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WATER AND ENERGY

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INTRODUCTION

Energy and freshwater resources are intricately connected: We use energy to help us clean and transport the fresh water we need, and we use water to help us produce the energy we need. As we approach a new century, physical and environmental constraints in our use of both resources are beginning to manifest themselves. This paper reviews the myriad connections between our demand for and use of energy and water, and suggests that there are strong parallels between the growing water crisis and conflicts over energy resources, as well as between the solutions to both problems. In particular, the arguments over the past two decades over energy prices, equity and efficiency of energy

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use, technological innovation, and supply versus demand are now being heard in the growing debates over freshwater resources.

Energy is required to operate modern water-supply and purification facilities. Without the input of substantial amounts of either electrical energy or heat, major water transfers from water-rich to water-poor regions, the desalination of brackish water or seawater, and massive pumping from groundwater aquifers would all be impossible.

On the other hand, the production and use of energy often requires a significant commitment of water. Water is required when an energy resource is mined, as a feedstock to alter fuel properties, for the construction, operation, and maintenance of energy-generation facilities, for power-plant cooling, and for the disposal of waste products. Sometimes this water is withdrawn and then returned to a water supply; sometimes it is consumed during operation or contaminated until it is unfit for further use. Even hydroelectric facilities are responsible for the consumptive loss of water that evaporates from reservoir surfaces. Water use in the energy sector can lead to changes in natural hydrological and ecological systems and increase the pressure for interbasin transfers of water to regions that are water poor. In some cases, constraints on water availability will limit choices of sites and types of energy facilities.

In the coming years, new demands for water from competing sectors of society and from growing populations will place new pressures on the amount of water available for energy production. Limitations on the availability of fresh water in some regions of the world may restrict the type and extent of energy development. At the same time, high energy costs or limited energy availability will constrain our ability to provide adequate clean water and sanitation services to the thousands of millions of people who lack those basic services. Developing rational water and energy policies will thus increasingly require policy-makers to integrate these connections into their decisions.

ENERGY FOR WATER

Energy is required to transport water from one region to another, and to clean water that was previously considered nonpotable. We now routinely remove salts, bacteria, chemicals, and other contaminants from water using desalination and wastewater treatment techniques, and we pump water from deep underground aquifers or distant sources. The availability and price of energy set limits on the extent to which unusual sources of water can be tapped. As a result, understanding the links between water supply and quality and energy will help us evaluate future constraints on meeting water needs. This section discusses energy requirements for moving water from one place to another, for pumping groundwater, and for desalinating brackish and salt water.

Energy for Moving Water

One of the most important characteristics of the global freshwater cycle is its grossly uneven spatial and temporal distribution. Although water is plentiful on a global average, we often do not get it when we want it, where we want it, or in the form it is needed. Only 3% of the world's water resources are fresh water, comprising a total volume of about 35,000,000 km^3. Yet almost all of this fresh water is effectively locked away in the ice caps of Antarctica and Greenland and in deep underground aquifers, which remain technologically or economically beyond reach. Less than 100,000 km^3—just 0.3% of total freshwater reserves on earth—are found in the rivers and lakes that constitute the bulk of our usable supply (1). As urban and rural demands grow, we are increasingly faced with the problem of supplying human needs that are far removed from reliable sources of water supply.

Society's first answer to the problem of the grossly uneven distribution of freshwater resources was to build water-supply facilities to make up for variations in precipitation or river runoff over time and to move water from regions of surplus to regions of deficit. Legend says that the early kings of Menes, the first of the pharaohs of Egypt, built a masonry dam across the Nile River near Memphis to control the annual flood. Other sources say the earliest known dam across a river, the Sadd el Kafara, was built more than 5000 years ago in the Middle East (2). By the time of Ramses II in the 14th century BC, an extensive system of irrigation canals and reservoirs had been developed (3). The ancient Mesopotamians made extensive use of canals to bring water to the city of Babylon. The Hanging Gardens of Babylon, famed as one of the seven wonders of the world, were supplied with water by these systems, and the fertility of Babylonia was a source of envy to the Greeks. Herodotus wrote, "Of all countries, none is more fruitful in grain" (4). Babylon grew corn, barley, wheat, emmer, sesame, flax, fruit trees, vineyards, herbs, and many other crops with water from the Tigris and Euphrates Rivers and from reliable groundwater aquifers supplied through irrigation canals and qanats—long, sloping tunnels dug from a natural spring to a community or agricultural field. Qanats determined the nature, size, and spread of human settlements in many parts of Iran, Iraq, and northern Africa thousands of years ago (T Naff, personal communication, 1992) (5).

Another remarkable aqueduct system was built by Sennacherib in 691 BC to bring water from a tributary of the Greater Zab to his capital Nineveh, 80 km away. Jerusalem was supplied in early times by a system thought to have been built under the kings of Judah around 1000 BC. Parts of this conduit system are still complete (3, 4).

In Asia, excavations at Harappa and Mohenjo Daro in the Indus Valley have revealed ceramic pipes for water supply and brick conduits under the streets for drainage that are thought to have been in operation around 3000 BC (3). More than 2000 years ago, the Chinese began construction of the Grand Canal with a 150-km-long canal built to meet the military needs of the Wu Kingdom. The Grand Canal is still in use today and extends over 1700 km (6). In fact, this canal is the focus of a massive current effort by the Chinese to bring water from the Yangtze river basin to the drier northern parts of the country.

The Romans are also renowned for their aqueducts and water-supply systems. The first of the Roman aqueducts was completed around 312 BC, and by the height of the Roman empire, nine major systems supplied the occupants of Rome with as much water per capita as are provided in many parts of the industrialized world today. This water was distributed through an extensive system of lead pipes in the streets, and the city was drained by well-built sewers (3, 4).

While significant amounts of water were often provided by these early systems, they were ultimately limited in the amount of water that could be supplied, and where that water could go, by the force of gravity. Water could be transferred from one place to another only as long as the source was uphill of the demand.

Modern civilization has greatly increased its ability to transfer water from one place to another by using energy to pump water over hills and mountains. When the demand for water in a region increases beyond the ability of the region to supply it, new sources of water farther and farther away must be tapped. Throughout the 20th century, large-scale water-transfer projects have been developed to permit continued growth in arid and semi-arid regions that would otherwise have been constrained by natural limits. And new projects are constantly being proposed and evaluated as populations and industrial water requirements increase.

These projects almost always involve a substantial investment of energy. To lift 100 m^3 of water per minute to a height of 100 m requires more than 1.5 MWe of power if the pumps are 100% efficient. To do this continuously for a year using electricity from a typical oil-fired power plant and pumps that are 50% efficient would require the energy content of nearly 50,000 barrels of oil.

Most long-distance water-transfer systems have both pumps for getting water over hills and mountains and hydroelectric generators to take advantage of the energy in the falling water as it comes down the other side. Whether a system is a net consumer or producer of energy depends on its geographical characteristics. Where additional energy must be supplied, it is typically generated with fossil-fuel or nuclear facilities, adding to the environmental costs of the water diversion itself.

Many major water-transfer projects have been built or proposed, primarily in industrialized countries. The State Water Project in California, authorized in 1959, now delivers nearly 5 billion m^3 of water every year from northern California to the drier southern parts of the state. If the plans are fully developed, this project would include 148 pumping plants, 40 power plants, 22 reservoirs and dams, and 1000 km of aqueducts. The total energy produced by the system's hydroelectric plants will average more than 7,000,000 MWh per year, but the energy required by the pumping plants to lift the water over the mountains will exceed 12,400,000 MWh per year, making this project a net consumer of energy.

Several other enormous projects that have been proposed would also be net energy consumers. The Texas Water Plan in the southcentral United States, originally proposed during a severe drought in the 1950s, would import 15–16 km^3 per year from the lower Mississippi River and from the rivers of the more humid eastern part of Texas (e.g. Red, Sabine, Sulphur, Neches) (7). This project would require pumping water up 900 m into west Texas. Overall electrical pumping capacity needed was estimated at nearly 7000 MWe, which would produce 40,000,000 MWh per year (at a 65% capacity factor). The project has so far been rejected on the grounds that the water would cost far more than irrigators (the major beneficiaries of the water) could afford to pay, and that the environmental impacts of the water transfer would be severe.

Another scheme is a proposed transfer of water to the High Plains region of the central United States, particularly the states of Colorado, Kansas, New Mexico, Oklahoma, Texas, and Nebraska. This transfer would have replaced a heavy dependence on nonrenewable use of groundwater from the Ogallala aquifer. The High Plains transfer scheme is a set of proposals to move water from the Missouri, Arkansas, White, Red, and Quachita rivers over canals to the High Plains areas. As with the Texas Water Plan, considerable pumping would be required to overcome elevation differences of as much as 1000 m; estimates range from 7,000,000 to 50,000,000 MWh per year for different planned diversions. Operational costs would be quite high because of these huge energy requirements, and this project, too, has never been built because of its high costs (7).

China, like many other nations, has enormous disparities in regional water supply and demand, leading it to propose several massive water-transfer projects. The project with the greatest chance of development is the so-called Eastern Route, which would transfer water from the Chang Jiang River west of Shanghai north to the North China Plain near Beijing. The canal would be more than 1100 km long, with an average capacity of 14 km^3 per year. Several large pumping plants would be needed in the middle of the project, requiring more than 5,000,000 MWh of electricity per year. An interesting characteristic of this project is that it would make use of parts of the ancient Grand Canal (8).

Enormous Siberian rivers schemes have also been proposed and cancelled many times, in many forms. One form would have diverted 120 km^3 per year from the Ob, Irtysh, Yenisei, Onega, Pechora, and Dvina Rivers toward central Asia and other more populated regions of the country, instead of north into the Arctic Ocean. A capacity of 5000–10,000 MWe would have been needed to pump the water over various mountain ranges (9, 10). Even before the disintegration of the Soviet Union, opposition to the project was high on environmental and economic grounds. Now, responsibility for designing, building, and operating such a project has been spread over several new independent nations and new institutions, making it even more unlikely to be built.

Perhaps the most grandiose water-transfer scheme ever conceived was the North American Water and Power Alliance, or NAWAPA, proposed in the early 1960s by the Ralph Parsons Company, a construction-engineering firm. NAWAPA would have collected water from the Fraser, Yukon, Peace, Athabasca, and other rivers of Alaska, British Columbia, and the Yukon territory and transferred this water throughout Canada, the western and midwestern United States, and to three states in northern Mexico. NAWAPA represents the ultimate fantasy of water engineers, effectively replumbing the entire face of western North America with 369 massive projects costing hundreds of billions of dollars. It would have provided more than 5000 km^3 of water storage and eventually transferred 136 km^3 per year (11). Massive amounts of water would have had to be lifted over the Rocky Mountains, which lie between the water sources and the water demands. The centerpiece of the project would have been the damming of the Rocky Mountain Trench, an 800-km-long gorge in the Canadian Rockies adjacent to Banff and Jasper National Parks (12). In all likelihood, the massive environmental and economic costs of this project guarantee that it will never be built, but the design stands as a monument to what we are willing to consider when water supplies are limited.

Today, even relatively modest projects face growing constraints and opposition. For such projects to succeed, the water to be exported must be considered a real "surplus" for the expected lifetime of the project, which is usually many decades. In addition, the total cost of the water to be delivered, of which the energy cost is often a substantial component, must be less than the cost of any alternative sources of water. This is rarely the case, given the large potential for improvements in water-use efficiency that are possible in every sector, at relatively low cost (13).

Finally, the environmental and ecological costs of such projects are often enormous, given the large volumes of water usually exported from a basin and the extensive construction and hydrologic modifications that must be done. For example, the export of water from northern California to southern California has been implicated in the decimation of several fish species and the loss of important aquatic habitats (14). The reduction in the flows of water and nutrients at the mouth of the Nile River are implicated in the destruction of the sardine fishery in the eastern Mediterranean Sea (15, 16). And the complete consumption of the waters of the Colorado River in most years has destroyed the brackish water estuary at the mouth of the river.

Energy for Groundwater Pumping

Legend suggests that irrigated agriculture first developed on the banks of the great rivers of the Middle East: the Nile, the Euphrates, and the Tigris. These developments relied primarily on the natural river flow, which was neither constant over time, nor reliably predictable. In some places, however, reliable and steady flows of groundwater were found and used. Qanats, described earlier, made groundwater available for irrigation, and there is a long history of substantial wells being dug to reach groundwater in the desert. Not until the 20th century, however, when cheap well drilling, pumping technology, and fossil fuels became available, could deep groundwater stocks be exploited in a substantial way.

As is the case with many other resources, our ability to extract and use groundwater far exceeds, even today, our understanding of the geophysical characteristics of groundwater basins. The dynamics of groundwater flow and recharge, the limits to regional groundwater supply, and the occurrence and migration of contaminants are all still imperfectly understood, and because there has traditionally been little regional competition for groundwater resources, legal mechanisms for allocation have rarely been developed or implemented (17).

The limits to how much water can be extracted from a finite groundwater aquifer are economical and environmental. When water is pumped out faster than it is recharged by natural processes, the water level in an aquifer drops and the distance water must be raised to the surface increases. Ultimately, pumping must cease when the energy costs rise to a point that exceeds the value of the water (a problem called "economic exhaustion"), the quality of the water in the aquifer falls below acceptable levels, or the well runs dry ("resource exhaustion").

Cheap fossil fuels have permitted overpumping of fossil groundwater aquifers—groundwater basins whose water supplies accumulated over hundreds to thousands of years, or longer. The Ogallala Aquifer in the Great Plains region of the United States underlies seven states and spans an area larger than California. In the late 1970s this aquifer supplied more than a quarter of the groundwater used for irrigation in the United States. By the early 1990s, however, severe depletion in many parts of the aquifer led to rising pumping costs, driving much irrigated agriculture in the region out of production and leading to a transition back to rain-fed or dryland production (18).

Saudi Arabia is also pumping its fossil groundwater aquifers far faster than they can be recharged, because of the lack of alternative water sources, the availability of cheap energy, and a government decision to subsidize the domestic production of several crops, such as wheat, that could be grown elsewhere at far lower cost. For example, in 1992, the Saudi government paid more than $2 billion in subsidies for the domestic production of 4,000,000 tons of wheat—five times what the wheat would have cost on the world market (19). The Saudis are now a major exporter of wheat, though they should not be considered a long-term reliable supplier, since production depends on groundwater reserves that are being rapidly depleted. Groundwater overdrafting is also widespread in many parts of India, China, Mexico, northern Africa, and the former Soviet Union. This unsustainable practice reflects both the urgent needs for water in many regions and the failure of traditional economics to consider long-term, multigenerational interests when valuing certain nonrenewable resources. Ultimately, these resources will be depleted, and future generations will be forced to make the difficult and expensive choices being avoided today.

Energy for Desalination

Ninety-seven percent of the water on the planet is too salty to drink or to grow crops, leading to great interest in devising ways of removing salt from water in the hopes of providing unlimited supplies of fresh water. Despite the lack of technical obstacles to desalination, the high energy costs of these processes continue to make unlimited freshwater supplies an elusive goal. In the energy-rich arid and semi-arid regions of the world with a great discrepancy between water demand and water supply, desalination is an increasingly important option. For poorer countries, desalination continues to be too expensive to pursue on a large scale.

Total global desalting capacity at the beginning of 1990 exceeded 13,200,000 m^3 of fresh water per day produced from more than 7500 facilities, excluding small systems onboard ships. Of this total capacity, more than one quarter is located in Saudi Arabia, followed by 12% in the United States, 10.5% in Kuwait, and 10% in the United Arab Emirates (20). While desalination provides a substantial part of the water supply in certain oil-rich Middle Eastern nations, globally, desalination provides just one one-thousandth of total freshwater use. Total global water withdrawals are estimated to be 3240 km^3 per year. The total annual supply of desalinated water is approximately 4.8 km^3 per year. Sixty-five percent of all desalination capacity is used to treat seawater and nearly 27% to treat brackish water (21).

The economics of desalination are directly tied to the cost of energy. The theoretical minimum amount of energy required to remove salt from a liter of seawater is 2.8 kilojoules (kJ). The best plants now operating use nearly 30 times this amount, though improvements in technology could reduce this to

Table 1 Energy requirements for desalting water[a]

Technology	Present requirements (10^6 J/m^3)	Future requirements[b] (10^6 J/m^3)
Distillation	210	90
Freezing	110	60
Reverse osmosis (seawater)	90	25[c]
Reverse osmosis (brackish water)	14	7
Electrodialysis (seawater)	150	70
Electrodialysis (brackish water)	20–40	10–20

[a] Source: (21)
[b] The theoretical minimum energy requirement to remove salt from water is 2.8×10^6 J per m^3.
[c] With energy recovery.

about 10 times the theoretical minimum (22, 23). Table 1 lists the energy requirements for different desalination methods. Today, desalinated water in the Middle East costs between $1 and $8 per m^3 depending on the technology used, compared to between $0.01 and $0.05 per m^3 paid by farmers in the western United States and about $0.30 per m^3 paid by urban users.

Solar energy has been used directly for more than a century to distill brackish water. When commercial plate glass began to be produced toward the end of the 19th century, solar stills began to be developed. One of the first successful ones was built in 1872 in Las Salinas, Chile, which has few alternative sources of fresh water. This still covered 4500 m^2, operated for 40 years, and produced about 20 m^3 of fresh water per day (24). The largest solar desalination plant in operation by the end of 1991 was a 500 m^3-per-day plant in the United Arab Emirates, which uses mirror technology to concentrate sunlight (20).

Some modern desalination facilities are now being run with electricity produced by wind turbines or other solar electric technologies, such as photovoltaics. The world's largest solar desalination plant under construction is a 2000 m^3-per-day system in Libya, designed to be powered by wind turbines (20). Table 2 lists solar desalination plants capable of producing more than 10 m^3 of water per day.

Most commercial desalination methods take advantage of inexpensive fossil fuels. The principal techniques for desalinating water involve distillation, where water is evaporated from a saline solution and condensed as fresh water, and reverse osmosis, which separates water and salt ions using selective membranes. Approximately 70% of all desalination capacity uses some form of the distillation process, and most of the rest use membrane technologies. Table 3 provides a broad overview of global desalination capacity.

Table 2 Wind and solar desalination plants with a capacity greater than 10 m^3 per day[a]

Country	Capacity (m^3/day)	Process[b]	Water supply	Date of operation	Energy source
Completed					
Egypt	25	RO	seawater	1987	Wind electric
France	12	RO	seawater	1980	Wind electric
France	60	RO	brackish	1987	Collector
Germany	20	MSF	seawater	1986	
Greece	20	other	seawater	1967	Collector
Indonesia	12	RO	brackish	1984	Photovoltaic
Italy	12	RO	seawater	1984	Photovoltaic
Japan	20	RO	seawater	1987	
Japan	15	RO	seawater	1982	
Japan	16	ME	seawater	1984	Collector
Kuwait	22	MSF	seawater	1984	
Kuwait	45	RO	brackish	1988	Parabolic collector
Pakistan	22	other	seawater	1972	Collector
Qatar	24	RO	seawater	1982	Photovoltaic
Qatar	20	MSF	seawater	1986	
Saudi Arabia	210	freeze	seawater	1987	Point focus
Saudi Arabia	250	RO	seawater	1987	Line focus
Saudi Arabia	14	ME	seawater	1988	Heliostat
Saudi Arabia	20	RO	seawater	1988	Heliostat
Spain	86	ME	seawater	1988	
Un. Arab Emirates	500	ME	brackish	1985	Mirror
Un. Arab Emirates	80	ME	seawater	1985	
United States	36	RO	seawater	1987	Fresnel lens
United States	19	ME	river	1987	
United States	60	RO	brackish	1987	Heliostat
Planned					
Libya	1000	RO	brackish		Photovoltaic
Libya	500	ME	seawater		Parabolic collector
Libya	2000	RO	brackish		Wind electric

[a] Source: (20) with permission of Wangnick Consulting.
[b] RO, reverse osmosis; MSF, multistage flash distillation; ME, multiple effect distillation.

The majority of distillation plants are installed in Saudi Arabia, Kuwait, and the United Arab Emirates; most reverse osmosis plants and vapor compression plants are in the United States. Fifty-six percent of the total installed or contracted capacity is based on multistage flash distillation and 31% is based on reverse osmosis, but the trend over the past decade shows a steady shift toward the construction of reverse osmosis facilities.

Multistage-flash distillation (MSF) delivers high-quality fresh water with a salt concentration of only 10 parts per million. Typical MSF systems consist of many evaporation chambers arranged in series, each with successively lower

Table 3 Desalting plants capable of producing at least 100 m^3/day, by type of process, as of December 31, 1989[a]

Process[b]	Number of plants	Percent of total	Capacity (m^3/day)	Percent of total
MSF	1063	14.1	7,442,496	56.0
RO	4157	55.2	4,113,015	30.9
ED	1032	13.7	677,674	5.1
ME	581	7.7	617,713	4.6
VC	589	7.8	368,174	2.8
Other	96	1.3	46,618	0.4
Hybrid	8	0.1	22,659	0.2
UF	9	0.1	8,038	0.1
Freeze	1	0.0	210	0.0
Total	7536	100	13,296,597	100.1

[a] Sources: (21) and (20)
[b] ED, electrodialysis; ME, multi-effect evaporation; MSF, multistage flash; RO, reverse osmosis; UF, ultrafiltration; VC, vapor compression.

pressures and temperatures that cause sudden (flash) evaporation of hot brine, followed by condensation on tubes in the upper portion of each chamber. At present, distillation techniques require more than 200 kJ to desalinate a liter of salt water, although improvements in techniques and increased efficiency of equipment may reduce this to less than 100 kJ per liter (23).

Multiple-effect distillation (ME) is one of the oldest and most efficient desalination methods. This approach reuses the heat of vaporization by placing evaporators and condensers in series and is based on the principle that vapor produced by evaporation can be condensed in a way that uses the heat of vaporization to heat brine at a lower temperature and pressure in the following chamber.

Reverse osmosis (RO) uses semi-permeable membranes that pass water but retain salts and solids when a pressure difference is maintained across the membranes. The energy requirement for RO depends directly on the concentration of salts in the feedwater, and reverse osmosis facilities are most economical for desalinating brackish water. To desalinate a liter of seawater using RO facilities requires about 90 kJ; to desalinate a liter of brackish water requires far less, around 15 kJ (23). The largest reverse osmosis plant in the world at the beginning of 1990 was located in the United States at Yuma, Arizona. This plant was designed and constructed specifically to fulfill water-quality obligations under an international treaty between the United States and Mexico on the Colorado River, and has a capacity of about 270,000 m^3 per day (25). There are serious doubts, however, if this plant will ever operate because of great economic and environmental concerns (G Gould, US Bureau of Reclamation, personal communication, 1993).

Electrodialysis (ED) depends on the natural ionization of salts in solution and uses membranes that are selectively permeable to ions (either cations or anions). With this method, brackish water is pumped at low pressure between flat, parallel, ion-permeable membranes, some of which allow cations and some of which allow anions to pass. Electric current flows across these parallel channels, pulling ions through the membranes. Like reverse osmosis, the energy cost of ED rises with the concentration of the salts in the water. Desalinating brackish water with ED requires about 36 kJ per liter. Desalinating seawater with this technique requires nearly 150 kJ per liter (23).

Ion-exchange methods use resins to remove undesirable ions in water. For example, cation-exchange resins are used in homes and municipal water-treatment plants to remove calcium and magnesium ions in "hard" water. The greater the concentration of dissolved solids, the more often the expensive resins have to be replaced, making the entire process economically unattractive compared with RO and ED.

The use of freeze separation takes advantage of the insolubility of salts in ice. Water is frozen out of a saline solution, and the resulting pure ice crystals are then strained from the brine. The most efficient freeze methods use vapor-compression freeze-separation systems. Freeze separation requires about 100 kJ to produce a liter of fresh water using present technology. Improvements are expected to be able to reduce this figure by about 40% (23).

In the long run, the use of desalination to provide fresh water will be limited by the amount of energy required to purify salt water and by the cost of that energy. Unless major technical advances reduce overall energy requirements or the price of renewable energy resources drops substantially, desalination will always be limited to extremely water-poor and energy-rich regions.

WATER FOR ENERGY

In addition to using energy when we manage water resources, water is required when we produce and use energy. In dry regions, the lack of water for cooling and chemical processes may lead to a decision to locate a power plant near a reliable source of water and to move the fuel instead, or to choose energy sources that require less water.

For coal-fired plants, for example, where the weight of the water used for cooling alone is many times the weight of the coal burned, moving the coal to the water has distinct economic advantages. The energy content of 40 tonnes of coal is about 10^{12} J(th) (joules thermal). A coal-fired power plant using once-through cooling consumes nearly 500 tonnes of water for every 10^{12} J(th), excluding water for all other aspects of the coal fuel cycle, and far more water than this would be withdrawn for use. Thus the weight of water consumed by a power plant is approximately 10 times the weight of coal required, making it more economical to site the plant where there is sufficient water and to transport the fuel. A plant using cooling towers, as would be expected in a semi-arid region, would consume nearly two-and-a-half times this amount of water just for cooling.

The amount of water needed to produce energy varies greatly with the type of facility and the characteristics of the fuel cycle. Fossil-fuel, nuclear, and geothermal power plants require enormous amounts of water for fuel processing and cooling. Some of this water may be lost to evaporation or contamination; much of it is often returned to a watershed for use by other sectors of society. Solar photovoltaic power systems, wind turbines, and other renewable energy sources often require minimal amounts of water, though some renewable or unconventional energy technologies are water intensive as well, such as geothermal plants or hydroelectric plants with reservoirs subject to evaporative water loss (see Tables 5 and 7).

Water-supply problems have already constrained energy production during periods of extreme shortage. During the severe drought in California between 1987 and 1991, large reductions in hydroelectricity production forced electric utilities there to purchase more fossil fuels than normal at an added cost of approximately $3 billion to electricity consumers (26). The decade-long drought in the 1980s in northeastern Africa caused reductions in hydroelectric generation from the Aswan Dam in Egypt, which supplies nearly half of Egypt's electricity demand (27, 28). Zimbabwe reported in February 1992 that its output of ethanol, which is mixed with gasoline to reduce the country's fuel imports, was reduced because of a severe African drought, which crippled sugar cane production (29). These examples highlight not only the problem with overall water availability, but also our increasing sensitivity to the natural variability of water supply.

Large conventional fossil-fuel power plants cannot be built in many regions of northern and northeastern Africa because there are no reliable cooling water supplies. In western North America, the development of synthetic fuels from oil shales and tar sands is constrained as much by the limited availability of water as by the marginal economics and severe environmental limitations of these processes (30). Even small energy developments in semi-arid or arid regions can dramatically affect water supplies. A proposal in the late 1970s for a small coal-gasification system in Southern California using groundwater for cooling would have led to a drop in local groundwater levels of more than 15 cm per year (31).

Energy use also affects water quality. The discharge of waste heat from power plant cooling systems raises the temperature of rivers and lakes, which affects aquatic ecosystems. Wastewaters from mining operations, boilers, and cooling systems may be contaminated with heavy metals, acids, organic materials, and suspended solids. Nuclear fuel production plants, uranium mill-tailings ponds, and, under unusual circumstances, nuclear power plants, have all caused radioactive contamination of groundwater and surface water supplies.

All thermal-electric generating facilities, whether they use nuclear, geothermal, fossil fuels, or even some solar sources of heat, convert water or other working fluids into steam or vapor to drive electric generating turbines. This vapor must be condensed in a cooling system in order to be recycled through the turbines. Many different cooling technologies are in use, including once-through circulation, wet and dry cooling towers, cooling ponds, and sprayers.

Once-through cooling has distinct economic advantages where sufficient fresh or salt water is available. In once-through cooling, large volumes of water are withdrawn from a river, lake, or aquifer (or the ocean), circulated a single time through the cooling system, and then discharged at a considerably higher temperature. Where water is scarce, or where the discharge of warm water is unacceptable, once-through cooling is often prohibited and closed-cycle systems are used (32).

Closed-cycle wet cooling systems rely primarily on evaporation to dissipate waste heat, either through cooling towers or ponds. There are three types of cooling towers in use: wet towers, dry towers, and hybrids. In each system, air is passed through the tower to remove heat from the water, either through direct contact in wet towers or through indirect methods that work in much the same way as an automobile radiator. Dry cooling towers are considerably more expensive than wet or hybrid systems, and are built only in extremely water-scarce regions. The other closed-cycle system is the cooling pond, which uses evaporation, conduction, and radiation to transfer heat to air from open ponds (32).

The choice of cooling system depends on a variety of factors, including withdrawal volumes required, consumptive losses, relative economic costs, and environmental and aesthetic factors. The consumptive use of water in wet cooling towers is roughly twice that of once-through systems, though total water withdrawals are considerably less. Consumptive losses from cooling ponds are about 30% higher than from wet cooling towers (30, 32, 33), and closed-cycle systems can reduce total water withdrawals by nearly 95% compared to the water required for once-through cooling (34). As a result, in regions without sufficient water for once-through cooling, such as arid and semi-arid regions, closed-cycle systems may be required, with their higher rates of consumptive use, but lower overall withdrawals.

Closed-cycle cooling systems entail environmental costs of their own not associated with once-through systems. Facilities that use ocean water for cooling can spread salt-bearing steam across nearby land, damaging agricultural capacity. The cooling towers such systems often use can cause local fogs

Table 4 Consumptive water use for energy production[a]

Energy technology	Consumptive use ($m^3/10^{12}$ J(th))
Nuclear fuel cycle	
Open pit uranium mining	20
Underground uranium mining	0.2
Uranium milling	8–10
Uranium hexafluoride conversion	4
Uranium enrichment: Gaseous diffusion	11–13[b]
Uranium enrichment: Gas centrifuge	2
Fuel fabrication	1
Nuclear fuel reprocessing	50
Coal fuel cycle	
Surface mining: No vegetation	2
Surface mining: Revegetation	5
Underground mining	3–20[c]
Beneficiation	4
Slurry pipeline	40–85
Other plant operation	90[d]
Oil fuel cycle	
Onshore oil exploration	0.01
Onshore oil extraction and production	3–8
Enhanced oil recovery	120
Water flooding	600
Thermal steam injection	100–180
Forward combustion/air injection	50
Micellar polymer	8900[e]
Caustic injection	100
Carbon dioxide	640[e]
Oil refining (traditional)	25–65
Oil refining (reforming and hydrogenation)	60–120
Other plant operations	70[d]
Natural gas fuel cycle	
Onshore gas exploration	negligible
Onshore gas extraction	negligible
Natural gas processing	6
Gas pipeline operation	3
Other plant operations	100[d]
Synthetic fuels	
Solvent refined and H-coal	175
Lurgi with subbituminous	125
Lurgi with lignite	225
In-situ gasification	90–130
Coal gasification	40–95
Coal liquefaction	35–70
TOSCO II shale oil retorting	100
In-situ retorting of oil shale	30–60
Tar sands (Athabasca)	70–180

Table 4 *Continued*

Energy technology	Consumptive use ($m^3/10^{12}$ J(th))
Other technologies	
Solar active space heat	265
Solar passive space heat	negligible

[a] Source: (21)
[b] Excluding water use by additional power plants required for the energy-intensive uranium enrichment process.
[c] Top end of range reflects once-through system with no recycle.
[d] Other plant operations includes plant service, potable water requirements, and boiler make-up water. For coal facilities, this also includes ash handling and flue-gas desulfurization process make-up water.
[e] Median of a wide range.

and road ice under certain climatic conditions. In addition, large cooling towers that are visible for miles are often considered aesthetic liabilities (30, 34).

Total cooling water withdrawals by the electric industry in developed countries are substantial. In the United States in 1990, 270 km^3 of water (67% of which was fresh water) were withdrawn for power-plant cooling. This is almost half of all water required for human uses in the United States and nearly 40% of all freshwater withdrawals in the country (35). Of this water, 73% goes to cool fossil fuel power plants, 27% to cool nuclear power plants, and a fraction of one percent to cool geothermal plants. In some countries of Europe, such as the Netherlands, France, Germany, and Austria, even greater fractions of total water withdrawals go to power-plant cooling (36, 37). Only 3% of the water withdrawn by the electric utility sector in the United States is actually consumed, accounting for about 5% of the total US consumptive use of fresh water (35, 38).

All cooling systems also generate low-quality wastewater—called "blowdown" when produced by cooling towers—that cannot be returned to the rivers or lakes without treatment. Cooling water returned to rivers and lakes is often at a much higher temperature than the water withdrawn from these water sources. Concern over the ecological impacts of this thermal pollution has led most industrialized nations to set some thermal limits to protect the environment, though temperature limits for drinking water are not usually set. Canada has a secondary (i.e. set for aesthetic reasons) drinking water goal of 15°C. The European Economic Community uses a guide number of 12°C and a maximum of 25°C. Much stricter standards limiting the temperature of cooling-water discharges from power plants and industries are set to protect natural aquatic ecosystems in the United States, but these tend to be set on a state or regional level. In the future, the increased use of closed systems to minimize thermal pollution will increase overall consumptive water use.

The following sections estimate water consumed per unit energy produced for a wide range of energy facilities and fuels used. The total volume of water withdrawn for use often far exceeds water consumed. Both measures can be important: Where total water availability is scarce, large volumes of water may simply not be available on a reliable basis for withdrawal by power plants, even if total consumptive use is low. In all regions, however, the consumptive use of water is a true measure of the quantity of water made unavailable for any other uses in a region. Tables 4 and 5 summarize water consumed per unit energy and electricity for a variety of commercially available energy sources.

Coal

Many parts of the coal fuel cycle are water intensive, including coal mining, reclamation of mined land, and coal combustion, which requires substantial water for cooling, ash handling, and waste disposal. Coal mining operations, particularly underground mining, can lead to the contamination of large volumes of water. Water draining from underground coal mines contains minerals and heavy metals and is usually highly acid. Some 12,000 km of streams in the eastern United States are seriously polluted from drainage from underground coal mining (33). In the late 1970s there was some effort to reduce this pollution, but enforcement of water-quality and reclamation regulations dropped off during the 1980s. As a result, many of these streams remain severely polluted today. Surface mining also causes significant water-quality problems by increasing sediment transport in streams and increasing dissolved mineral content if soluble minerals are exposed during mining.

Estimates of average water use in underground coal mining range from 3 to 20 m^3 of water per 10^{12} J(th) of energy in the coal.[1] About 2 m^3 per 10^{12} J(th) are required to produce coal in surface mines if no revegetation is required. These estimates include water used for disposing of mining wastes (39). Another estimate, from the Council for Mutual Economic Assistance, is for 17 m^3 per 10^{12} J(th) for underground coal, which can be reduced to less than 5 m^3 per 10^{12} J(th) with a water-recycling system (40). The greater water use in underground mining arises, in part, from water used for suppressing dust for health and safety reasons. No good estimates of the volume of water contaminated in mining are available, per unit energy in mined coal.

Strip-mined land is sometimes required to be "reclaimed"—i.e. to be re-

[1]Water use numbers are presented here as either (*a*) m^3 per 10^{12} J(th), the number of cubic meters required per trillion joules of thermal energy, or (*b*) m^3 per 10^3 kWh, the number of cubic meters per 1000 kilowatt-hours of electricity produced. The two are not strictly comparable without making assumptions about the efficiency of conversion of thermal to electric energy.

Table 5 Consumptive water use for electricity production[a]

Energy technology	System efficiency[b] (percent)	Consumptive use (m^3 per 10^3 kWh(e))
Conventional coal combustion		
Once-through cooling	35	1.2
Cooling towers	35	2.6
Fluidized-bed coal combustion		
Once-through cooling	36	0.8
Oil and natural gas combustion		
Once-through cooling	36	1.1
Cooling towers	36	2.6
Nuclear generation (LWR)		
Cooling towers	31	3.2
Nuclear generation (HTGR)		
Cooling towers	40	2.2
Geothermal generation (vapor dominated)		
Cooling towers; Geysers, U.S.	15	6.8
Once-through cooling; Wairakei, New Zealand	8	13.0
Geothermal generation (water dominated)		
Cooling towers; Heber, U.S.	10	15.0
Wood-fire generation		
Cooling towers	32	2.3
Renewable energy systems		
Photovoltaics: Residential		negligible
Photovoltaics: Central utility		0.1[c]
Solar thermal: Luz System		4.0
Wind generation		negligible
Ocean thermal		no fresh water
Hydroelectric systems[d]		
United States (average)		17.0
California (median)		5.4
California (mean)		26.0

[a] Source: (21)
[b] Efficiency of conversion of thermal energy to electrical energy.
[c] Maximum water use for array washing and potable water needs.
[d] Assumes all evaporative losses are attributable to the hydroelectric facilities. For reservoirs with significant nonhydroelectric uses, such as recreation and flood control, this assumption overestimates hydroelectric consumptive use.

stored to an approximation of the original contour and vegetation. In such circumstances, water is required to establish vegetation on reclaimed land. The amount of water needed depends on the natural climatic conditions in a region. In the semi-arid western United States, where much of the US strip-mined coal originates, nearly 3 m^3 per 10^{12} J(th) are needed to establish vegetation on reclaimed land (41–43).

Following mining, coal is often "refined" to separate coals of different quality and to increase the thermal performance of the fuel. Such refining, including washing, beneficiation (which removes nonfuel contaminants), and thermal processing, may severely degrade water with organic and inorganic impurities, and any water used will require either additional treatment or isolation from the environment. The volumes of water used in this manner are small, typically less than 5 m^3 per 10^{12} J(th) (43).

One method for transporting coal is the slurry pipeline, which moves large quantities of coal suspended in water. Such pipelines require enormous amounts of water (typically equal volumes coal and water), and in some cases this means exporting water from regions of existing water scarcity, such as the arid western United States, where coal is often mined.

Several coal slurry pipelines have already been built. The largest is the Black Mesa project in the United States, which transfers 5,000,000 tonnes of coal per year over 400 km from mines in Arizona to the 1500 MWe Mojave Power Plant in southern Nevada. Water for suspending the coal is supplied by wells pumping 4,000,000 m^3 per year from groundwater aquifers (this is equivalent to about 45 m^3 per 10^{12} J(th) energy in mined coal). Recharge of these aquifers is negligible compared to this rate of withdrawal; hence this is a nonrenewable use of water. After the coal is taken out of the slurry at the power plant, some of the water is treated and used for other plant operations, including power-plant cooling. At the Mojave plant, about one seventh of the total cooling demand is supplied using recovered water from the slurry pipeline (33).

A number of other slurry pipelines have been proposed in recent years, including the Energy Transportation Systems, Incorporated line (ETSI), which was to have delivered coal from South Dakota to Oklahoma and Arkansas. For a variety of economic and environmental reasons, this project has now been cancelled. Other pipelines would link Colorado and California, Wyoming and Texas, and Virginia and various southeastern states. The longest pipeline proposed would have carried 25,000,000 tonnes of coal per year over 2000 km. Total consumptive water use by slurry pipelines has been estimated at between 40 and 85 m^3 per 10^{12} J(th) (11).

Once it has been mined, processed, and transported to a power plant, coal can be turned into useful energy using many different processes: gasification, liquefaction, and combustion in a variety of direct-fired systems such as fluidized beds and pulverized boilers. The amounts of water used per unit energy produced by these different processes vary considerably, as shown in Table 4.

The most typical form of coal-fired power plant burns coal directly to generate steam, which is then used to drive a turbine to produce electricity. The overall efficiency of the system depends on the pressure at the outlet of the turbine. Reducing this pressure to increase efficiency is accomplished with a cooling system, which accounts for the greatest consumption of water in the entire traditional fuel cycle as described above. For coal-fired power plants, consumptive use for cooling ranges from just under 1 m^3 per 10^3 kWh(e) for once-through cooling systems to more than 2.5 m^3 per 10^3 kWh(e) for facilities with cooling towers.

Additional water is used in coal facilities for dust suppression, for drinking and sanitation, for ash handling, as flue-gas desulfurization make-up water, and for other plant operations. These demands total approximately 90 m^3 per 10^{12} J(th) (44).

Oil and Natural Gas

The production of oil and natural gas has usually required relatively modest amounts of water. Water is used during the exploration and drilling process, for treating the oil or gas before use, and for human sanitation and drinking water. Overall, between 2 and 8 m^3 per 10^{12} J(th) of water have historically been required to extract oil, including water for drilling, flooding, and treating. One source indicates that 45,000,000 m^3 of fresh water are used annually in the United States for mixing drilling mud to produce about 500,000,000 tonnes of oil (about 2 m^3 per 10^{12} J(th) of oil produced) (39). Oil production also results in the simultaneous production of large quantities of saline water found with the oil. This water must be disposed of safely. Drilling for natural gas only requires water for preparing drilling fluid (39, 42, 43).

As the largest fossil-fuel reservoirs have been drawn down, however, methods of increasing the percentage of these fuels recovered from wells have been developed. These secondary and tertiary recovery methods increase overall water requirements. In particular, some of the most common and effective oil recovery techniques are water intensive. Secondary recovery uses water flooding to increase the flow of oil to the wells. One-third of all US and Canadian oil production uses water-flooding recovery methods. The most widely used tertiary recovery technique is steam injection, in which steam is pumped into the depleted oil field and the heat increases oil flow and recovery rates. This technique is used for three quarters of all US tertiary oil recovery today (33). Several other enhanced-oil recovery methods are in use, with widely varying water requirements ranging from less than 100 to 9000 m^3 per 10^{12} J(th) of oil recovered (31), listed in Table 4. This water use is entirely consumptive, though in coastal regions salt water may be used for some of these processes.

After oil is extracted, it must be refined into different forms of liquid fuel. Average water withdrawals for traditional refining facilities in industrialized countries are about 325 m^3 per 10^{12} J(th) of crude oil input; consumptive use ranges from 25 to 65 m^3 per 10^{12} J(th) of oil input. Of this consumptive loss, 70% is lost in evaporative cooling, 26% is boiler feed water, and the rest goes to other in-plant uses. Recent changes in fuel formulations and improvements in techniques for restructuring organic molecules have increased water requirements, since hydrogen, obtained by dissociating water, is used to upgrade the quality of the product in a process called hydrogenation. Refineries where substantial hydrogenation and reforming take place use between 60 and 120 m^3 per 10^{12} J(th) (33, 41, 42).

The generation of electricity by burning oil or natural gas also requires water for cooling. Because the thermal efficiency of these plants is comparable to that of coal-fired plants, about the same amount of water is used for cooling—between 1 and 2.6 m^3 per 10^3 kWh(e).

Oil Shale and Tar Sand

Large resources of fossil fuels are bound up in shale or tar sands, but the economic and environmental costs of extracting them are too high at present for any significant commercial operations to proceed. If oil shale or tar sands are to become commercially successful, they are likely to be extracted using surface mining or underground mining methods. In situ retorting processes, in which the fuel is separated from ore in place, have also been developed. While these methods have some environmental advantages, they are not economically or technically competitive with more traditional extraction processes.

Synthetic fuels production has the potential to consume vast amounts of water; ironically, the greatest deposits of the fuels tend to occur in regions with scarce natural water supplies. Estimates of the volume of consumptive water demand for oil shale and tar sands production range widely depending on the process (45). The largest uses of water for both oil shales and tar sands come from waste disposal, processing, power generation, and land reclamation. Because of the low oil content of shales and tar sands, extremely large volumes of the raw material are needed in order to produce commercial volumes of oil. For example, in order to produce just more than 400,000 tonnes of oil per day (3,000,000 barrels of oil per day), more than 3,000,000 tonnes per day of raw shale would have to be mined and processed, considerably more material than the total daily production of coal in the United States in 1990. And the energy content of this shale oil per unit of raw material mined is far less than the energy content of the coal produced.

The only operating synthetic fuel facility of commercial size using tar sands or shale oil is at Athabasca, Canada, where tar sands are mined and processed. Water consumption at this facility under normal operation is about eight tonnes of water for every tonne of final product, or 180 m^3 per 10^{12} J(th). Larger and more efficient facilities could reduce this consumptive use somewhat (33, 45). An estimate for oil shale suggests that 2.5–4 times as much water is used as oil is produced, the equivalent of 70–100 m^3 of water per 10^{12} J(th) of oil (39). Most of this water goes for processing the shale, for cooling, and for disposing of the residual ore and slurry.

Large volumes of waste are produced from both oil shale and tar sands facilities. These wastes have the potential to contaminate downstream water resources, and they must be handled carefully. These waste products are typically composed of 50% or more water and occupy considerably more volume than the original ore, requiring that large areas of land be set aside for disposal. Additional dry waste material is used in the construction of dikes as high as 100 m to retain the liquid tailings produced. Recycling to remove suspended solids from the water may ultimately permit reuse of some part of the wastewater, but technical problems have prohibited this so far.

Retorting oil shale in place requires about the same amount of water as refining crude oil—1–2.5 volumes of water per volume of petroleum input or 25–70 m^3 per 10^{12} J(th) of product. The environmental impacts on water resources of oil shale retorting include the generation of inorganic and organic pollutants and thermal pollution, but no good estimates of the volumes of water contaminated are available.

Nuclear Power

Electricity generated from nuclear fission reactors provides 12% of total global electrical demand, and a considerably higher fraction in several industrialized nations. France, Belgium, and South Korea, for example, all produce more than 50% of their total electrical needs with nuclear plants (50). As with other large thermal plants, the greatest use of water in the nuclear fuel cycle is for power-plant cooling. Other aspects of the fuel cycle also require water, and consumptive uses are described in Tables 4 and 5.

Uranium mining requires water for dust control, ore beneficiation, and revegetation of mined surfaces. The quantity of water required is approximately the same as for surface mining of coal, about 20 m^3 per 10^{12} J(th) energy in the ore. The mining of uranium also causes the mobilization of radioactive minerals that may reach waterways and pose a health hazard. Waste ore from mining and processing activities is often disposed of in evaporation ponds that threaten surface and groundwater quality, which in turn can have human and ecological health implications.

The second largest consumptive use of water in the nuclear fuel cycle comes from milling, refining, and enriching uranium. An early estimate of water consumption in the nuclear fuel cycle (46) suggested that milling of uranium consumes about 10 m^3 per 10^{12} J(th) of product, almost entirely as evaporation from tailings ponds. Another 1.2 m^3 per 10^{12} J(th) is consumed during the production of uranium hexafluoride and reprocessing of used fuel. The principal method for enriching uranium is gaseous diffusion, which requires an additional 10–15 m^3 per 10^{12} J(th). Most of this water is consumed by evaporative cooling. Alternative methods of enrichment, such as centrifuge separation, require considerably less water but are not in widespread use. Water is also required at power plants that provide energy for uranium enrichment, which is extremely energy intensive. Including these water requirements would increase overall consumptive use by an additional 20 m^3 per 10^{12} J(th) (39, 47).

The current generation of nuclear plants is less efficient than fossil-fuel plants because of technological characteristics, restrictions on maximum steam temperatures, and because fossil-fuel plants emit substantial waste heat through the flue gases. A typical nuclear plant operating at 31% efficiency requires much more water for cooling than a comparably sized fossil-fuel plant, as shown in Table 5. High-temperature gas reactors (HTGRs) or other high-efficiency designs, which could operate at 40% efficiency, would reduce consumptive water use per unit electricity produced to approximately the level of present oil- and gas-fired facilities.

Finally, low-probability, but high-consequence accidents associated with nuclear plants could also affect water resources. The meltdown or burning of a reactor core could result in long-term radioactive poisoning of land and water supplies. The accident at Chernobyl in the Ukraine in 1986, for example, led to the contamination of nearby lakes and groundwater aquifers. The extent and severity of this contamination is not yet fully known or reported.

Geothermal

Two forms of geothermal resources are currently technologically and economically feasible: vapor-dominated dry-steam systems and liquid-dominated hot-water systems. Considerable geothermal energy potential exists, though total development has been limited. Where the heat resource lies fairly close to the surface, and is sufficiently hot, geothermally produced electricity can be economically attractive compared to fossil fuels. In California, for example, the electricity from geothermal facilities is among the cheapest forms of electricity produced.

Vapor-dominated systems consist of wells drilled into a steam field. Steam is then used to drive a turbine-generator to produce electricity. Nearly 2000 MWe of dry-steam systems are in operation, mostly in the Geysers region of California, in the United States. At the Geysers, no outside source of cooling water has been required because water condensed from the geothermal steam condensate is used for cooling. Where outside cooling water is necessary, between 7 and 13 m^3 per 10^3 kWh(e) output will be required for vapor-dominated systems (33, 39, 42, 48, 49).

Several forms of liquid-dominated geothermal systems are in use, including flash-steam systems and binary systems. The temperature of the geothermal fluid determines which technology is appropriate for use in producing electricity. At the present time, flash conversion is the simplest and least costly of liquid-dominated systems. In flash-conversion systems, a high-temperature geothermal fluid is brought to the surface under pressure, where it "flashes" into steam to drive a turbine. Such systems are in use in Italy, Iceland, Mexico, New Zealand, the Philippines, and the United States. Flash geothermal systems also use geothermal condensate for cooling whenever possible, minimizing outside water requirements (31).

Binary systems, in which low-temperature (150°C) geothermal fluid vaporizes a working fluid, are closed and nonpolluting, since all geothermal fluids are reinjected down into the well field. This, however, creates the need for an outside source of cooling water. One estimate is that up to 15 m^3 of cooling water are required per 10^3 kWh(e) output for water-dominated systems, such as at Heber in California (33, 39, 42, 48, 49). For all plants, some additional water is required for fire protection, facility maintenance, landscaping, and sanitation.

Hydroelectricity

The most obvious use of water for the production of energy is in hydroelectric facilities, where the energy in falling water is used directly to turn turbines, which generate electricity. In many areas of the world, water is also used to do mechanical work, such as grinding grain.

At the beginning of the 1990s, there were approximately 615,000 megawatts (MWe) of installed hydroelectricity capacity worldwide, 24% of total world electrical generating capacity. Hydroelectric potential has been unevenly developed around the world. More than half of all hydroelectric capacity is in North America and Western Europe; only 3% of it is in Africa. Table 6 lists hydroelectric capacity and generation by continent for 1990. North America and Europe have developed approximately 60 and 36% of their large-scale hydropower potentials, respectively, Asia and Latin America have harnessed around 10%, and Africa only 5% (50).

In 1990, hydroelectric dams generated more than 2,000,000 GWh of electricity, or just under 7% of the world's primary commercial energy and 20% of global electricity. In South and Central America, 70% of all electricity comes from hydroelectric plants; Canada and the United States together provide 20% of their total electricity demand with hydropower (50).

Global hydroelectricity production increased more than 20% during the

Table 6 World hydroelectric capacity and generation, 1990[a]

Continent/Region[b]	Installed hydroelectric capacity (1000 MWe)	Percent of total	Hydroelectric generation (million MWh per year)	Percent of total
North America	156.8	25.5	599.6	28.4
Central and South America	80.3	13.1	353.4	16.7
Western Europe	155.0	25.2	444.7	21.0
Eastern Europe	15.1	2.5	26.3	1.2
Soviet Union	64.4	10.5	217.3	10.3
Middle East	3.1	0.5	12.6	0.6
Africa	18.9	3.1	43.2	2.0
Far East and Oceania	121.3	19.7	415.8	19.7
Totals	614.9		2112.9	

[a] Source: (21)
[b] Regional sums use original 1990 country data. Since then, substantial changes in Eastern Europe and the Soviet Union have occurred.

1980s. In the industrialized nations, however, the development of new hydroelectric facilities has slowed greatly, as the best sites have already been developed and the environmental costs of further construction are rising. Indeed, the greatest development of hydroelectric facilities is now occurring in those regions that have seen little development to date. During this same 10-year period, hydroelectric production increased 50% in Asia and more than doubled in parts of Latin America and China (50).

Hydropower facilities have a variety of effects on freshwater systems. The creation of a reservoir displaces wildlife and replaces a flowing-water ecosystem with a standing-water one. The storage of water in a reservoir leads to consumptive water losses from evaporation and seepage. Hydroelectric dams are subject to the risk of catastrophic dam failure with extensive loss of life and property, an unusual risk associated with few other energy sources, most notably nuclear power. And when hydroelectric facilities are developed on rivers that are shared by two or more nations, political conflicts can arise (51, 52).

Disputes have arisen over dams throughout the world, including the Farakka Barrage in India, the Itaipú Dam on the Paraná River between Argentina, Brazil, and Paraguay, the Kumgansan hydroelectric dam on the Han River between North and South Korea, the Aswan High Dam in Egypt, whose reservoir displaced thousands of people living in the Sudan, and many other facilities (53).

In evaluating and comparing all of these effects, a number of criteria must be evaluated, including the size and type of hydroelectric plant, the temporal and spatial distribution of harm, the possibility of irreversible effects, the coincidence of risks and benefits, and the uncertainty surrounding the nature of the evidence of environmental harm.

Different environmental analysts have quite different interpretations of both the magnitude and extent of the environmental costs of hydroelectric facilities. Some believe that hydropower is a benign alternative source of electrical generation; others have concluded that new large dams may be "...arguably the worst electricity option in terms of damage to ecosystems per unit of electricity" (54). These issues have been widely discussed over the past decade, but many issues remain unresolved (34, 55).

The greatest consumptive use of water resources from hydroelectric facilities comes from the evaporative loss of water from the surface of reservoirs, though these losses are often left out of environmental assessments. This water represents the loss of a resource that would otherwise be available for downstream human and ecological uses. Conflicts over water among agricultural users, industrial users, commercial users, and ecological support functions are intensified by this water loss. As water has become more precious in various regions, evaporation from artificial reservoirs has received more and more attention.

The evaporation of water is directly related to the surface area of the body of water and varies with the temperature, wind conditions, and humidity of a region. Average annual evaporation from standing water in the United States varies from 0.5 m in northeastern regions to more than 1 m in the desert regions of the southwest. For 700 reservoirs and regulated lakes in 17 western US states with a total effective surface area of approximately 14,000 km^2, average annual evaporative losses based on variations in location and climate were approximately 15.2 km^3 in volume, or 1.1 m in depth (56). Evaporative losses can be much higher, depending on the climate of a region. At the Aswan High Dam on the Nile, about 14 km^3 of water (11% of reservoir capacity) are estimated to evaporate annually from a surface area of 5200 km^2 (15, 57). This is equivalent to nearly 3 m of evaporative loss per year.

A recent study estimated evaporative losses from a set of 100 diverse California hydroelectric facilities at between 0.04 and 200 m^3 of water per 10^3 kWh electricity produced, with a median estimate of 5.4 m^3 of water per 10^3 kWh. This is several times larger than the consumptive water use of nuclear or fossil-fuel facilities per unit energy produced (58). Evaporative losses from all US reservoirs are approximately half this amount, because the evaporative losses in the more semi-arid western United States are higher than in other parts of the country.

Differences in evaporative losses also result from the type and size of the hydroelectric plant. Table 7 breaks down evaporative losses for plants over and under 25 MWe installed capacity and for differences in the ratio of gross

Table 7 Annual evaporative water losses from California hydroelectric facilities[a] (m^3 per 10^3 kWh per year)

Category[b]	All facilities	Plants over 25 MWe	Plants under 25 MWe
All facilities: Range	0.04–210	0.04–160	0.2–210
All facilities: Median	5.4	2.4	14
DH < GSH: Range	0.04–120	0.04–120	0.2–83
DH < GSH: Median	1.2	0.7	3
DH > GSH: Range	1.9–210	3.6–160	1.9–210
DH > GSH: Median	34	68	34

[a] Source: (58)
[b] DH, dam height; GSH, gross static head.

static head (GSH) to dam height (DH). The gross static head is the vertical distance from the surface of the reservoir to the top of the water in the tailrace, below the dam. It effectively represents the distance the water falls during electricity production. In general, where the GSH exceeds the dam height—typical of dams with long penstocks carrying the water downslope to a power plant—the median water losses are smaller than where GSH is smaller than the DH—typical of large dams with powerhouses at their base. When the size of the power plant is considered, plants under 25 MWe lose more water to evaporation than plants larger than 25 MWe per unit energy generated: 14 vs 2.5 m^3 per 10^3 kWh (58).

Seepage losses from porous foundations underlying hydroelectric reservoirs can also lead to a consumptive use of water. It has been estimated that an average of 5% of the volume of reservoirs is lost annually to seepage (59), and seepage losses at some facilities have become big political and environmental problems. The Anchor Dam in Wyoming, for example, is built in a location that is so porous that the reservoir has never totally filled in 30 years of operation (60).

Evaluating data on reservoir storage in the 18 hydrographic regions of the United States reveals that there are approximately 210 km^3 of storage in hydroelectric reservoirs and more than 2100 km^3 of storage in 49,000 reservoirs. Hydroelectric production from these facilities averages about 290 billion kilowatt-hours annually. Assuming seepage losses of about 5% annually from these reservoirs, losses of 36 m^3 per 10^3 kWh can be expected. For the California reservoirs studied, about 40 m^3 of water are lost to seepage for every 10^3 kWh of hydroelectricity produced, in good agreement with the overall US estimate (58).

Seepage and evaporative losses have an important qualitative difference. Water lost to evaporation usually leaves the hydrologic basin and thus is a true loss. Water lost to seepage remains in the basin and may become available downstream or for groundwater pumping.

Calculating consumptive water requirements for hydroelectric facilities is complicated by the multiple-use nature of many dams and reservoirs and by the way they are operated. The mode of operation itself is determined by a set of economic criteria, together with competing upstream and downstream demands for the water. On occasion, the mode of operation is determined by requirements set to maintain certain ecological conditions, such as temperature or flow rates needed to support fish populations. All of these factors need to be considered in evaluating overall water requirements.

Solar Thermal Electricity

Energy from the sun can be used to heat and vaporize water or another working fluid in order to produce electricity. Among the different designs for such systems are centralized utility solar power towers that use mirrors to focus sunlight onto a boiler, and individual concentrating collectors with tubes of a working fluid located at the collector's focal point. As with other power plants, the working fluid must then be condensed and reused. Estimates of water consumption, which include make-up cooling water and water for washing the mirrors, range considerably depending on the type of facility. Most published estimates of water consumption are low, around 1 m^3 per 10^3 kWh(e). Water consumption at the 10 MWe power tower built in southern California, for example, was estimated at only 0.1 m^3 per 10^3 kWh(e) output, though there are questions about the reliability of this estimate (43). The consumptive water use of the most advanced, commercially available system, built by the Luz Corporation in southern California, is considerably higher. This project now consists of more than 300 MWe, with fields of mirrors directing sunlight onto tubes of a working fluid at each collector's focal point. Though the company that built these plants is in financial reorganization, the plants are continuing to operate well. The Luz plants consume more than 4 m^3 per 10^3 kWh(e), primarily to operate the condensers and cooling towers (D Rib, D Gaskin, personal communication, 1992).

Water requirements for solar ponds are likely to be extremely high, since the most effective ponds will be built in regions with high evaporative loss rates. One estimate for make-up water for cooling and evaporative losses from solar ponds is more than 25 m^3 per 10^3 kWh(e) (61).

Photovoltaics

Photovoltaic cells produce electricity directly from sunlight. Water use for photovoltaic electricity production is considered negligible (34). No estimates are available of water consumed in the manufacturing process, but such cells can be made in water-rich regions and shipped anywhere for the production of electricity. Some minor volumes of water may be required for periodic cleaning of photovoltaic arrays.

Wind Energy

Wind energy facilities require no water for the production of electricity and almost none for the construction and erection of the wind turbines. As with photovoltaic cells, wind turbines can be fabricated anywhere and set up in regions with energy demand and sufficient wind resources.

Summary

Water is required for practically every aspect of energy production and use. Because of the wide variations in energy fuel cycles and choices around the world, no overall water requirements for each energy source have been provided here, and great care should be taken in simply summing up water requirements for different aspects of each energy technology. Data are not available for all aspects of each fuel cycle, and the "boundaries" of analysis are not always consistent. In addition, water use in many portions of the energy cycle is poorly understood or quantified at present. Our knowledge of the severity and extent of water contamination by various fuel-cycle activities, for example, is especially limited. Similarly, no data on water use in energy transportation are available, except for on coal slurry pipelines and natural gas pipeline operation, and no data on facilities construction are included.

Despite these uncertainties, water requirements for the production and use of some forms of energy are substantial. In water-poor regions, or in regions subject to highly variable water supply, there may simply be insufficient water overall or during parts of the year to support the cooling needs of conventional fossil-fuel power plants, for example, or the emergency cooling requirements of a nuclear plant. In these regions, particular care must be taken in choosing and building energy systems.

CONCLUSIONS

The supply and use of both water and energy resources are intricately connected, and we can no longer consider the formulation of rational energy policy and water policy to be independent. Indeed, the passage of the federal US Energy Policy Act of 1992 (62) set uniform water-efficiency standards for household water fixtures because of the direct implications for energy of water use. For example, the per-capita energy use associated with residential plumbing fixtures installed before 1984 is 57 kWh per year; after 1994 these fixtures will require only 22 kWh per year, including energy for water treatment, wastewater treatment, and heating (63).

Globally, gross inequities in energy use between developed and developing nations will have to be addressed in the near future, with the concomitant implications for water use. Individuals in developed countries of the world—less than one quarter of the world's population—use an average of 7.5 kW per person. The other three quarters of the world's population in the developing world use far less, about 1.1 kW per person, for a total global energy use of nearly 14 TW (10^{12} W) in 1990, and these averages hide even larger discrepancies between the richest and the poorest people. Yet supplying even this total amount of energy is severely straining the planet's environmental, technological, and managerial resources, without successfully meeting crucial human needs (64). Even assuming great progress in energy efficiency and the closing of the gap in energy use between the rich and the poor, providing 9 billion people in the middle of the next century with an average of 3 kW each would require doubling today's global energy use.

Increasing energy use in developing countries through traditional expansion of fossil-fuel combustion will lead to severe environmental problems and enormous increases in the consumptive use of water. At the same time, improvements in health, economic conditions, and our overall quality of life will require better access to clean drinking water, sanitation services, and water for other activities.

Where water supplies are plentiful, energy planners have a wide choice of technologies and sites, and decisions about the form and size of energy facilities ultimately rest on other economic, environmental, and social factors. Where energy is plentiful and inexpensive, such as in the Persian Gulf region, water planners have greater flexibility in developing water supplies, including the possibility of long-distance transfers and the use of desalination facilities.

Where water or energy is partially or seriously limited in quantity, choices about both energy futures and water supplies will be far more difficult and constrained. In arid and semi-arid regions especially, water availability may begin to play a central role in defining energy choices. Similarly, in regions with ample average supply but with large temporal variations in water availability either annually or interannually, water constraints must be included when planning new energy facilities. At the same time, the cost of energy will limit options for providing fresh water.

Where water-quality criteria are stringent, a different set of concerns apply. Energy developers must carefully select systems that can meet necessary limits. For example, limits on thermal discharges will require planners to consider alternatives with modest thermal wastes or with closed-cycle cooling systems. Processes that produce significant quantities of hazardous, chemical, or solid wastes will be at a competitive disadvantage with cleaner facilities, and in water-short regions will have to meet environmental restrictions and minimize consumptive water use.

Many of the renewable energy sources, such as photovoltaics and wind generation, require far less water per unit energy produced than do conventional systems. In water-short regions, sources of energy with low water requirements may increasingly be required. At the same time, the growing recognition of the serious problems associated with long-distance water transfers and massive groundwater pumping have increased the amount of attention given to alternative water-supply options, including water trading and marketing, technological improvements in water-use efficiency, proper water pricing, and the elimination of subsidies. These approaches have the potential to reduce the pressure on our requirements for both water and energy.

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