Thirst for energy

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Power generation as well as the production of fuels for transportation requires water, and the supply of high-quality freshwater is energy intensive. A growing population and climate change will increase the pressure on both resources.

Water and solar energy enable trees and plants to grow today, just as hundreds of millions of years ago. Creation of the deposits of biomass that became fossil fuels depended on these two resources. The technological advances that have changed human life profoundly over the past decades and centuries have altered, but not resolved, this close coupling between water and energy. Current technologies for power generation, with some exceptions such as wind turbines and photovoltaic solar cells, rely heavily on the availability of large amounts of water. Primarily this water is needed for cooling thermoelectric plants and supplying fluid pressure and flow for hydroelectric power generation. But in a changing climate, it is not clear whether sufficient volumes of water will continue to be available where needed. And if, in an attempt to combat climate change, petrol is replaced by biofuels at a significant scale, more water will be needed for irrigation.

Furthermore, clean fresh water is a basic necessity for human health and development. Large quantities of water can be provided — as long as sufficient energy supplies are available to reach deep aquifers, treat dirty water or desalinate the oceans. But a scarcity of energy implies a scarcity of water, just as constraints on water availability threaten the supply of energy, at least with the current infrastructure. Because of this interconnection (Fig. 1), water and energy cannot be treated in a disaggregated fashion, as is common today with both markets and policy makers.

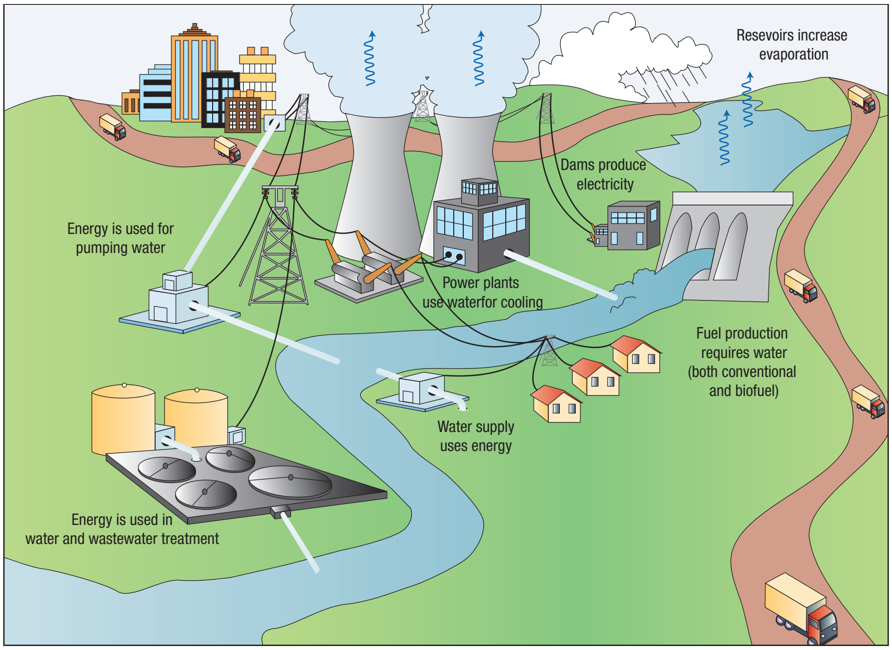

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Figure 1 Interrelationships between water and energy. Water is used to power hydroelectrical power plants (where some is lost to evaporation), for cooling thermoelectric plants, and in the home. Energy is necessary to deliver water to the end users, for wastewater treatment and to pump up groundwater. Adapted from ref. 1.

THE NEED FOR WATER IN POWER GENERATION

Large power plants present a strain on water resources. In the US in 2007, thermoelectric power generation, primarily comprising coal, natural gas and nuclear fuels, generated 91% (3,500 million MW h) of total electricity. These thermoelectric power plants require cooling by water, air or a combination of the two (Table 1), amounting to 40% of US freshwater withdrawals.

Open-loop (or once-through) cooling withdraws large volumes of surface water, fresh and saline, for one-time use and returns nearly all the water to the source with little of the overall water being consumed by evaporation. While open-loop cooling is energy efficient and low in infrastructure and operational costs, the discharged water is warmer than ambient water, causing thermal pollution, which can kill fish and harm aquatic ecosystems. Thus, environmental agencies regulate discharge temperatures, taking into account a water body's heat dissipation capacity. Closed-loop cooling requires less water withdrawal because the water is recirculated through use of cooling towers or evaporation

Table 1 Water and energy relationships

Water for thermoelectric energy (ref. 15)

Cooling method	Power-plant fuel	Water withdrawal (l (MW h)$^{-1}$)	Water consumption (l (MW h)$^{-1}$)
Open-loop	Fossil fuel	76,000–189,000	1,100
	Nuclear	95,000–227,000	1,500
	Combined cycle	28,000–76,000	400
Closed-loop (cooling tower)	Fossil fuel	1,900–2,300	1,800
	Nuclear	3,000–4,200	2,700
	Combined cycle	870	680
Closed-loop (evaporation pond)	Fossil fuel	1,100–2,300	1,000–1,900
	Nuclear	1,900–4,200	1,700–3,400
Air-cooling	Any	Negligible	Negligible

Energy for water treatment (refs 6, 16)

Water type	Source/treatment type	Energy use (kW h Ml^{-1})
Water (public supply)	Surface water	370*
	Ground water	480*
	Brackish ground water	1,000–2,600
	Sea water	2,600–4,400
Waste water	Trickling filter	955
	Activated sludge	1,322
	Advanced treatment without nitrification	1,541
	Advanced treatment with nitrification	1,911

Water for light duty vehicle transportation (US) (refs 11, 17)

Fuel	Consumption (l km^{-1})	Withdrawal (l km^{-1})
Petroleum gasoline and diesel	0.1–0.3	1.0–1.5
H2 fuel cell — electrolysis via US grid	0.9	27
H2 fuel cell — electrolysis via wind/photovoltaic	0.1	0.1
Electricity (PHEV/EV) — US grid	0.5	17
Electricity (PHEV/EV) — wind/photovoltaic	~0	~0

*Includes distribution

ponds. However, because the cooling is essentially achieved through evaporation, closed-loop cooling results in higher water consumption (Table 1). The alternative, air-cooling, does not require water, but instead cools by using fans to blow air over a radiator similar to that in automobiles. The power efficiency of this is lower, up-front capital costs are higher and real-estate requirements are larger, making it a less attractive option economically.

Water is obviously central to power generation in hydroelectric dams. In the US in 2006, hydroelectric power plants generated approximately 7% (268 million MW h) of total electricity. Fifty-eight percent of US hydroelectricity is generated in California, Oregon and Washington alone, making the power supply vulnerable to regional changes in water availability. Though hydroelectric power is attractive for many reasons, it is least reliable during droughts when the need for water may take precedence over hydroelectricity.

THE NEED FOR ENERGY IN WATER PRODUCTION

The relationship goes the other way too, in that energy is necessary for producing and delivering fresh and potable water, just as water is necessary for generating energy. For example, energy is needed to convey, heat and treat fresh water and waste water. Heating water in homes and businesses for cooking, cleaning and other municipal and commercial uses consumes 3.6 quads, or 3.6%, of total US energy consumption. Thus, the need for hot water represents an important end-use for energy. Combined heat and power systems are efficient because they use otherwise wasted heat to do useful tasks.

Supply and conveyance of water is one of the most energy-intensive water processes, estimated to consume over 3% of total US electricity[1,6]. However, the energy use for supply and conveyance of water varies widely depending on the local infrastructure. Many gravity-fed systems require little energy, whereas long-haul systems, such as that in California, require vast energy investments to move water across the state and over mountain ranges. The average surface water treatment plant consumes over 370 kW h Ml^{-1}. Tapping into groundwater sources also requires energy for pumping, which is dependent on aquifer depth: at a depth of 120 m, 530 kW h Ml^{-1} is required[1,6].

Recent news articles illustrate the competition between water resources and power generation: the debate of whether to use water from a reservoir to serve municipal needs for drinking water versus generating hydroelectric power arose with Uruguay's Salto Grande dam and the US Colorado River lakes; a natural gas power plant and private landowners argued over groundwater rights in Texas; and hydroelectric dams were taken offline in response to drought in Georgia, among others[2–5].

As freshwater supplies become strained, many have turned to water sources once considered unusable, including brackish ground water and sea water. Although use of these water sources mitigates constraints on drinking-water supplies, treatment of brackish ground water and sea water requires as much as 10–12 times the energy use of standard drinking-water treatment. However, usually, untreated saline water can be used to cool the thermoelectric power plant that may be required for desalination. Partly because of the high energy requirements, proposed desalination water treatment plants in Carlsbad, California, and Chennai, Tamil Nadu India have been opposed[7,8].

Wastewater treatment also requires large amounts of energy, which will increase as discharge regulations in the US become stricter, requiring increasingly energy-intensive treatment technologies. Estimates range from 250 kW h Ml^{-1} for trickling filter treatment, which uses a biologically active substrate for aerobic treatment, to 350 kW h Ml^{-1} for diffused aeration as part of activated sludge processing, and 400–500 kW h Ml^{-1} for advanced wastewater treatment that uses filtration and the option of nitrification[6]. Sludge treatment and processing alone can consume energy in the range of 30–80% of the total energy used in a wastewater plant; other physical and chemical treatment processes use much of the remaining percentage.

A THIRST FOR TRANSPORTATION FUELS

Two of the earliest fuels were wood and dung. They are still the major primary energy fuels for many regions of the world, providing 8.5% of the primary energy globally[10]. Trees require water for growth, as do the animals that supply dung. But modern liquid fuels such as gasoline, ethanol and diesel also require water for their extraction, farming, processing and refining. This 'embodied water' is not directly used in a vehicle, but rather indirectly required to make the fuel.

Water use for transportation can be considered in a similar fashion as for power generation in the form of withdrawal — that is, the amount of water that is necessary, but may eventually be returned to the system — and consumption, for example, through evaporation. However, in the context of transportation, consumption can additionally be associated with irrigated farming and as a feedstock. Generally, while driving light duty vehicles using current petroleum-based gasoline (assuming an average fuel economy of 20.5 miles per gallon (mpg) = 8.7 km l^{-1}) and diesel (28.2 mpg = 12.0 km l^{-1}), embodied water is withdrawn and consumed from nature at rates of up to 1.5 l km^{-1} and 0.3 l km^{-1}, respectively. Using liquids converted from other fossil fuels (coal, oil shale and tar sands) means that the rates of water consumption and withdrawal are 2–4 times and 1–2 times higher, respectively, and they are much more concentrated in regions where the fossil fuel resources exist.

Propelling vehicles using hydrogen and electricity also has substantial water impacts when drawing from the average US electric grid (owing to water used for power plant cooling as discussed earlier). Under these assumptions, driving 'electric' miles using a fuel-cell vehicle with hydrogen via electrolysis and a plug-in hybrid electric vehicle (PHEV) or electric vehicle (EV) consumes water at 0.9 and 0.5 l km^{-1} while withdrawing 27 and 17 l km^{-1}, respectively[11,12]. Using wind and photovoltaic solar power to supply required electricity for transportation makes water intensity negligible. However, even if every US light duty vehicle mile were driven via US electric power with current technologies, US water demand would only increase by 0.9% (3.4 billion litres per day).

Most of the fuels under consideration to replace petroleum are more water intensive, with biofuels residing at the top of the list. Only for fuel crops that are not irrigated is the water intensity comparable to petroleum fuels. But many fuel crops are irrigated, and accounting for irrigation can cause water consumption rates to be 2–3 orders of magnitude higher than without irrigation. Although only 15–20% of US corn and 5–10% of US soybean bushels are irrigated to any degree, there was still a substantial water contribution to biofuel crop farming at nearly 5,700 gigalitres (3.5% of US water consumption) in 2005 for the production of ethanol alone. Given that agricultural irrigation is the most water-consumptive sector of the US economy, high water usage is not surprising. But by switching to biofuels, this water consumption is likely to grow. Additionally, competing water demands often make the siting of ethanol plants difficult because they require large amounts of water. Ethanol processing plants consume water for cooling processes, including the exothermic fermentation reaction, requiring 1–3 million litres per day to produce 250,000–750,000 litres per day of ethanol[13,14].

LOOKING TO THE FUTURE

We see trends towards more water- intensive liquid fuels, more energy-intensive water sources and a growing population that will require more of both. These challenges will be exacerbated by climate change, which may cause geographic and temporal changes in the amount, annual distribution and form of precipitation (for example, as rain or snow). Because cities and their infrastructure are built on the basis of past precipitation patterns, such climatic changes may require substantial adjustments. In regions where water becomes scarcer, people must weigh the pros and cons between moving the people to the water and moving the water to the people (the latter of which requires continuous additional energy). Regional climate projections will be needed to inform planning and policy.

When siting new power plants, governments and power generators need to consider water availability over the plants' lifetimes, normally on the order of several decades. Policy for energy and water resources should be integrated to consider less-water-intensive options in agriculture, such as forestry, and in electricity generation, such as wind, photovoltaic solar and air-cooling technologies. In the fuel sector, water consumption and withdrawal need to be included in environmental impact analyses such as those dictated by the Energy Independence and Security Act of 2007, which requires life-cycle analysis for understanding the greenhouse-gas impacts of renewable fuels.

Like diversified long-term financial investment strategies, future water and energy infrastructure should also be diverse and multiscaled in order to create resilience in an uncertain climate and energy future. For example, Ghana has had highly fluctuating reliability of electricity supply owing to heavy dependence upon hydropower or other single energy sources, without extensive electric grids to help transport electricity in tough times.

Distributed energy systems provide smaller-scale systems and add resilience to electric grids dominated by large centralized power plants, but they are usually considered more expensive owing to conventional financial and appraisal systems that account for capital but not operating expenses. For new power plants at greenfield sites in the US, open-loop cooling has been outlawed for all practical purposes by the environmental constraints on water intake velocity. The trend since the 1980s has been towards closed-loop cooling. However, closed-loop cooling makes the use of sea water more difficult, because evaporating water with high proportions of dissolved solids can create foul-up problems. Nevertheless using sea water, waste water and other low quality water for cooling should be encouraged where possible.

We also need policy that allows the operating costs and energy consumption of buildings and homes to be integrated into the construction, sales and finance phases of development. More energy-efficient buildings within larger cities require less bulk city services. We must ask ourselves why we require no energy return on investment for crown moulding yet claim photovoltaics do not pay back fast enough. Fortunately sustainable concepts such as LEED (Leadership in Energy and Environmental Design) and projects such as the China EcoBlock[18] guide and demonstrate integrated water and energy infrastructure via whole system design.

Water and energy cannot be separated. With an unlimited supply of available energy, we would be able to supply as much clean water as the world needs. In the real world of resource constraints, we need to simultaneously conserve water and energy. Thankfully, water conservation and energy conservation are synonymous with each other, so we have the opportunity for swift progress.

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