important to consider, but it must be recognized that rainwater is not considered in the estimates.

**Table 2. Average Water Consumption for Production of Transportation Fuels[10]**

| source | water for material recovery (gal/million BTU) | transformation (gal/million BTU) | total gal/million BTU |
|---|---|---|---|
| traditional oil | 1.4 | 12.5 | 13.9 |
| conventional natural gas | 0 | 2 | 2 |
| shale natural gas | 12.5 | 2 | 14.5 |
| oil sands | 260 | 12.5 | 272.5 |
| enhanced oil recovery (fracking) | 1257 | 172 | 1429 |
| irrigated corn (ethanol) | 15750 | 9 | 15759 |
| irrigated soy biodiesel | 44500 | 9 | 44509 |

Traditional oil and gas production use less water than production from tar sands and fracturing. Developing agricultural-based bioenergy substitutes produces additional stress on water resources. The need for water posts a significant constraint on corn-based ethanol production in the United States. Water demand for ethanol fuel production ranges widely. For example, to produce a gallon of ethanol, from 995 to 2967 gal of water is required.[10] These differences are due to variations in climate and irrigation requirements. Switch grass requires from 1.9 to 9.8 gal of water per gallon of ethanol.[11] Gasoline production requirements range from 2.8 to 6.6 gal of water per gallon of gasoline.[12] In 2001, 707 million bushels of grain were used for ethanol production. By 2010, 5020 million bushels of corn were utilized for ethanol production. The 2010 figure represents about 40% of the 12447 bushels of corn produced.[5,13] To put water use and energy use in perspective, it requires about 2 million BTU to drive an automobile on a round trip from New York City to Washington, DC. Table 3 presents the amount of water necessary to produce the various fuels required for such a trip.

**Table 3. Gallons of Water Consumed To Produce Fuel for a Round Trip Drive from New York City to Washington DC**

| fuel type | gal of water to produce fuel |
|---|---|
| natural gas (as on land) | 5 |
| shale natural gas | 33 |
| traditional oil | 32 |
| oil sands mining | 616 |
| irrigated corn (ethanol) | 35616 |
| irrigated soy | 100591 |

Hydraulic fracturing, or “fracking,” is used to extract gas and oil from rock formations where oil and gas are not normally accessible. However, after fractures are developed in the rock formations using horizontal drilling and high levels of hydraulic pressure, gas and oil can move through the fractures and become accessible. These more accessible oil and gas reserves can then be exploited by wells.[14] The Marcellus shale basin, one of the largest, extends from northern Georgia to New York. Various other formations are found in Texas, Oklahoma, Indiana, Michigan, Arkansas, Louisiana, and the Rockies.[15] Other areas of the country offer similar opportunities for oil and gas production, including North Dakota, Pennsylvania, Wyoming, and Montana[5,17] Fracking has resulted in the ability to recover vast new quantities of petroleum and natural gas, lowered energy costs, and improved energy independence for the United States. Production estimates for the Eagle Ford area in Texas are expected to reach 2−3 million barrels of oil per day by 2035. This would represent as much as 1.5−2% of current gasoline production from this single area. To accomplish this, water demand in the Eagle Ford region will increase 10-fold by 2020.[17]

It is anticipated that shale gas will make up 46% of the total energy supply of the United States by 2035. Fracking raises a major concern because of the volumes of water required and the risk of contamination of aquifers needed for food production and domestic drinking water needs. The average shale gas well requires 3−4 million gallons of water and will yield 800 million cubic feet of gas over the 7.5 year lifetime of a well.[15]

The large volumes of water required by the fracking process pose particular problems in semiarid areas where water tables are receding. This generates a competition with agricultural irrigation and domestic water needs.[16] In addition to the vast quantities of water required for fracking, the wastewater from fracking contains a variety of compounds that make it unsuitable for irrigation or domestic use. Fracking fluid contains hundreds of chemical compounds. Companies involved in fracking reported to a Congressional committee that up to 750 different chemicals are used and/or formed in the fracking process. They range from the innocuous such as sodium chloride, citric acid, coffee, and walnut hulls to toxic ones such as lead, benzene, and methanol. Twenty-nine known or possible carcinogens have been reported in fracking wastewater.[15]

A major challenge for the industry is to develop processes to clean this water enough that it can be used for other purposes, such as irrigation, potable water, or environmentally benign release to the environment. There is rising public concern about water competition where fracking is conducted in arid regions.[17]

Thermoelectric power consumption whether coal, oil, or gas requires cooling water, which comes from surface water.

Table 4. Cost and Environmental Factors for Electricity-Generating Technologies[26]

| energy technology | av levelized cost of electricity ($/MWh) | median water withdrawal by cooling type (gal/MWh) | median water consumption by cooling type (gal/MWh) | $CO_2$ (lb/MWh) |
|---|---|---|---|---|
| **existing technology** | | | | |
| conventional coal | 62 | 531–36350 | 250–471 | 1886 |
| natural gas combined cycle | 57 | 253–11380 | 100–198 | 797 |
| nuclear | 59 | 1101–44350 | 269–672 | |
| **new technology** | | | | |
| conventional coal | 95 | 531–17914 | 493–779 | 1886 |
| advanced coal | 109 | 390 | 372 | 1755 |
| advanced coal + carbon capture and sequestration (CCS) | 126 | 596 | 540 | 206 |
| natural gas combined cycle (NGCC) | 66 | 253–5950 | 198–240 | 797 |
| NGCC + CCS | 89 | 496 | 378 | 86 |
| advanced nuclear | 104 | 1101–7050 | 610–672 | |
| hydroelectric | 86 | | 4491 | |
| wind, onshore | 97 | | 0 | |
| wind, offshore | 243 | | 0 | |
| solar thermal | 312 | | 8–1000 | |
| photovoltaic | 211 | | 26 | |

Currently, cooling for thermoelectric power withdraws up to 75% of the surface water in some areas, however, much of it is returned for other uses.[18]

When greenhouse gases are sequestered, their cooling water demand could double because of the energy and water required for compressing the carbon dioxide.[19]

Water is very likely to become the most limiting resource in the nexus scenario. More work is needed to improve the efficiency of our water use, enhance our ability to provide clean water where needed, and purify wastewater from domestic use, energy production, and agriculture. We also need to continue development of drought- and heat-resistant crops.

## ■ ENERGY

The energy system, as defined by Hanlon et al.,[1] includes operations necessary to generate, transport, and distribute electricity and the steps required to produce and distribute fuels required for transportation and industry. Electrical energy is generated in a variety of power plants, which operate through the combustion of fossil fuels (coal or natural gas) or nuclear fission. These processes all generate heat, which is converted to steam, which turns turbines and ultimately generates electricity. Electricity is also generated from flowing water, wind, sunlight, and the Earth's heat (e.g., geothermal). Most electricity-generating facilities consume water either to process the raw materials used in the facility for fuel, to cool thermoelectric generation plants (fossil fuel and nuclear), or to generate the electricity itself (i.e., hydroelectric).

Thermal power plants require large amounts of water to remove excess heat. Up to 39% of all freshwater withdrawals in the United States are used for thermoelectric energy production. The needs for cooling water frequently are in competition with agriculture and municipal demands. If drought conditions increase as predicted with continuing GCC, some river flows will be very low in the summer, putting additional strain on power production and waterway transportation.[20]

In thermoelectric power plants in the United States, 1 kilowatt hour (kWh) of electricity requires the evaporation of about 2 U.S. gal (7.6 L) of water to eliminate waste heat from the process. In hydroelectric plants an average of 18 gal (68 L) of water is evaporated to generate 1 kWh of electricity. In practical terms, this means that 8–16 gal of water IS required to burn one 60 W light bulb for 12 h. This would mean that annually one incandescent light bulb would consume 3999–6300 gal of water. If it is assumed that the 111 million occupied housing units (U.S. Census Bureau 2005) burned one 60 W light bulb for 12 h a day for a year, it would require between 336 and 656 billion gallons of water use.[21]

Extraction and pumping water from ground and surface sources to sites of use requires electrical energy. The energy intensity of treatment required for different types of water source varies, depending on water sources. Fresh surface waters use energy mainly for pumping over long distances. Use of seawater adds the energy requirements for desalination. The energy required for residential end use water is very high relative to other parts of the water supply cycle. Processes such as heating water, washing clothes and dishes, and cooking all require intense energy input. Hot water usage is responsible for making end use the most energy-intensive stage of the water cycle.[22] Potable water must be pumped from its source (underground or surface) to the treatment plant, pretreated, and then pumped to consumers. In areas without adequate fresh water, it may be necessary to bring water from very long distances, making the energy footprint for this water extremely high.

Table 4 compares the cost of energy to the amount of water (withdrawals and consumption) and carbon dioxide emissions produced by various means of power generation. The data provide insight into the trade-offs of different means of energy production. Nuclear power has no carbon dioxide emissions but requires large amounts of cooling water. This water (like water for hydroelectric power generation) is suitable for reuse in agriculture or domestic use. Coal uses relatively modest amounts of water but generates high levels of carbon dioxide, which is a significant contributor to greenhouse gas and related global warming.

Southern California receives potable water from the Sacramento–San Joaquin Delta, which requires pumping water over hundreds of miles over low-lying mountains using 9200 kWh per million gallons.[23] In California the conveyance, storage, treatment, distribution, wastewater collection, and discharge of water consumes 19% of the state's electricity, 30% of its natural gas, and 88 billion U.S. gallons (330,000,000 $m^3$) of diesel fuel annually. The River Network reports that the United States consumes at least 521 million megawatt-hours a year for water-related purposes, which is equivalent to 13% of the nation's electricity consumption.[24−26]

## FOOD

From a global perspective food security would exist "when all people at all times have physical, social and economic access to sufficient, safe, nutritious food to meet dietary needs and food preferences".[27] Increases in demand for food and energy have made clear the concerns for sufficient water. Table 5 summarizes the amount of water required to bring selected foods to market. The water demand for animal protein foods is much higher than that for plant-based foods. This begs the question as to the sustainability of high animal protein production under ever-increasing population growth.

**Table 5. Water Requirements for Food Commodities[27]**

| product | unit | equivalent water ($m^3$/unit) |
|---|---|---|
| cattle | head | 4000 |
| sheep and goats | head | 500 |
| fresh beef | kg | 15 |
| fresh lamb | kg | 10 |
| fresh poultry | kg | 6 |
| cereals | kg | 1.5 |
| citrus fruits | kg | 1 |
| palm oil | kg | 2 |
| pulses, roots, and tubers | kg | 1 |

The production and processing of food are the largest users of fresh water, consuming an average of 70% of the human use of fresh water. Modern agriculture and food production requires large amounts of energy and also affects the water resources because of land degradation, changes in runoff, disruption of groundwater recharge, water quality, and availability of water and land for other purposes such as natural habitat. Modern agriculture, which is required to feed the current population, uses approximately 30% of total global energy. Fuels are required for land preparation, fertilizer production, irrigation and sowing, harvesting, transportation of crops, and processing and distribution of foods.[27]

All food production requires significant amounts of water. The quantities are determined by growing conditions and the nature of the food. Animal production, because of the inherent inefficiencies, utilizes relatively large amounts of water compared to cereals and pulses. Table 5 illustrates the range of water required to produce some basic agricultural commodities. To produce a kilogram of beef requires 15500 L of water, the same amount required to produce 12 kg of wheat or 118 kg of carrots. Making a hamburger requires >2400 L of water, not including the bun.

Table 6 contains the water requirements to produce some processed foods and fruits. This offers an interesting perspective on how much water is required for various foods. The values include production as well as processing requirements.

The Food and Agricultural Organization of the United Nations (FAO) projects that to feed the 9 billion people anticipated in 2050, global food production will need to rise by 70% and in the developing world will need to double. Currently we are not providing sufficient food to prevent global hunger. The FAO reports that in the past decade the number of chronically hungry people rose to one billion. The FAO estimated the number of people suffering from chronic hunger at 642 million in Asia and the Pacific, 265 million in sub-Saharan Africa, 53 million in Latin America and the Caribbean, and 42 million in the Near East and North Africa.[27]

**Table 6. Water Requirements for Processed Foods[27]**

| product | quantity | equivalent water (L) |
|---|---|---|
| glass of beer | 250 mL | 75 |
| glass of wine | 125 mL | 120 |
| glass of milk | 200 mL | 200 |
| glass of apple juice | 200 mL | 190 |
| cup of coffee | 125 mL | 140 |
| glass of orange juice | 200 mL | 170 |
| cup of tea | 250 mL | 35 |
| bag of chips | 200 g | 185 |
| slice of bread | 30 g | 40 |
| egg | 40 g | 135 |
| slice of bread with cheese | 30 g + 10 g | 90 |
| hamburger | 150 g | 2400 |
| potato | 100 g | 25 |
| tomato | 70 g | 13 |
| apple | 100 g | 70 |
| orange | 100 g | 50 |

The use of agricultural land for biofuels will further stress food production agriculture. The FAO projected that biofuel production by 2030 will require 35 million hectares of land, an area about the size of France and Spain combined. The projected 70% increase in food production is challenged by rising energy prices, depletion of aquifers available for water withdrawal, and the continuing loss of farmland to urbanization.

Energy conversion from solar energy to food products is inherently inefficient. Photosynthesis converts <2% of incoming solar radiation to biomass. Conversion of that biomass to food by feeding animals compounds the inefficiency, because only 5−10% of feed is converted to edible beef. Poultry is only slightly better with a 10−15% conversion. The United States expends approximately 10 units of fossil or other energy to recover one unit of food energy. To put this in perspective, a healthy male might expend 2500 kcal/day, which equates to 10000 BTU per day or 125 W.[28] If one extrapolates these numbers to the 9 billion mouths to feed in 40 years, energy for food production must be considered to be equally challenging to the water issues. In addition to developing more energy-efficient production practices from farm to fork, we also need to improve efficiency by reducing food waste. Wasted food not only does no good from a nutritional point of view, but requires energy to dispose of it. Table 7 summarizes estimated food wasted in the United States. Clearly reducing waste will

**Table 7. Food Wasted in the United States[28]**

| food group | % ultimately wasted |
|---|---|
| grains | 32 |
| vegetables | 25 |
| fruit | 23 |
| tree nuts, peanuts | 16 |
| dairy | 33 |
| meat, poultry, fish | 16 |
| eggs | 31 |

ultimately improve sustainability and total food supply. However, we need to consider the entire food system, including the consumption and use of animals and the inherent inefficiencies of current animal food production.

In recent years there has been a growing interest in "eating local". Consuming locally produced foods reduces transportation and frequently addresses freshness and quality issues with produce. In some cases the locally produced products have a larger energy input than foods imported from miles away. For example, when marginal land is used, it may require more chemical input (fertilizers and pesticides), where yields per acre still remain much less.[28] Locally produced food is often labor-intensive and does not provide the efficiencies of large farming operations. It is an important niche in food production, but not likely to substantially affect food production for the 9 billion population of the future.

Establishing a model or simple measure of energy requirements to move food from farm to dinner plate is difficult because of the wide diversity of agriculture and the inherent variability of locale and climate. The cost of energy to produce food products can be extremely high, particularly when we consider production of animal protein foods.[29]

From Tables 8−10 it is clear that animal production is far less efficient than the production of corn. The efficiency also translates to other commodity crops. It is unlikely that we can convince meat-eating societies to switch to vegetarian diets in the near future. In addition, as low-consumption meat-eating societies become wealthier, it is likely that they will demand more meat protein in their diet. One approach would be to produce ground meat and sausage products that are blends of meat with pulse crops (dry beans and lentils). Pulse crops maintain protein levels, contribute fiber, and lower fat and cholesterol. Pulses are efficient crops to produce, requiring relative low levels of water and energy for production. Therefore, pulse/meat blends could provide energy-efficient and healthier options.

**Table 8. Energy Use at Various Stages of Food Production[30]**

| use segment | energy use (quads[a]) |
|---|---|
| farm fuel | 1.0 |
| farm chemicals | 1.5 |
| farm machinery | 0.6 |
| farm irrigation | 0.5 |
| processing | 1.2 |
| packaging | 2.3 |
| transportation | 1.4 |
| retail and commercial | 2.5 |
| residential | 7.1 |

[a]A quad is $10^{15}$ BTU.

**Table 9. Energy Required To Produce 1 lb of Various Foods[30]**

| food | energy (kWh) to produce 1 lb |
|---|---|
| corn | 0.43 |
| milk | 0.75 |
| apples | 1.67 |
| eggs | 4 |
| chicken | 4.4 |
| cheese | 6.75 |
| pork | 12.6 |
| beef | 31.5 |

**Table 10. Energy Efficiency of Various Foods Measured as Food Calories per Energy Used in Production[30]**

| food | cal/lb | energy efficiency (%) |
|---|---|---|
| corn | 390 | 102 |
| milk | 291 | 45 |
| cheese | 1824 | 31 |
| eggs | 650 | 19 |
| apples | 216 | 15 |
| chicken | 573 | 15 |
| pork | 480 | 8.5 |
| beef | 1176 | 4.3 |

## ■ SOLUTIONS MUST BE SUSTAINABLE

The solutions to the water, energy, and food crisis must be carefully integrated to meet the needs to produce resources for the 9 billion inhabitants in the next 40 years. Without joint solutions the entire system will fail. Sustainable food production requires optimizing health, safety, quality, and consumer appeal of sufficient foods to sustain the growing world population. Agricultural food production has helped sustain this growth by increasing food production 20% from 1990 to 2010. If we are to meet the food needs of the anticipated population growth, this rate of increased production must continue for the next 25 years.[31] In addition to increasing population, improved nutrition and health care are extending life expectancy, further increasing the need for more high-quality food. These increases must continue in the face of limited energy supplies, limited water supplies, and increased global warming, which results in lower production using current practices.

To meet the growing need for food production, we must face the following considerations:

1 − production of more food on less desirable land using less water;
2 − decreasing energy required for production;
4 − sufficient water in the proper location at a low cost;
3 − increased globalization of best means to provide energy and water resources for food;
4 − globalization of compliance regulations.

Within the food system sustainability is regarded quite differently depending on the particular segment. For example, for food producers sustainability relates to land, water, and energy management. In addition to these macroconcerns, producers must consider fertilization and pest management, focusing on the sustainable environmental factors as well as energy resources for production of the chemicals. To help address these concerns, in recent years the U.S. Environmental Protection Agency (EPA) registration of new pesticides is now largely devoted to biorational or biopesticides, rather than further modification of synthetics from the 20th century.[32] This should help improve overall water quality by reducing residual agricultural chemicals. When food sustainability is considered from the food health and nutrition viewpoint, consumer health and nutrition are particularly important (e.g., vitamin, antioxidant, and mineral balance and avoiding undue levels of fats, carbohydrates, sodium, and synthetic additives).[33−37] Food processors' sustainability issues are focused on preserving and distributing foods, including maximizing shelf life for quality and safety.

There is growing momentum demonstrating the benefits of new biopesticides, biofuels, and biobased products used in the production, processing, and distribution of foods.[38] Food processing results in the production of considerable waste, but much of the waste material could be recovered and used as an energy source as summarized in Table 7. Food waste needs to be minimized and value captured whenver possible. Capturing and using the energy from processing and food wastes through approaches such as anaerobic fermentation to biogas and recovering the energy as electricity would make use of biomass and result in net energy savings.[39]

The "9 Billion Problem" has implications for the way research, education, and outreaches are supported at the National Institute of Food and Agriculture (NIFA). The science, policies, and regulations must align with addressing the global challenges in a sustainable manner, including food security, hunger, food safety, health and nutrition, childhood obesity, energy, water, and climate change.

The nexus between food, water, energ,y and health is critical as to how we deploy resources to address the same because of the need to consider them collectively, rather than individually. The increase in population will contribute to escalating the scarcity of land, water, energy, and food.[40]

Addressing these complex issues will take a commitment to seeking collaborative efforts between federal and state agencies, private enterprise, and nongovernmental organizations. Investing in enabling sound science and policies that address these complex issues and investments in ensuring food security and sustainable bioenergy and water will be a significant part of NIFA's portfolio. NIFA along with other federal agencies including the National Science Foundation, the Department of Energy, and the Bureau of Land Management must continue to support the best and brightest scientists at academic institutions and in private and nongovernmental sectors to find innovative solutions to these challenges. By making the right investments in science, our expectation is that NIFA-supported reseach will enable the scientific community to make great discoveries that can be translated into innovations beneficial to the lives of the American people, and for that matter, globally.[40] For example, drought-resistant and heat-tolerant crops produced through biotechnology could help maintain or increase usable production land for commodity crops such as corn. The corn would lower food production costs and potentially provide feed for production of more animal protein for the growing population. Improving the feed efficiency for milk and meat production also provides challenging but potentially impactful means to provide desirable foods for the growing population.

The dilemma of food, energy, and water present us with a worldwide multidimensional problem that links resources, politics, and quality of life for all on the planet now and for the 9 billion that will inhabit the plant in the next 40 years.

## IMPLICATIONS

We must adopt a nexus approach to deal with the relationships of food, energy, and water. None of these issues can be effectively resolved in isolation. Development of new technology in any of the sectors must consider the impact on the other sectors as well as the environment. Specifically, the development of a new energy or food crop must consider water use, energy consumption, and waste or byproduct production during the process. Government and international policy needs to be developed to ensure integrated implementation of technologies considering growing population stresses, the associated energy and food needs, and how these affect the environment and potential for global warming. We must avoid isolated silo approaches and consider broad effects of new technologies and their impact on the food, water, and energy systems. The nexus must involve individuals, policy makers, and thought leaders. As scientists we need to take leadership in communicating the issues clearly and bring forth new technologies that solve problems while also considering the broad implications of these new technologies.

In summary, it is critical that we develop environmentally sustainable sources of energy. The use of carbon-based energy sources needs to be restricted in favor of lower carbon emission sources including solar, wind, and nuclear energy. Water use and protection are major concerns. It is imperative that groundwater pollution be restricted and water used in processes such as fracking be purified to a degree that it can be used for agricultural or domestic applications. Agriculture is the largest user of water, and thus improved practices to minimize water use are needed. Biotechnology should continue to develop drought-tolerant crops for use throughout the world. With GCC the need for drought-tolerant crops will become even greater. With the potential problem of feeding 9 billion people in 40 years, we must seriously consider how much agricultural land should be used for biofuels. Land not suitable for agriculture can be used for crops such as switchgrass that may be viable alternatives for biofuel production. As part of this consideration, however, the impact on the local environment and the habitats of wildlife must be assessed. In addition, sugar cane could be a sustainable source for biofuels. The decreased consumption of sugar from antiobesity campaigns may result in increased sugarcane supplies at prices favorable for biofuels. A major concern is the sustainability of animal products. As discussed, animal production requires large amounts of water and energy compared to grain- and pulse-based products. It is important that we consider greater use of plant-based foods to meet long-term needs for the growing population.

The pressures on energy, water, and food for the growing population are being exacerbated by climate change. At the current pace of growth of food, water, and energy needs, the planet will not be able to provide sufficient resources to meet these demands. There is no one simple solution to resolve these complex issues. Additional investment is needed by government, universities, and industry to identify, fund, and develop integrated and sustainable solutions to address our current and future needs for food, energy, and water. Solutions must include environmentally benign approaches through continued research on sustainable processes. Alternative solutions that provide greener processes need to be encouraged with tax incentives. Assessments and metrics need to be based on long-term solutions that reflect their true impact.

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### Notes

The authors declare no competing financial interest.

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