CHAPTER 16

Water and energy nexus – Role of technology

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ABSTRACT: The aim of this chapter is to provide an overview of the inter-linkages between water, energy and the environment, and the role technology can play to reduce demand and impact and increase supply. Demand, supply, and effects on the environment are the main drivers of our energy and water systems, with all three of them set to undergo significant change. Stress on water and energy resources is exacerbated by low efficiencies, for example in the agricultural sector when it concerns water use and losses in water distribution systems. Boosting water and energy use efficiency through investments in relevant technologies and infrastructure is therefore critical.

To improve water efficiencies it is important to understand the complexity of water treatment. The appropriate water treatment technology will be determined by characteristics of the water sources available and quality characteristics for the discharge/re-use. It is concluded that technology alone cannot address the water and energy efficiency challenge. While water is a local issue, ensuring the allocation of sufficient supplies at the right time, in the right place, and of the right quality, sustainable water management requires increasingly consideration of the interconnectivity of larger contexts and many diverse stakeholders.

Keywords: energy, water, development, linkages, technology

1 THE WATER AND ENERGY SYSTEMS TODAY SET THE CONTEXT FOR THE FUTURE

Energy and water are both essential for most aspects of life: domestic use, food, industry, transportation, ecological services, leisure, cultural identity, etc. There are some hard truths about energy and water availability which taken together mean we are entering an era of revolutionary transitions. A step change in the rate of growth of energy demand is foreseen and increasingly it is recognized that this also will be true for water.

Shell Energy scenarios (Shell, 2008) estimated that in 2007 the primary energy the world needs is about 480 exajoule ($EJ = 10^{18}$ J) or 235 million barrel of oil equivalent ($BOE = 5.63 \times 10^9$ J; conversion factor used as a typical average) per day. In 2007 total final consumption is estimated to be around 335 EJ/yr or 160 million BOE/day. This means we lose approx. 30% of the primary energy we put into the system. And in the last 20 years it has been getting gradually worse (1987 = 28%). As people grow richer they use more energy (Figure 1) and it is expected that population and GDP will grow strongly in non-OECD countries, since China, India and Brazil are just starting on the energy ladder.

Easy access oil and gas (relative low cost and high availability) will not be able to match the pace of energy demand. In fact all energy sources together (renewable and non-renewable) will struggle to match demand, which will have to be met partly by new energy efficiency technology.

We are going to need all the energy we can get. This is due to a combination of constraints on the availability of resources, the huge infrastructure investments required to develop them and political constraints. For example, bio fuels need arable land, and to meet 10% of the USA's transport demand by ethanol from maize in 2020 requires 30% of USA's arable land. Coal will be constrained by logistical limits on the ability to construct new railways and ports to move massive amounts of coal from producing to consuming areas. Growth in nuclear power will become

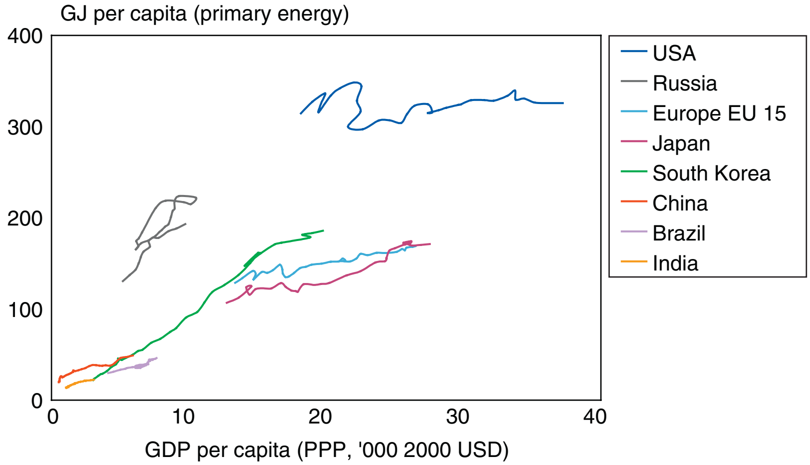

Figure 1. Per capita energy consumption (Shell, 2008).
Source: Shell International BV, Oxford Economics and Energy Balances OECD and Non-OECD Countries © OECD/IEA 2006.

constrained by political controversy, the high rate of decommissioning of old plants and the recreation or large scale expansion of three industries: uranium mining, plant construction and waste management

Less than 3% of the world water is fresh and most of it is locked up in Antarctica, the Arctic and glaziers and not available for man. Thus man and the environment must rely on only 5% of all freshwater. Where is this fresh water? 10×10^6 km^3 is stored in underground aquifers, 119,000 km^3 of rain falling on land after accounting of evaporation, 91,000 km^3 in natural lakes, over 5,000 km^3 in man made storage facilities, and 2,120 km^3 in rivers, constantly replaced from rainfall and melting of snow and ice (UNESCO, 2003).

A challenge in managing water resources is the scattered knowledge of the patterns in water use. The Third Edition of the United Nations World Water Development Report (UNESCO, 2009) states that there is a consensus that the estimate for total global freshwater use in 2007 is about 4,000 km^3/yr. Another 64,000 km^3 is directly used in agriculture.

Nature is the most important user of water. An estimated 70,000 km^3/yr of water is evaporated from forest, natural vegetation and wetlands.

There are also significant losses in the systems, however they are difficult to quantify, e.g. evaporation losses from human made reservoirs in arid areas.

While there is a strong relationship between water investment and growth, the relationship between quantity of water and growth is less conclusive. Many water poor economies have developed, while the ratio of water use to GDP in many developed countries is declining.

Taken into consideration uncertainties in population and GDP growth, freshwater withdrawals are predicted to increase by 50% by 2025 in developing countries, and 18% in developed countries (WBCSD, 2006). As traditional fresh water resources are under stress because of over exploitation, water supply for human, industrial and agriculture purposes will need to transition to greater use of non-traditional water resources like saline surface water and waste water. To balance supply and demand there will be a significant role for new water efficient technology.

The increase in environmental stresses, including loss of habitat, pollution and changes in biological processes (such as fish spawning) is another factor that intensifies this water and energy story. Maintaining environmental flows are critical to ensure river systems can supply water to human use and ecosystems. Impacts from climate change on both regional and global hydrological

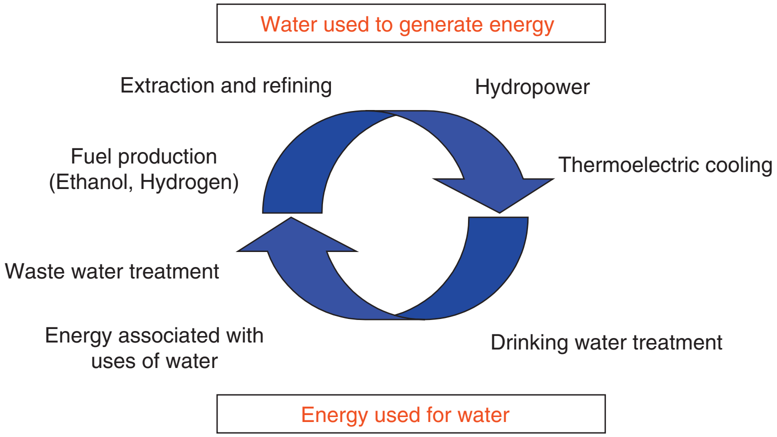

Figure 2. Water is used for energy generation and energy is used in water management.

systems will increase, bringing higher levels of uncertainty and risk about water availability, with some regions more impacted than others.

Increasing temperatures in northern climates impact melting of snow packs; globally rising sea levels and changes in precipitation patterns are already being seen. Small islands will be critical hotspots as well as coastal mega cities. It also means an increasing need to prepare for extreme weather events (droughts and floods) and the uncertainty in their occurrence.

2 WATER AND ENERGY ARE INCREASINGLY INTRINSICALLY LINKED

Water is used in a variety of ways in the energy sector. Water is used as an input into the production of both non-renewable energy sources such as coal, natural gas, nuclear fuels, and oil, and renewable energy sources such as biomass, geothermal, solar, wind, and hydropower. It is used for irrigation (energy crops), drilling, mining, transportation, fuel conversion, cooling, cleaning, and other technology-specific applications. On the other hand, energy is consumed for various water activities such as water extraction, conveyance, distribution, treatment, and desalination. Historically water and energy supply have been examined independently. As the world faces water stress in the face of growing energy demands, considering both sides of the water-energy nexus is essential to any major planning decision (Figure 2).

3 WATER DEMAND FOR PRIMARY ENERGY PRODUCTION

Data is increasingly published on the water footprint of the various energy pathways. Water foot printing is an emerging science. The water footprint is an indicator of water use that looks at both direct and indirect water use of a consumer or a producer. The water footprint of an individual, community or business is defined as the total volume of freshwater that is used to produce the goods and services consumed by the individual or community or produced by the business. Following is an overview of the current understanding of the water footprint of some of the key primary energy carriers and power generation. Significant more work is needed to have a good understanding in terms of their lifecycle, e.g. *from well to wheel* or *from cradle to grave*. In addition, the water footprint must be seen in the context of local impacts, for example whether a crop is rain-fed (green water) or irrigated (blue water).

This element of the water footprint is perhaps more important than the water use component itself. Knowing your water use without knowing where you are using it, is less valuable than knowing where you are using water, even if you do not know your water use.

3.1 *Biomass*

Driven by climate change and energy security concerns biomass is expected to grow as a primary energy carrier, bio fuels potentially becoming a significant part of it. The Shell energy scenarios to 2050 (Shell, 2008) predict that this may reach 15% of the total energy demand in 2050. While the current debate on the feasibility of such growth is centred about the land-use competition with food and ecosystem services, water linkages are often ignored. Water may be in some cases the limiting factor since the water footprint of bio-crops is significant. However, large differences in crop water requirements exist among countries due to different climates and production efficiencies. An illustrative range of the average water footprints for biomass production ranges from 24 m^3/GJ (24,000 m^3 per 1,000 GJ) (GJ = 10^9 J) in the Netherlands to 143 m^3/GJ (143,000 m^3 per 1,000 GJ) in Zimbabwe (Gerbens-Leenes *et al.*, 2008). These numbers are conservative as they do not take into account efficiency losses to secondary energy carriers.

3.2 *Enhanced oil recovery*

As easy oil is used up, it is common to use water for improved oil recovery. Water is injected by pumps to the required formation to recover the pressure in the reservoir and/or sweep the oil out of the reservoir. The water quality (and energy) requirements depend on the injected depth, hydrogeological parameters of the reservoir, and process efficiency. This injected water is also trapped in the reservoirs and as a consequence removed from the water cycle. To extract oil, including water for drilling, flooding and treating (Khatib, 2007), between 2 and 8 m^3 of water per 1,000 GJ have historically been required. However, when thermal steam injection or enhanced oil recovery, like water flooding is included in the process, this number can increase, on average, to 1,058 m^3 per 1,000 GJ.

3.3 *Hydropower*

Hydropower produced 89% of the world's renewable electricity in 2006, and 16.6% of total electricity generation worldwide. Two-thirds of worldwide economic potential remains unexploited – this resource is concentrated in the developing world (WBCSD, 2006).

The construction and operation of dams and hydropower plants can contribute to reducing greenhouse gas emissions, smooth operating peaks and store energy and water as well as provide improved ship traffic safety. Although hydropower does not directly consume water (consumption is limited to the loss by evaporation in the dams which vary as a function of the climatic conditions), its generation may conflict with other uses, especially irrigation, since its release schedule does not always correspond to the timing of other water needs. 25% of dams worldwide are used for hydropower and only 10% have hydropower as their main use. Most of them are used for flood control or irrigation, or for multiple purposes (Gerbens-Leenes *et al.*, 2008).

3.4 *Solar energy*

Concentrating solar power reflects and concentrates sunlight to create high-temperature heat, usually to create steam to drive traditional turbines. This power source is best harnessed through large, centralised power plants located regions with high direct normal radiation. There are plans currently to significantly increase the solar thermal power generation in such places as California, Arizona, Spain, Australia and Northern Africa. However, a solar thermal power plant water consumes about 1 m^3 of water per 1,000 kW·h (electric) or 277 m^3 of water per 1,000 GJ (Gleick, 1994). Concerns about water availability and environmental impacts have driven the Solar Millennium group to select dry cooling at their proposed project locations in Nevada and California, saving water consumption by up to 90%. In this technology the steam cycle is cooled with air, mainly from large ventilators.

Photovoltaic cells that produce electricity directly from sunlight are considered to have negligible water use.

3.5 *Canadian oil sands*

While 173,000 million barrels (BOE) of the Canadian oil sands resource rated economically recoverable with today's technologies, and therefore deemed proven, the ultimate potential of the Canadian oil sands is even greater given the estimated 1,700,000 million BOE in place[1]

Oil sands extraction is a water-based process. Large volumes of water are needed to separate bitumen molecules that are trapped in sand and clay. On average, the oil sands industry uses two to three barrels of fresh water to extract one barrel of bitumen. This fluctuates depending on recycling rates from tailings. About half to three quarters of a barrel of water is needed to convert the bitumen into synthetic crude oil.

The primary source of fresh water is the Athabasca River. Industry plans to increase oil sands mining production from 1.2 million barrels/day (current production) to 3.5 million barrels/day. This production level, on average, will use less than 3% of the mean annual flow in the Athabasca River. The Athabasca River is a natural river with no dams to moderate or interrupt natural seasonal flow variations. During winter low-flow periods poorly managed water withdrawal could impact the river in the future. However, regulatory limits are already in place to restrict water withdrawals by the oil sands industry during winter low-flow conditions. In addition, research programs and a multi-stakeholder committee have been established to recommend future withdrawal limits to ensure the Athabasca River remains protected.

4 WATER AND POWER GENERATION

There is a critical relationship between power generation, carbon capture and storage and water. Water consumption can vary by primary energy source (nuclear, coal, gas) and the type of carbon capture and cooling system employed.

The National Energy Technology Laboratory, in a report prepared for the Department of Energy of the USA (Khatib, 2007), calculated that there is almost a fourfold increase in water consumption per net kW·h between the lowest water consuming platform (Natural Gas Combined Cycle) and the highest (Nuclear). The addition of CO_2 capture and compression increases water consumption by 50% to 90%. Many of the advanced power platforms use less water and have a lower increase in water demand associated with incorporation of CO_2 capture equipment than do current technologies.

The water consumption factors are based on a cooling system in which the effluent cooling water is cooled in an evaporative cooling tower and re-circulated. *Consumption* represents water that must be made up to account for both evaporation in the cooling tower and a relatively small amount that is consumed in unit operations within the generation process. There is also the open loop water cooling, where water is withdrawn from a river, lake or the sea, and then returned to it after cooling. The average amount of water consumed is approximately zero. However a significant amount of water is required, which is then returned calculated at approximately 160 m^3/MW·h (equivalent to 44,444 m^3 per 1,000 GJ)[2].

5 WATER PRODUCED IN PRIMARY ENERGY PRODUCTION

Due to ageing reservoirs and increased oil recovery operations, pumping oil from reservoirs is now associated with more water production per amount of oil produced than ever before. The volume

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[1] Government of Alberta, Energy, Oil Sands Statistics [http://www.energy.gov.ab.ca/OilSands/791.asp].

[2] Figures based on average values from EDF (*Électricité de France*) from nuclear power plants along rivers in France.

Table 1. Energy required to deliver 1 m^3 of clean water from different sources. Based on Scientific American (2008).

Source	Energy required (kW·h/m^3)
Lake or river	0.37
Groundwater	0.48
Wastewater treatment	1.0–2.5
Waste water reuse	0.62–0.87
Seawater	2.58–8.5

of water produced worldwide from the oil and gas industry is still increasing at a rate of about 10% per year. Water to oil ratios ranged from <1 to up to 40 depending on maturity of the field, with the lowest ratios generally observed in the Middle East (UNESCO, 2009). The water quality varies depending on location, formation where it originates from, and the type of hydrocarbon being produced, e.g. oil or gas. Apart from hydrocarbons, salt content is another major issue when considering the beneficial reuse of this water.

Coalbed methane (CBM) or coalbed gas is a form of natural gas extracted from coal beds. In recent decades it has become an important source of energy in the USA, Canada, and other countries. Australia has rich deposits where it is known as coal seam gas.

Because of its large internal surface area, coal stores 6 to 7 times more gas than the equivalent rock volume of a conventional gas reservoir. In order for gas to be released from the coal, its partial pressure must be reduced and this is accomplished by removing water from the coal bed. Large amounts of water, sometimes saline, are produced from coal bed methane wells, especially in the early stages of production. Increasingly this water is seen as a resource rather than a waste, in particular in water scarce areas in Australia and the USA.

6 ENERGY FOR WATER MANAGEMENT

Energy is used to extract, transfer and treat water (Table 1). The numbers are illustrative and do not incorporate critical elements such as the distance the water is transported or the level of efficiency, which vary greatly from site to site. For example, water transfer over 350 km (horizontally) uses 3.6 kW·h/m^3, or the same amount of energy needed to desalinate 1 m^3 of seawater. It is clear from this data that seawater desalination is the most energy intensive process to produce clean water, even though significant efficiency improvements have been achieved over the past decades.

Some studies have estimated that approximately 56,000 million kW·h are used for supply and treatment of drinking water in the USA, the equivalent of approximately 44.8 million tonnes (1 tonne = 1,000 kg) of greenhouse gas to the atmosphere at a cost of approximately US$ 4,000 million (EPRI, 2002).

7 POLICY CHOICES

Water policy therefore influences energy choices and vice versa creating a need for policy integration. Having the right price, policy and regulatory frameworks are critical to encourage behavioural changes, trigger innovation, ensure sustainable use of water and energy resources and to simultaneously adapt to and mitigate climate change. Within such frameworks, different solutions may be applied to local circumstances.

Research and knowledge have expanded and discussion progressed within technical circles. Some places in the world have successfully integrated both water and energy into planning, from investment to institutional decision-making. For example, in December 2008, the US

Environmental Protection Agency announced an inter-agency agreement between the offices of Air and Water to collaborate on energy and climate efforts at water utilities. Nevertheless, there is still a significant gap in communications addressing the linkages at a global scale. Only a limited number of publications, scenarios and perspectives about energy and climate change currently also address water issues.

Understanding both water and energy footprints for the different energy carriers and water users, and optimising both footprints by integrating them in the project design, should be undertaken. The different energy and water footprints have several economic, social, and environmental constraints (e.g. constraints with large water footprint associated with biofuels, or the large energy footprint associated with deep water injection, etc.) and so by considering the tradeoffs between the various footprints, this will allow a better utilization of the appropriate technologies to meet these constraints.

8 ROLE OF TECHNOLOGY

Demand, supply, and the effects on the environment are the three main drivers of our energy and water systems, with all three of them set to undergo significant change. Therefore we know that the next 50 years will see a revolution in the system and considerable turbulence along the way.

There are no ideal answers but some outcomes are clearly better than others, and while prices and technology will drive some of these transitions, political and social choices will be critical. Thus profound change is inevitable. Will national governments simply seek to secure their own energy and water supplies? Or will new coalitions emerge between various levels of societies and government, ranging from the local to the international that begin to add up to a new resource management framework?

Stress on water and energy resources is exacerbated by low efficiencies, for example in the agricultural sector, when it concerns water use and losses in the water distribution systems. The agriculture sector is facing outmoded water systems, poor regulatory enforcement, ineffective price signals, and the lack of incentives for change in behavior, particularly by those who claim historical rights to water access.

Boosting water and energy use efficiency through investments in relevant technologies and infrastructure is therefore critical. This efficiency challenge leads to the business challenge of innovation – not only in producing new products and services, but also in avoiding or addressing legacy constraints – for example, established infrastructure and technology standards, social habits and attitudes and standard business practices.

These behaviors and norms were appropriate for a bygone era (for example, a context of abundant cheap energy) and within a certain socio-economic and political context (for example, food security and priority for agricultural water uses), but not for current or future conditions (for example, increasing urbanization and post-industrial economies).

9 TECHNOLOGY TRENDS

In order to improve efficiencies, it is important to understand the complexity of water treatment. First one must have a good understanding of the characteristics of the water sources available such as: surface, groundwater or waste water. Then it is important to understand relevant quality characteristics for the discharge/re-use quality such as: salinity, solids, fines, dissolved and dispersed hydrocarbons, and bacterial activity. The water treatment technology will be determined by these two characteristics, namely source characteristics and discharge quality.

Reduction in the cost of membranes has been the principal driver for membrane technology becoming one of the technologies which is now extensively applied in water treatment. The pore size of the membrane, expressed in nanometers (nm) will determine what components can be removed as illustrated in Table 2.

Table 2. Membrane characteristics.

Filtration Spectrum	Pore size	Removal
Filtration	100–1,000 nm	giarda, crypto, bacteria
Ultra Filtration	10–100 nm	colloids, viruses
Nano Filtration	1–10 nm	colour, hardness, pesticide
Reverse Osmosis	<1 nm	salts

State-of-the-art sweet water purification units are now based on ultra filtration, however it needs large amounts of relatively hazardous chemicals to avoid bio-fouling and scaling. These chemicals might involve a health hazard, especially when a mistake is made during the cleaning process. It is therefore important not only to consider water treatment efficiency, but also the impact it may have on the environment in general, and on energy efficiency in particular. Some examples of game changing technologies that address both water and energy efficiency are:

- Biogas generated by the application of anaerobic treatment may be used for power generation, fuel for transport or heating.
- Heat transfer from groundwater and wastewater resources, respectively for both heating and cooling systems which provide generic solutions when the costs of fossil fuel based energy are on the increase.
- Microbial Fuels Cells (MFC) for green production of chemicals based on electricity produced directly during biodegradation of waste organic matter.
- New cooling systems can be designed in power plants to have an optimal trade-off between water and energy requirements and impacts (e.g. parallel condensing systems that combine wet and dry cooling systems).
- Reuse of output heat in the industrial processes as part of an ad-hoc recycling of waste streams (e.g. low grade steam in cooling systems, produced heat streams in desalination or waste water treatment processes).

10 AN EXAMPLE FROM THE OIL AND GAS SECTOR

Natural wetlands and mangroves mitigate flooding, and can be used for water storage, thus reducing the impacts of climate change, whilst also effective in improving water quality. The use of constructed wetlands, which mimic this natural phenomenon for treatment of surplus water associated with the production of oil and gas, has been pioneered by the Petroleum Development of Oman (PDO) (Society of Petroleum Engineers, 2004). In one of their oilfields more than 20 barrels of water are produced for every barrel of oil. This *produced* water is then disposed of via Deep Well Disposal (DWD). The dilemma faced by PDO is that from 2009 onwards the water disposal rate is expected to reach capacity constraints, which may result in oil deferment. Some 250,000 m^3 of water are produced each day; to dispose of this volume requires six pumping stations, each having two or three wells. The continued use of DWD is unsustainable because of the prohibitive and increasing cost, the high gas usage and the growing inaccessibility of low-pressure aquifers – in the face of ever increasing water production. Replacing DWD could reduce operating and capital expenditures and over 30 years, liberate gas for other uses. PDO has opted for constructed wetlands to treat this surplus water. Production water flows into the treatment beds through buried perforated pipes, then through the root zone of reed plants, and out through perforated drainage pipes in the base of the beds. Naturally occurring soil bacteria already present in the soil will degrade the hydrocarbons in the water in the time it takes for the water to flow through the beds.

Treated water is applied to the production beds via surface irrigation. Here a crop of reed plants will be grown. Initially, the crop will be mulched and left in the field. Later, the crop may be harvested for a commercial – non-food chain – use. Remaining water is evaporated in evaporation ponds, leaving salt. Salt may be buried at the end of facility life, but may also be harvested and sold if its composition is suitable. The application of constructed wetlands in Oman will be one the largest scale applications ever and has the potential to transform water management in Oman.

11 CONCLUSIONS

It is illustrated that the increased demand for water and the scarcity in supply leads to innovation – not only in producing new products and services, but also in avoiding or addressing legacy constraints – for example, established infrastructure and technology standards, social habits and attitudes, and standard business practices. These behaviors' and norms were appropriate for a bygone era of abundant cheap, low water intensity energy world. However technology alone is not the answer to the water and energy challenges. While water is a local issue, ensuring the allocation of sufficient supplies at the right time, in the right place, and of the right quality, increasingly requires consideration of the interconnectivity of larger contexts and many diverse stakeholders. Human security and development cannot be isolated from the health and viability of the earth's underlying life support systems. The interconnectivity challenge requires us to be able to think and act in terms of multiple geographies of connection, from nation states and city limits to watersheds and river basins, and in terms of multiple timeframes, in order to ensure that short-term interests do not foreclose longer-term possibilities. The interconnectivity challenge also requires us to take into account not only *blue water* issues of the water we see, such as the water in lakes and rivers, but also the so-called *green water* contained in healthy soils, and the *virtual* or embedded water contained in traded products and services. Human security and development also increasingly depend on the ability to consider links in actions and policies relating to food security, energy security, and water security.

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