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Water for Electricity: Resource Scarcity, Climate Change and Business in a Finite World

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

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EXECUTIVE SUMMARY

The need to keep climate change within safe thresholds will require rapid emission reductions, and widespread deployment of low-carbon technologies to help achieve them. Yet some low-carbon energy sources require considerable amounts of water – and given competing demands, resource depletion and projected climate impacts, sufficient water may not always be available to meet all needs in all places.

This report, based on research conducted as part of a partnership between the business leaders' initiative 3C (Combat Climate Change) and the Stockholm Environment Institute, examines the potential impact of low-carbon electricity-generation technologies on water resources – and how these water considerations might shape renewable-generation choices.

We begin by exploring the ways in which a changing climate and associated hydrologic changes may impact current electricity generation strategies; in particular, where future climate change may significantly decrease water availability. We then examine the water use implications of different electricity generation pathways, as well as potential ways to reduce the water use of electricity generation technologies. Finally, we provide a case study of water and energy considerations in California, a renewable-energy leader in the USA.

The goal of this report is to provide a general framing of the interplay between electricity management and water management that can inform the sort of site-specific analysis and planning that will be required to discover strategies that contribute to a low-carbon future without placing undue stress on water resources.

WATER AND THE LOW-CARBON ECONOMY

Water is used in the production and processing of fuels, in electricity generation, as a coolant in power plants, in energy storage, and for other energy-related purposes. Yet predicting how the low-carbon economy will intersect with water resources is challenging, both because of inherent uncertainties in climate scenarios and water-supply projections, and because it is hard to estimate the future technical potential and adoption of key technologies.

This analysis focuses only on one aspect of the low-carbon economy: electricity generation. The links between climate, water and energy are much broader; the water management implications of biofuels production, for example, are a pressing concern. However, focusing on electricity provides a more manageable scope for our study, and better matches both the expertise of the authors and the profile of the 3C member companies.

ELECTRICITY GENERATION AND WATER TRADEOFFS

Water is required in nearly all electricity production. Fossil-fuelled and nuclear power plants, which generate the majority of many countries' electricity, rely heavily on water for cooling. Hydropower depends on river flow and reservoir storage and contributes to substantial manipulation of hydrologic regimes, as well as to potential water losses through evaporation from reservoirs. Water availability thus constrains the operation and siting of power plants, and any shortages will have implications for energy production. Yet some of the same factors that restrict water supplies – competing demands due to economic and population growth, and expected thermal extremes due to climate change – will likely increase energy demand, and with it, demand for water for the electricity generation sector.

Water requirements for power generation depend on several factors, including the generation technology, the type of cooling technology used in thermoelectric power generation, and electricity demand itself. In general, however, because of the substantial need for cooling, fossil-fuel electricity generation is typically more water-intensive than many alternatives – although some low-carbon technologies have similarly large water requirements.

Climate-related water constraints are already affecting electricity generation in many places, sometimes forcing power plants to curtail output or shut down. For example, in 2006, a drought in Uganda reduced hydropower capacity by one-third, leading to electricity shortages. And in 2003, increased river water temperatures due to a heat wave led authorities in Germany and France to curtail nuclear power generation – by 4,000 MW in France alone.

As these examples suggest, acute water-energy conflicts are already arising during droughts and summers, when energy demand is high and water availability is low. Climate change may exacerbate this problem, and bring scarcity and drought risks to new areas, where streamflow regimes currently support hydropower and cooling-water withdrawals.

Water use in electricity production is measured in two ways: withdrawal and consumption. Water withdrawal involves removing water from a source and either returning it to the source, or making it available elsewhere. Consumed water is not returned to the system, typically due to evaporation.

Conventional coal, nuclear, natural gas and oil power plants account for 90 per cent of U.S. electricity generation and 81 percent of global generation, according to the U.S. Energy Information Administration (US-EIA). These thermoelectric power plants heavily rely on water for cooling purposes: in the U.S., they accounted for 41 per cent of freshwater withdrawals in 2005, the single biggest share. In addition, thermoelectric power plants require smaller amounts of water for resource extraction, fuel processing and post-combustion activities.

Cooling systems in use today fall into three categories: once-through, wet-recirculating and dry cooling. Once-through cooling systems take water from nearby sources, circulate it through the plant, and return almost all the freshwater, albeit at a warmer temperature, to its source, with perhaps a 1 per cent lost. In wet-recirculating cooling systems, less water is withdrawn from the source, but 70-90 per cent is lost through evaporation and flushing operations. Dry-cooling systems use air to cool plant elements and can reduce water consumption by more than 90 per cent compared with wet-recirculating systems, but they are expensive and less efficient in terms of electricity output.

According to U.S. government estimates, most thermoelectric power plants currently use once-through (43 per cent) or wet-recirculating cooling (56 per cent); only 1 per cent use dry cooling. Unless companies install more dry cooling systems or shift generation to non-thermal renewables, rising demand for electricity is likely to lead to an increase in overall water use by the electricity generation sector.

WATER USE IN A LOW-CARBON ECONOMY

Low-carbon energy sources produce fewer greenhouse gas (GHG) emissions than conventional fossil fuels, but that doesn't necessarily mean they have no environmental impacts. Hydropower, by far the most prevalent low-carbon electricity source, can significantly disrupt the flow of rivers, especially when large dams and reservoirs are built. This can affect flora and fauna in and around the river; in terms of water consumption, evaporation from reservoirs can also be a significant issue.

Solar thermal and geothermal technologies both require water for cooling, which, particularly for solar thermal, can be a serious concern because this technology is generally best suited for water-constrained areas. Water requirements for biomass vary widely depending on feedstock, generation technology and cooling technology, but they can be on par with fossil-fuel technologies' water use.

CASE STUDY: WATER AND ELECTRICITY IN CALIFORNIA

California is the most populous U.S. state, with 37 million residents as of 2010, and has a larger economy than Brazil, with a $1.89 trillion gross state product in 2009. California is also increasingly water-constrained, with warmer winters and reduced snowpack in its mountainous areas, and high water stress in its drier southern areas. These constraints, and concerns about how climate change may worsen them, have forced California to confront the so-called water-energy nexus – both in terms of water use for energy, and in terms of the energy used to transport water across the state.

California has also been a leader, since the 1970s, in supporting renewable energy development through market-based incentives. In 2009, approximately 20 per cent of all electricity generated within California came from renewable resources such as wind, solar, geothermal, biomass and hydroelectric facilities, and this is expected to rise to 33 per cent by 2020 under the state's Renewables Portfolio Standard (RPS), which was adopted in 2002 and enhanced in 2011. Our case study evaluates the carbon emissions and water use implications of the RPS, and investigates the potential impacts of modifying the RPS to favour technologies that reduce both emissions and water use – a scenario we call RPS+Technology.

We find that under business as usual (BAU), greenhouse-gas emissions, water withdrawals and water consumption all increase going forward as overall electricity demand increases. Under the RPS, emissions and water withdrawals drop, but water consumption increases. The scenario serves to illustrate how various generation, cooling, and carbon management strategies can be packaged in an attempt to reduce both GHG emissions and pressure on water resources. The exact "optimal" combination of strategies for a particular area, in terms of economic considerations, is a topic worthy of further investigation.

For the RPS+Technology scenario, we assume the same fuel mix as the RPS scenario, but switch technologies. We alter the RPS solar portfolio, dominated by solar thermal (70 per cent vs. 30 per cent photovoltaic), to a 50:50 mix by 2020, and change a portion of once-through systems to wet-recirculating, and a portion of biomass and natural gas wet-recirculating to dry cooling. Because some of these changes affect energy efficiency, leading to slightly higher greenhouse gas emissions, we also add carbon capture and sequestration (CCS) technology to some recirculating natural gas plants (17 per cent of the state's generation capacity). Adding CCS modestly reduces the water savings, but also leads the RPS+Technology scenario to yield larger emission reductions than the standard RPS scenario.

MORE OPTIONS TO CONSERVE WATER

Given projected water shortages and competing demands in many places, it is crucial that all energy planning – including efforts to boost renewable capacity – carefully consider future water availability under multiple usage and climate scenarios, and that any new generation capacity be viable even in the lowest water availability scenarios. In water-constrained areas, this means energy planners may want to prioritise low- and no-water renewable energy technologies such as solar PV, wind, small hydro and binary-cycle geothermal. Thermoelectric renewables such as solar thermal and geothermal steam technologies are arguably at a higher risk than conventional thermoelectric power plants, as they must be sited near solar and geothermal resources, respectively, which are often in hot, arid areas.

It is also important to pursue other measures to reduce water demand from the electricity sector. One helpful approach – with carbon emission reduction benefits as well – is to reduce demand for *electricity*, through efficiency improvements in electrical devices, electricity transmission and distribution systems, and power plant operations.

Water recycling and reuse could also decrease the need for water withdrawals. Several types of wastewater are being considered for power plant cooling: treated municipal wastewater, also called grey water, is a huge unclaimed water resource, and is already successfully used in several power plants. Water discharged during oil and natural gas mining, wastewater from industrial processes, and agricultural runoff may also be options.

We also see potential for energy storage technologies to help reduce stress on water resources. Such systems can help even out demand for power generation (smooth the load) and enable power plants to operate at maximum efficiency, making it critical to a low-carbon future. Technologies such as pumped hydro and compressed energy storage system (CAES) offer the largest and most economical grid-scale energy storage options. In terms of water use, these technologies can also give power plants more flexibility to reduce production during times of drought or high demand for other uses.

INTRODUCTION: WATER, CLIMATE CHANGE, AND THE LOW CARBON ECONOMY

Climate change poses multiple, sometimes conflicting, challenges for the public and private sectors alike. Given the urgent need to reduce greenhouse gas emissions, the development of low-carbon energy production is a priority, but sustainable land use is also important, as is the need to adapt to new constraints on key resources, most notably water. The implications for public policy and for business are not fully understood.

This report, based on research conducted as part of a partnership between the business leaders' initiative 3C (Combat Climate Change) and the Stockholm Environment Institute, examines the potential impact of low-carbon electricity generation technologies on water resources – and the implications of potential water management challenges on both fossil-fuel and renewable-energy technologies.

Water is used to produce and process fuels, in hydroelectric power generation, for cooling in power plants, for energy storage, and in carbon storage technologies. Yet understanding how a low-carbon transition will interact with the management of water resources is challenging, for two main reasons:

- There are inherent uncertainties in climate scenarios that affect estimates of future water supply.
- The future technical potential and system penetration of low-carbon technologies for energy storage, carbon capture and sequestration (CCS) and electricity generation is difficult to anticipate, as are their associated water requirements.

Fully recognising these uncertainties, here we seek to illuminate some critical issues at the intersection of water and energy planning, with a focus on electricity production, as a means of highlighting issues of potential concern and opportunities of potential interest. First, we explore the ways in which a changing climate and associated hydrologic changes could affect water availability for electricity generation strategies, and to provide some sense of the scale of the potential challenges. We then explore the water requirements of different electricity generation technologies – both those currently in widespread utilisation, and emerging low-carbon technologies. Finally, we offer a case study of California, a state with significant water constraints that has also been a U.S. leader in renewable energy development. The report closes with some thoughts on important considerations regarding efforts to discover to management tradeoffs between electricity generation and water management.

We should note that this is by no means an exhaustive review of the links between climate, water and energy, which go well beyond electricity generation; the water management implications of expanded biofuels production, for example, are a pressing research topic. Second, reflecting the authors' regional expertise, this report focuses significantly on electricity generation systems in the United States. We provide some data from other regions, but also believe that the insights from our analysis can have broad relevance and utility.

UNDERSTANDING ELECTRICITY GENERATION/WATER TRADEOFFS

Water is required for nearly all forms of energy production, and there is growing interest in the interactions between water and energy – often referred to as the water-energy nexus – especially in the context of climate change. This is reflected in several recent reports (Cooley *et al*. 2011; WEF 2008; WEC 2010; Hoff 2011; Averyt *et al*. 2011). Part of this nexus includes the link between water and electricity generation. Fossil-fuel and nuclear-powered plants, which generate the majority of many countries' electricity, rely heavily on water for cooling. Hydropower generation depends on river flow and reservoir storage and contributes to substantial manipulation of hydrologic regimes. This makes water availability a key factor in power plant operation and site selection, and in planning for the long term. In addition, continued economic and population growth, coupled with expected thermal extremes due to climate change, will likely increase electricity demand and, in turn, the amount of water required for electricity generation. The goal of this section is to lay out the context within which the implications of a transition to a low-carbon future on water resources, under climate change, can be explored.

Since the 1990s, global electricity generation has increased 40 per cent from around 12,000 TWh to over 20,000 TWh in 2009 (IEA 2011b). The majority of the world's electricity is now generated from fossil fuels, and thus the power sector is a major source of greenhouse gas (GHG) emissions, accounting for 36.5 per cent of total GHG emissions in 2005 (WRI 2010). In the United States, the power sector is also one of the largest water users; 49 per cent of total U.S. water withdrawals in 2005 were for thermoelectric power (Kenny *et al*. 2009). And although water *consumption* – the amount of water that is used and not released back into the system – was only 1/40th of withdrawals in 2005, the National Energy Technology Laboratory has estimated that a planned 18 per cent increase in thermoelectric generating capacity between 2005 and 2030 will increase the sector's water consumption by 28 to 49 per cent (NETL 2008). This could be significant in places where water resources are already under pressure and in regions where climate change could impose additional stress on water management.

Water requirements for power generation depend on several factors: the level of reliance on water-intensive technologies, the type of cooling technology, as well as electricity demand – which is driven by population growth and levels of development. In general, however, as we explain in more detail in the next section, fossil-fuel electricity generation is typically more water-intensive than most alternatives, though some low-carbon technologies have significant water requirements. This is particularly the case for nuclear power, which requires large volumes of water for cooling, but also for some categories of solar power generation technologies.

In this context, it is easy to see how vulnerable power generation can be to climate change impacts such as heat waves, droughts and extreme rains – especially in areas where water systems are already stressed. In times of water scarcity, power plants either have to curtail output or shut down to prevent a water crisis, or continue operating and risk exacerbating the issues. Table 1 provides some recent examples, which illustrate the kinds of challenges that both water and electrical utility managers increasingly face.

What these examples indicate is that electricity generation is very sensitive to climate change and, specifically, to water shortages. Thus, in order to be sustainable, a transition to low-carbon electricity will have to take into account the trends in water availability, and avoid contributing to water supply problems. The rest of this section focuses on how climate change in particular could affect hydrologic regimes and impact electricity generation. It is important to note that while the problems are global, the solutions will have to be specific to local energy-water systems. The evidence also suggests that current approaches to water and electricity management may not be robust enough to cope with the effects of climate change (UNFCCC 2011).

Table 1: Climate change and the water-energy nexus

Year	Region/ Country	Climate Event	Consequence
2011	Texas, USA	Drought and heat wave	Farmers, cities and power plants compete for the same limited water resource. After the driest 10 months on record (since 1895), at least one plant was forced to cut its output, and some plants had to pipe in water from new sources to maintain generation. If the drought continues throughout 2012, several thousand MW of electricity may go offline (O'Grady 2011; Averyt *et al*. 2011).
2010	Washington, USA	Low snow-pack, followed by heavy rains	Given changes in precipitation regime, the peak streamflows were not aligned with power projections, straining hydropower generation and affecting electricity prices (Averyt *et al*. 2011).
2010	Lake Mead, Nev. & Ariz., USA	Low water levels	Lake Mead water levels in dropped to levels not seen since the 1950s, prompting the U.S. Bureau of Reclamation to reduce the Hoover Dam's generating capacity by 23% (Walton 2010; Averyt *et al*. 2011).
2007	North Platte River, Neb. & Wyo., USA	Extended drought	After a 7-year drought, power generation from the North Platte Project, which includes hydropower plants on North Platte River, was reduced by about 50%. A Laramie River coal-fired Station (Wyo.) was at risk of insufficient cooling water and avoided impacts to power production by consuming water from local irrigation districts and the High Plains aquifer (Cooley *et al*. 2011; Averyt *et al*. 2011).
2006	Midwest	Heat wave	Nuclear plants forced to reduce output at time of peak demand; high river water temperatures, typically used for cooling, forced a Minn. plant to reduce generation by 50% (Averyt *et al*. 2011).
2006	Uganda	Drought	Hydropower capacity was reduced by one-third, with subsequent electricity shortages (Collier 2006).
2003	Germany	Heat wave	Increased river water temperatures led German authorities to close a nuclear power plant and reduce output at two others (Cooley *et al*. 2011).
2003	France	Heat wave	Increased river water temperatures induced the French government to shut down 4,000 MW of nuclear generation capacity (Cooley *et al*. 2011).
2001	Brazil	Drought	Combined with increased energy demand, country experienced 'virtual breakdown' of hydro-electricity and reduced GDP (Bates *et al*. 2008).

FUTURE WATER AVAILABILITY FOR POWER GENERATION

Water availability is affected by land cover change, urbanisation, industrialisation and engineering schemes designed to maximise human access to water, such as reservoirs, irrigation systems and inter-basin transfers. As pressure increases on scarce water sources, conflicts between energy production and water availability are expected to continue. Future climate change may have a profoundly negative effect on water resources, but impacts are regional or even more narrowly location-specific. Water-energy conflicts are already particularly acute during droughts and summers (see Table 1, above), when energy demand is high and water availability is low. Climate change will affect the distribution and availability of water supplies; new areas may become water scarce and drought-prone (Cooley *et al*. 2011).

In recent decades, population and economic growth, shifts in lifestyle and consumption patterns, and the expansion of water supply systems have led to an increase in water use. The Intergovernmental Panel on Climate Change (IPCC) *Special Report on Emissions Scenarios* (Nakicenovic *et al*. 2000), from which we later draw conclusions about climate impacts on water, depicts a more affluent global society across all emissions scenarios. Depending on the technologies and policies employed, there could be significant consequences for total water use. For now, the biggest component of water use is irrigation, accounting for 70 per cent of total water withdrawals and more than 90 per cent of water consumption globally (Bates *et al*. 2008). Water used to generate electricity is also a major component of water withdrawals.

The World Health Organization estimates that one-third of the world population lacks a sufficient water supply, and by 2050, the United Nations estimates that half the population will live in nations that are short of water (World Energy Council 2010). Population growth and urbanisation, coupled with the expected impacts of climate change, could result in 400 million to 1.7 billion additional water-stressed people by 2020, 1 to 2 billion more by 2050, and 1.1 to 3.2 billion more by 2080 (Arnell 2004; Kundzewicz *et al*. 2007). These global numbers are based on defined water stress thresholds, but they do suggest the severity of the water crisis already underway in certain parts of the globe.

A recent global-scale analysis of threats to freshwater resources found that nearly 80 per cent of the world's population is exposed to high levels of threat to water security due to catchment disturbance, pollution, water resource development, biotic factors, or any combination thereof (Vörösmarty *et al*. 2010). Regions of intensive agriculture and dense settlement show particularly many threats to fresh water, including much of the USA, most of Europe (except Scandinavia and northern Russia), large portions of central Asia, the Middle East, the Indian subcontinent and eastern China. Over 30 of the world's 47 largest rivers show moderate threat levels at the river mouth, with eight rivers showing very high threats in terms of human water security (Figure 1).

As populations and cities grow, we could witness a shift in society's valuation of water, resulting in changes in how we prioritise domestic, industrial and agricultural demands. In the Millennium Ecosystem Assessment (MEA) scenarios, per capita domestic water use in 2050 is broadly similar in all regions, reflective of a commitment to reducing the number of people in water-stressed situations (MEA 2005). One way to achieve this, as Vörösmarty *et al*. (2010) underscore, is to invest in technology to limit exposure to threats. The second map in Figure 1, which shows the adjusted incident threat to human water security, highlights how high-income countries such as the USA and parts of Europe have reduced their vulnerability, whereas other regions, such as most of sub-Saharan Africa, have made few such investments (and may not have had the capacity to do so). It cannot be forgotten, however, that water management technological investments to reduce vulnerability can also have negative impacts on the status of aquatic ecosystems.

REGIONAL CHANGES IN WATER AVAILABILITY DUE TO CLIMATE CHANGE

A substantial body of work has emerged on the regional implications of climate change on water resources. Climate change is a key driver of changes in the availability, allocation, production and consumption of energy and water. Climate impacts will generally exacerbate water stress and competition between uses in areas where such competition is already present, creating significant management challenges for water and energy security (World Energy Council 2010). In some places, increased annual runoff could lead to increased total water supply – though this could also be a short-lived effect if the increase is due to melting snow pack and glaciers. And even if the increased runoff is beneficial, the gains are likely to be offset by the

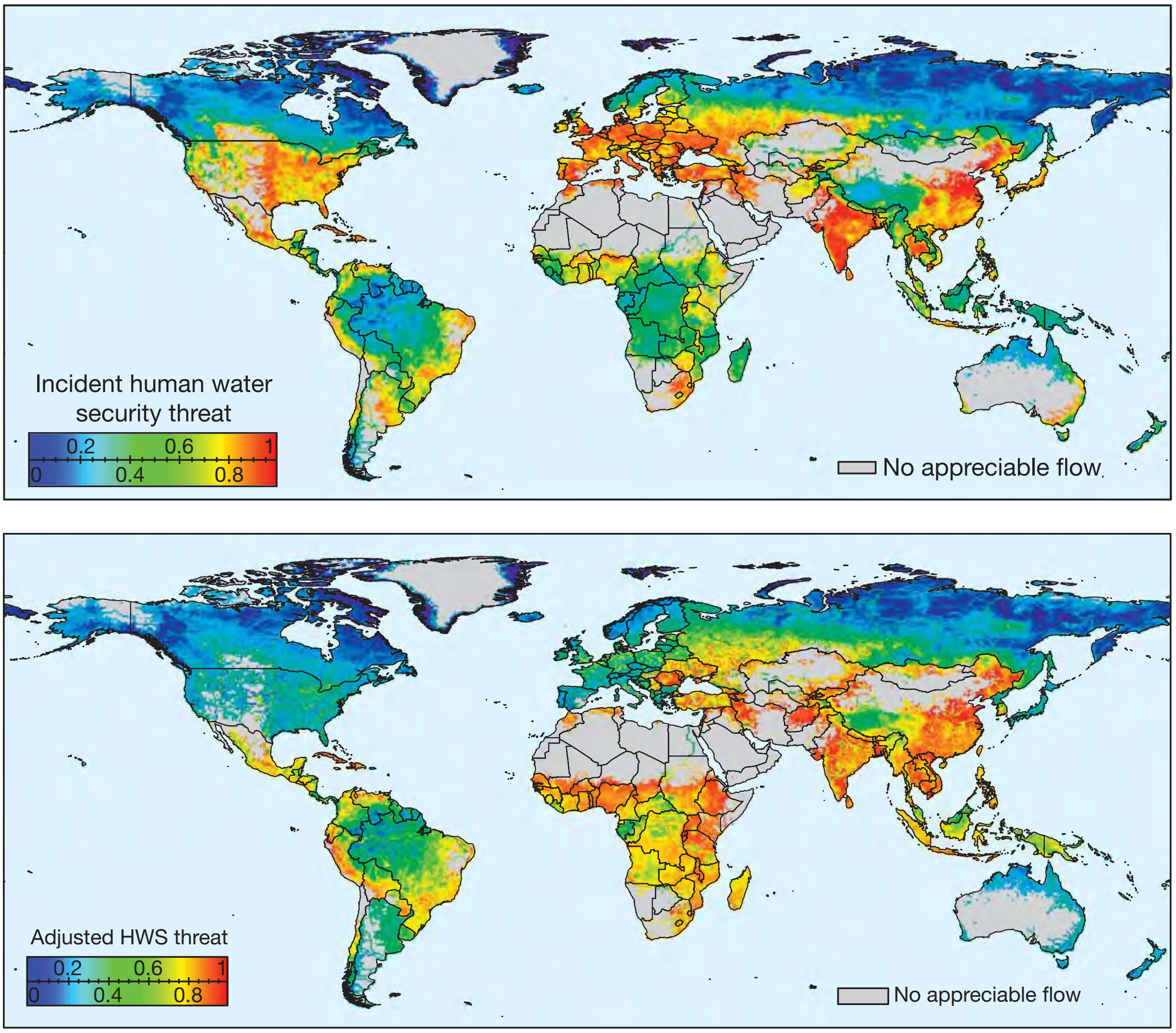

Figure 1: Global geography of incident threat to human water security (top) and adjusted geography after accounting for water technology benefits (bottom) Source: Vörösmarty *et al*. (2010).

negative consequences of altered precipitation regimes that affect agricultural cycles, water quality, flood risks and operating rules for existing water infrastructure such as reservoirs, hydropower facilities, and drainage and irrigation systems.

The best available information on climate impacts on water is contained in the materials produced for the IPCC *Fourth Assessment Report* (Kundzewicz *et al*. 2007) and in a 2008 IPCC technical paper, *Climate Change and Water* (Bates *et al*. 2008), which is a comprehensive synthesis of water-related insights drawn from the IPCC review.

The IPCC SRES report projects a general increase in precipitation in the tropics and at high latitudes, and generally decreases in the subtropics (Nakicenovic *et al*. 2000). By 2050, the IPCC projects that annual average runoff and water availability will increase by 10 to 40 per cent at high latitudes and in wet tropical areas, while decreasing 10 to 30 per cent in dry regions at mid-latitudes and in the dry tropics, some of which are already water-stressed. In general, rising global water and air temperatures will disrupt rainfall patterns and reduce the available amount of water in some regions (Kundzewicz *et al*. 2007; Bates *et al*. 2008; U.S. Global Change Research Program 2009).

Rising ambient temperatures are associated with glacial melt in the Alps, the Himalayas, the Andes and elsewhere. Over the course of the 21st century, water that is currently stored in glaciers and annual snow cover will decline in volume, constraining the availability and use of glacial melt water (Kundzewicz *et al*. 2007). This is already being observed. Since the 1960s, scientists estimate that mountain glaciers, worldwide, have lost an estimated 4000 cubic kilometres of water. The rate of loss has been increasing since the 1980s, with 10 to 20 per cent of Europe's alpine glacier ice lost in less than two decades (WWF 2003). Over the last 30 to 40 years, tropical glaciers between Bolivia and Venezuela have lost 15 per cent of their surface area (Vergara *et al*. 2007).

Countries that rely on glacial melt will initially see an increase in stream flow, then a sudden drop as glaciers accumulate mass much more slowly (or not at all); this is of particular concern for the Himalayan and Andean regions. Andean glaciers are very sensitive to climatic fluctuations and El Niño events, while their non-tropical counterparts have a long period of accumulation in the winter. Changes in snow and glacier melt of the Himalayas will affect 25 per cent of China's population and hundreds of millions in India (Stern 2007; Bates *et al*. 2008). In Latin America, changes in available glacier melt water will affect the supply for multiple upstream and downstream users, including agriculture, urban water utilities, and hydropower (Escobar *et al*. 2011). Given the contribution of glacier melt water to dry-season stream flows, it is not surprising that substantial hydropower production has occurred in glacier-fed rivers. The links between climate, water and energy in these systems must be further explored.

Disruptions in rainfall patterns are problematic globally. Mulligan *et al*. (2011) modelled climate impacts on river basins in Africa (Limpopo, Niger, Nile, Volta), Asia (Indus-Ganges, Mekong, Yellow, Karkheh) and South America (Andes, São Francisco). While their research focused on food security, their findings on basin vulnerability can be extended to hydropower generation and the availability of cooling water, where relevant. In general, basins with high precipitation seasonality and, in particular, basins with concurrent high temperatures and low precipitation are the most vulnerable to constraints on water availability and reduced dry-season productivity. A substantial portion of Africa is vulnerable by this definition; more than 75 per cent of Africa's continental area is arid and semi-arid, and 75 per cent of Africans live in these regions (Vörösmarty *et al*. 2005; Douglas *et al*. 2006).

In Asia, the Yellow River basin has become warmer and drier from the 1960s to 2000 and long-term annual runoff has decreased about 25 per cent since the 1950s due to both decreased precipitation and increased withdrawal for irrigation (Mulligan *et al*. 2011). For monsoonal basins, such as the Mekong and Ganges, precipitation seasonality contributes to supply vulnerability, especially where low precipitation and high temperatures occur in the same season (ibid.). In Central Asia, changes in runoff could significantly affect countries such as Tajikistan, currently the third-largest hydropower producer in the world (Bates *et al*. 2008). Australia and parts of New Zealand are expected to face significant water supply issues, and drought is already a serious problem. In both countries, climate change is expected to have mixed effects on energy production, reducing water availability for some hydropower and thermal power plants, but also increasing winter stream flow in some areas (Bates *et al*. 2008).

Change in river flow, discharge and groundwater recharge will result from altered precipitation regimes, higher temperatures, and increased evaporation rates. The correlation between changes in stream and river flow and projected climate change depends on the area, but any reduction in rainfall has serious implications in arid and semi-arid regions because of the small difference between rainfall and potential evapotranspiration (Ludwig and Moench 2010). For example, in West Africa, precipitation declined by 20 to 40 per cent in the period 1968-1990 compared with 1931-1960 (Bates *et al*. 2008). In colder regions, stream flow is typically related to snowmelt, and changes in precipitation and temperature will change the timing of melt, with a range of implications for reservoir storage, hydropower generation and downstream flood management.

In places where availability of surface water is expected to decrease during certain parts of the year, there may be an increased reliance on groundwater to meet demand. For example, in India, 50 per cent of irrigation water is groundwater. Higher reliance on groundwater, coupled with reduced groundwater recharge, could prove to have extreme adverse effects on water supplies in some regions (Ludwig and Moench 2010; Bates *et al*. 2008).

CLIMATE CHANGE AND ELECTRICITY GENERATION

Climate change will affect electricity demand by changing demand for cooling and heating. At the same time, climate change could constrain energy production by limiting water supplies for hydropower generation and thermal cooling. Expected warmer temperatures will reduce the efficiency of thermal power plants and of transmission and distribution lines (Sathaye *et al*. 2011). The efficiency of various cooling technologies will be affected differently. Warmer temperatures affect dry-cooling systems more than wet-cooling ones (see below for more information on different cooling technologies). To compensate for these losses, power plants will have to increase their output with commensurate increases in the total water withdrawn and consumed; it is possible that in some cases, the efficiency loss could negate the benefits of switching to dry cooling (Averyt *et al*. 2011).

Performance of hydropower facilities is sensitive to changes in precipitation and temperature that affect river flow, glacial melt water, reservoir storage and evaporation rates and subsequently generation capacity (Maurer *et al*. 2009; Harrison *et al*. 2005; Arnell 1999; Gleick 1986; Nash and Gleick 1993). For example, in the Colorado River Basin, every 1 per cent decrease in precipitation results in a 2 to 3 per cent drop in stream flow, and every 1 per cent decrease in stream flow results in a 3 per cent drop in power generation (U.S. Global Change Research Program 2009). Bates *et al*. (2008) cite several studies that project future conflicts between water supply, flood control, hydropower and minimum stream flow (required for ecological and water quality purposes) under changing climatic and hydrological conditions. To compensate for reduced hydropower capacity, managers may have to increase reliance on other sources of electricity (Averyt *et al*. 2011).

In 2008, hydroelectricity contributed about 10 per cent of the EU's electricity generation and 60 per cent of total renewable power (IEA 2011b). By the 2070s, hydropower potential in Europe is expected to decline by 6 per cent, but with significant regional variations: a 20 to 50 per cent decrease around the Mediterranean and semi-arid Southern Europe, a 15 to 30 per cent increase in Northern and Eastern Europe, and a stable hydropower pattern for Western and Central Europe (Bates *et al*. 2008; Lehner *et al*. 2005). In Northern Europe, climate change could lead to *more* rainfall and even increase hydropower potential by 20 to 40 per cent (Andréasson *et al*. 2007).

Hydropower is a major electricity source for many Latin American countries and is vulnerable to large-scale rainfall anomalies due to El Niño and La Niña, as well as from climate change (Escobar *et al*. 2011; Bates *et al*. 2008). Glacier retreat affects regional hydropower generation, as is already occurring in Bolivia and Peru, and further retreat and disappearance of small glaciers is expected to affect more of Peru as well as Colombia (Bates *et al*. 2008; Ramírez *et al*. 2001). Most of the effects are expected to be negative, but in Ecuador, for example, some scenarios project increases in precipitation that could allow for a hydropower expansion (Cáceres-Silva 2000).

Escobar *et al*. (2011) review the hydropower generation of four regions in South and Central America: Southern Cone, Andean Group, Caribbean and Central America (see Figure 3). The Southern Cone produces the most hydroelectricity (484 TWh), while the Andean group produces 166 TWh. Countries in the Caribbean region and Central America produce less energy overall, and, with the exception of Costa Rica, are less reliant on

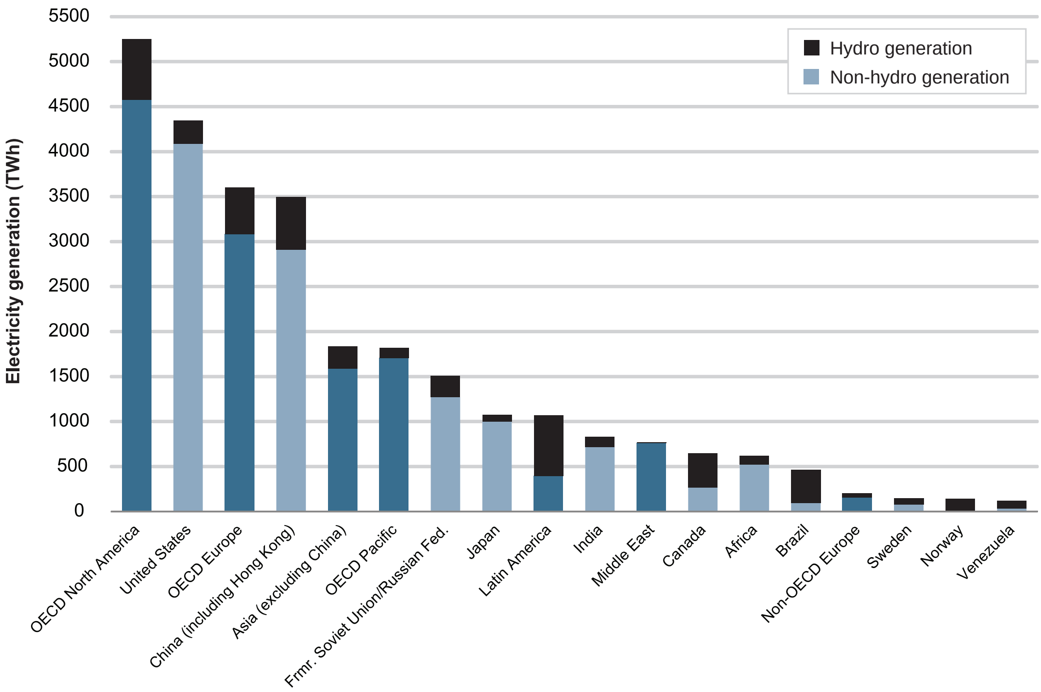

Figure 2: Prevalence of hydropower in 2008 electricity mix, by region and country

Source: Authors' calculations based on IEA Energy Statistics & Balances *(IEA n.d.)*

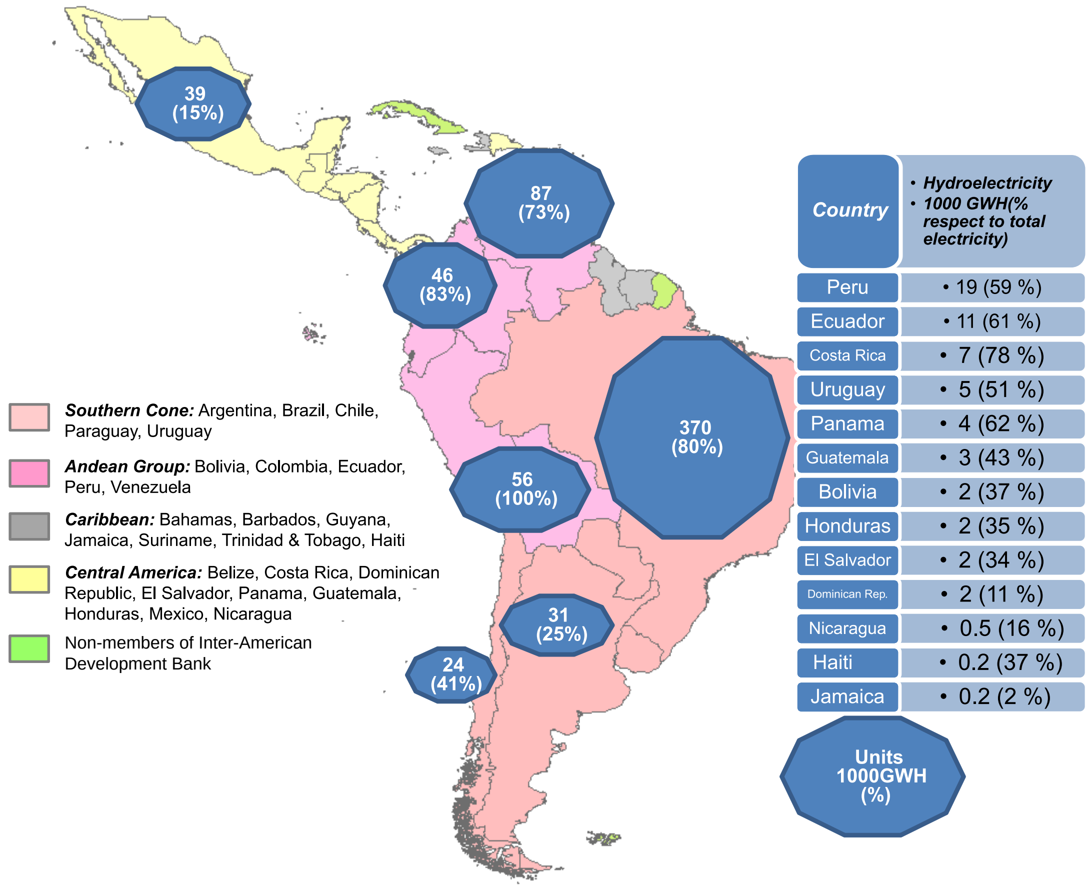

Figure 3: Hydropower generation in Latin America

Source: Escobar *et al*. (2011)

hydroelectricity. For Latin America as a whole, hydropower is currently the source of about two thirds of the electricity generated in the region, and more than half of the new generating capacity to be built is expected to come from hydropower (Ray 2010). Estimates of the share of Latin America's hydropower potential that has been exploited range from 21 to 38 per cent, depending on whether technical or economically feasible potential is measured; either way, it is clear that significant untapped potential still exists (Escobar *et al*. 2011), although climate change could influence the scope of this potential.

Looking at Africa, Collier (2006) suggests that an over-reliance hydropower by some countries "carries considerable risk", given the region's climate sensitivity. At the same time, he estimates that of the 290 GW economically feasible hydropower potential in Africa, only 7 per cent is developed, creating a large opportunity for least- and less-developed countries such as the Democratic Republic of the Congo, Cameroon and Ethiopia, which have the largest potential. If a low-carbon economy is one that relies in the world's ability to expand hydroelectricity capacity, the technology's climate sensitivity will need to be accounted for.

CONTEXTUAL SUMMARY

At this point is should be clear that water plays an important role in the productions of electricity and that possible changes in hydrologic regimes associated with climate change could impose significant challenges to both electricity and water managers. Against this backdrop, efforts to mitigate future climate change through a transition to a low-carbon future are unfolding. This raises the critical question of how a transition towards low-carbon electricity generation could change the electricity-water interplay, with the possibility that these changes could be negative, or positive.

A secondary question relates to the choice between low-carbon electricity generation technologies, with the most prominent currently being nuclear and hydropower, given that the water management implications of different technological choices are so varied. The scope of this variation is explored in the next section of the report.

ENERGY TECHNOLOGIES AND WATER USE

With these concerns in mind, we now take a closer look at the different water requirements of a range of electricity generation and carbon management technologies: the currently dominant ones, and low-carbon alternatives.

Water use is measured in two ways: withdrawal and consumption. Withdrawal involves removing water from a source and either returning it to the source, or making it available elsewhere. Consumption indicates that the water is not available for return or reuse, typically due to evaporation. The vast majority of water used in electricity generation is withdrawn but not consumed; however, technology shifts that reduce withdrawals may also increase consumption (NETL 2008; Kenny *et al*. 2009).

CONVENTIONAL TECHNOLOGIES' WATER USE IN ELECTRICITY PRODUCTION

Conventional coal, natural gas, oil and nuclear (even thought nuclear is a low-carbon technology, we discuss its water use here as a conventional source) power plants account for 90 per cent of electricity generation in the United States and 81 per cent of electricity worldwide (US-EIA 2011b; US-EIA 2012c). These thermoelectric power plants heavily rely on water for cooling. In the United States, thermoelectric power plants accounted for biggest share of freshwater withdrawals (41 per cent) followed by crop irrigation (37 per cent) and public supply (13 per cent) in 2005 (Kenny *et al*. 2009), but have a much smaller contribution in terms of overall water consumption.

Thermoelectric power plants primarily require water for cooling, but smaller amounts of water are also required for resource extraction, fuel processing and post-combustion activities. The three methods of thermoelectric cooling being used today are once-through, wet-recirculating and dry cooling installations. Once-through cooling systems take water from a source, circulate it through the plant, and return almost all the water to the system, albeit at a warmer temperature, with only about a 1 per cent reduction in volume. In wet-recirculating cooling systems, less water is withdrawn from the source, but 70 to 90 per cent of the water withdrawn is lost through evaporation. In the USA, the 1977 Amendments to the Clean Water Act, which regulate cooling water temperature, have driven a trend towards recirculating cooling systems in recent years, resulting in a slight reduction in withdrawals by the power sector (see Figure 4); in addition, electricity generators have turned to these systems when they are unable to site power plants near water sources.

Dry-cooling systems use air and reduce water consumption by over 90 per cent, but they are expensive and less efficient. According to estimates from the U.S. government's National Energy Technology Laboratory, 43 per cent of current thermoelectric power plants use once-through cooling, 56 per cent use wet-recirculating, and 1 per cent use dry cooling systems (DiPietro *et al*. 2009). Unless companies implement more dry-cooling systems or shift generation to non-thermal renewables, we may see an increase in overall water consumption by thermoelectric plants (World Energy Council 2010b). Furthermore, as our demand

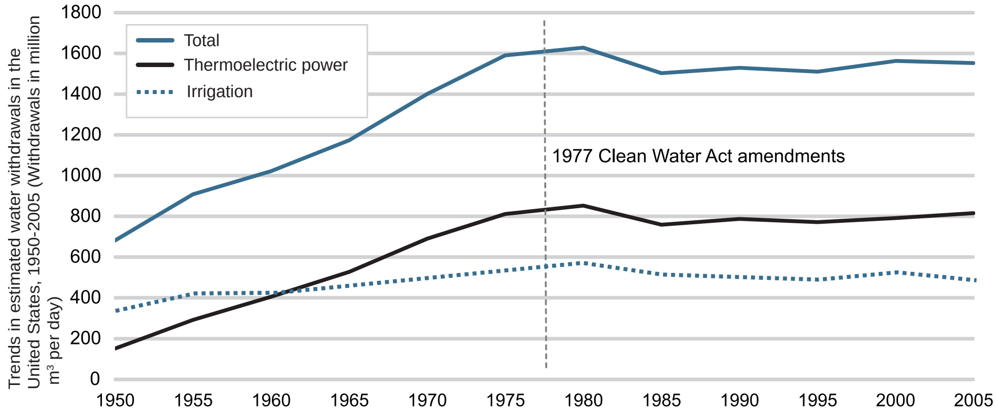

Figure 4: Trends in estimated water withdrawals in the United States, 1950–2005

Source: Authors' graphic based on data from Kenny *et al*. (2009)

for electricity continues to rise, the water dependence of many power plants puts the electricity sector and other water users at growing risk of potential conflict and tradeoffs (UCS 2010).[1]

Coal

Coal is the most widely used fuel for electricity generation: coal-fired power plants produce more than 42 per cent of the world's power supply (IEA 2010c). Depending on the specific features of a facility, coal-fired plants can require water for cooling, maintenance, fuel transport, and pollutant control. In the United States, coal plants are split between once-through and wet-recirculating cooling, with very few dry-cooled installations due to size, cost and efficiency constraints (U.S. Department of Energy 2010b).

In addition to affecting water requirements, the type of cooling system used in coal plants affects the overall efficiency of the plants. The U.S. Environmental Protection Agency estimates that coal steam power plants that use dry cooling produce about 7 per cent less power than those with wet recirculating systems (EPA 2001). Because coal power derives all of its energy from producing steam, unlike natural gas plants,[2] dry cooling has a greater impact on the efficiency of coal plants than of natural gas plants (GAO 2009).

A more efficient coal technology called integrated gasification combined-cycle (IGCC) is now being commercialised. This process is more expensive than conventional coal technology, but reduces particulate emissions by over 90 per cent and decreases water use by 20 to 35 per cent (Tenaska Energy 2008). While this is a promising technology, its implications in terms of water resources are not explored extensively in this report.

Natural gas

More than 20 per cent of global electricity in 2008 was produced with natural gas (US-EIA 2011b). Natural gas power plants can use simple gas combustion turbines, which do not require cooling, single-cycle steam turbines, or efficient natural gas combined-cycle (NGCC) power plants. In the United States, over 80 per cent of natural gas-powered generation comes from NGCC systems; another 12 percent use steam turbines, and 5 per cent use combustion turbines (US-EIA 2011c). Because gas combustion turbines require no cooling, the overall combined cycle system requires much less water for cooling than traditional steam turbine technologies associated with other thermo-electric generation technologies associate with other thermo-electric generation technologies (U.S. Department of Energy 2006).[3]

NGCC plants, meanwhile, require so much less cooling than other thermoelectric plants that they can more easily afford dry-cooling systems. In NGCC plants, dry cooling units can be one-third the size of those needed for a coal or nuclear plant with the same electricity output (GAO 2009). Unlike coal and nuclear power plants, which rarely use dry cooling, about 60 per cent of natural gas combined cycle plants in the USA use dry cooling technology; the remainder mainly use wet-recirculating (about 30 per cent), with less than ten per cent using once-through systems (U.S. Department of Energy 2008). Due to increased fuel efficiency and decreased water requirements, significant growth is expected in NGCC technologies.

Carbon capture and sequestration (CCS)

As previously noted, the energy sector is a major emitter of carbon dioxide (CO_2), the single largest driver of climate change. Electricity and heat production produced 43.5 per cent of global CO_2 emissions in 2008 (WRI 2010); according to the IEA, coal-fired power plants alone produce 28 per cent of global CO_2 emissions (IEA 2010c), and while they produce less emission natural gas generation plants also contribute to the fossil fuel total. Given the urgency of climate change mitigation and the enormous challenge of replacing all fossil fuels with low-carbon alternatives, many have embraced carbon capture and sequestration (CCS) as at least a short-term solution. If successfully applied, the technology could significantly reduce CO_2 emissions from fossil-fuelled power plants.

The IEA has argued that CCS is one of several crucial technologies for rapid mitigation; in a scenario that would halve energy-related CO_2 emissions by 2050, CCS would contribute 19 per cent of the reductions (IEA 2010a). Figure 4 shows the regional distribution of CCS deployment in that scenario.

1 For additional reading, see Mittal (2009), GAO (2009), DiPietro *et al*. (2009).

2 Natural gas combined-cycle and simple combustion turbines generate electricity at least in part using the force of the gases from the combustion, therefore requiring less cooling for the same electricity output.

3 It should be noted that water is also used to extract and refine natural gas; while conventional natural gas extraction consumes negligible quantities of water, hydraulic fracturing is more water-intensive, and also has raised concerns about potential water supply contamination (see, for example, Mielke *et al*. 2010).

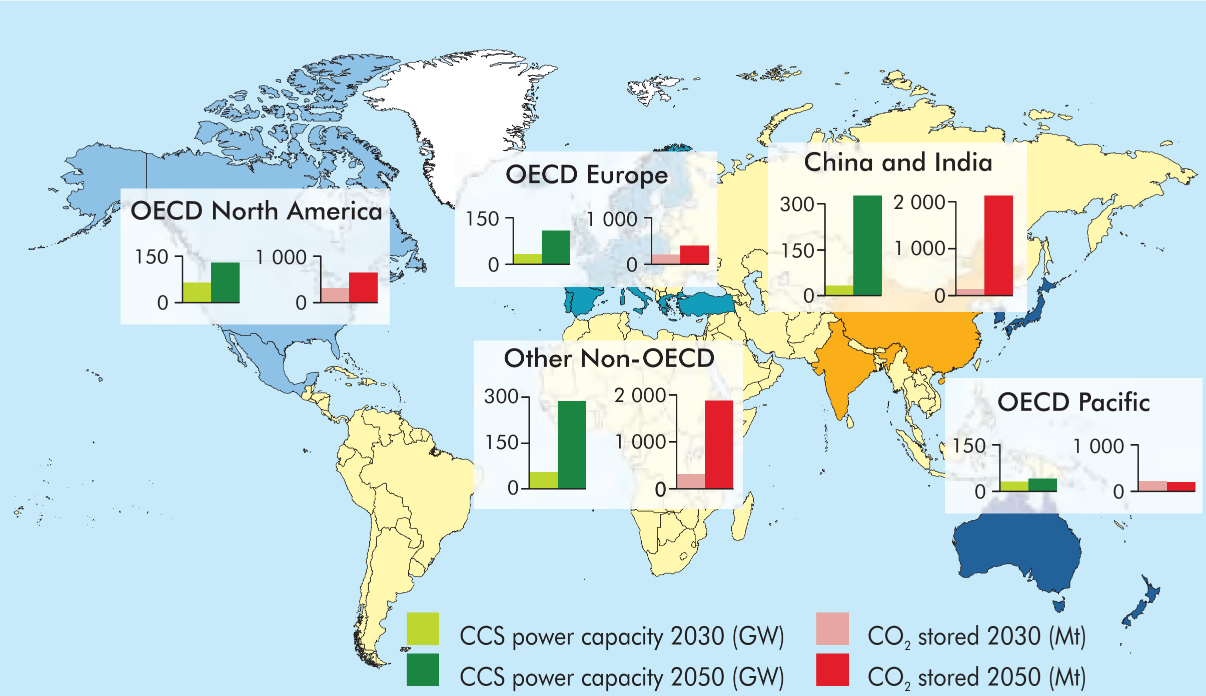

Figure 5: Regional deployment of CCS in power generation in the IEA's 'BLUE' scenario

Source: IEA *(2010a)*, Figure 3.12

Achieving such significant emission reductions with CCS, however, would require deploying the technology with more than 90 per cent of coal power, according to the IEA scenario; this may not be economically or technically viable with some existing plants (IEA 2010c). There are also efficiency losses; retrofitted plants may consume 20 to 30 per cent more fuel per unit of electricity supplied. For now, CCS remains in the early stages of development, with very limited deployments – mostly in small-scale pilots.[4]

CCS deployment also increases water use by power plants. Based on a review of research, the IEA finds that adding CCS to a coal-fired plant roughly doubles water withdrawals and increases consumption by one-third or more, compared with a baseline scenario (IEA 2010a, Chap. 17). Scenarios developed by the U.S. National Energy Technology Laboratory, meanwhile, show 41- to 95 per cent increases in raw water withdrawals, 45- to 91 per cent increases in raw water consumption, when coal-fired and natural-gas plants go from zero to 90 per cent capture of CO_2 emissions, with the largest increases for NGCC plants (NETL 2010, Exhibit ES-2).

As the latter suggests, water use with CCS will vary significantly depending on both the energy and the CCS technology involved. Many existing coal plants use a steam cycle to produce their electricity. These plants are most likely to use a liquid chemical solution called monoethanolamine (MEA) to absorb CO_2 from their flue gases after the coal has been burnt. MEA carbon capture methods are expected to be 90 per cent efficient in removing CO_2 from flue gases (Massachusetts Institute of Technology 2007). After combustion, CO_2 is diluted and captured by mixing it with air, an expensive process (Freese *et al*. 2008). After capture, the MEA solution will need to be cooled, dried and compressed to prepare it for transportation to a storage area. This same method can be used with NGCC natural-gas plants (NETL 2010).

Integrated gasification combined cycle (IGCC) plants are a newer and more promising option for use with CCS, as they produce electricity more efficiently while still allowing for capture of CO_2. A key advantage of these systems is that CO_2 can be separated out before combustion through a shift reaction. This process is expected to remove about 90 per cent of the CO_2 released from the power plant, although it would decrease overall plant

4 For a more in-depth review of CCS, see Varnäs, A., Nykvist, B., Chandler, C., Erickson, P., Nilsson, M., Han, G., Lazarus, M. and Hallding, K. (2012) *Driving Technological Innovation for a Low-Carbon Society: Case Studies for Solar Photovoltaics and Carbon Capture and Storage*, produced as part of a related 3C project.: http://www.sei-international.org/publications?pid=2049.

efficiencies by about 7 per cent (Massachusetts Institute of Technology 2007).

In all cases, the carbon dioxide removal process is energy-intensive and thus decreases the power output of the generator. Thus, in order to maintain the same power output as a plant without CCS, the fuel input needs to be increased. This means a larger boiler, steam turbine, and generator is necessary, proportionately more carbon capture maintenance equipment needs to be installed, and proportionately more water would be needed. For example, the median water consumption per MWh for a subcritical coal plant with wet-recirculating cooling is 1.78 cubic metres (m^3), but with CCS, it is 3.57 m^3 (Macknick *et al*. 2011).[5]

After carbon is captured at the power plant, it must be transported to a geologic sequestration site where it would ideally remain safe over the very long term (potentially hundreds of thousands of years). In terms of the kinds of geologic formations considered most suitable for CO_2 sequestration, researchers have identified depleted oil and gas fields, coal seams that cannot be mined, deep saline aquifers and deep ocean waters. In North America, these formations together represent a CO_2 storage potential of 1.8 to 20.5 trillion tonnes, the overwhelming majority attributed to saline formations (U.S. Department of Energy 2010c). Most U.S. coal-fired power plants are situated near potential CO_2 sequestration sites; for projects that do not have this advantage, it is expected that commercial projects would transport CO_2 through pipelines, increasing the costs and water requirements of the project (Massachusetts Institute of Technology 2007).

While CCS has important implications in terms of power plant efficiency and water consumption associated with coal and natural gas electricity generation, in a world where dramatic reductions in greenhouse gas emissions are sought, CCS might play an important role in a low carbon emissions future in the event that low-carbon technologies in and of themselves cannot be deployed to meet important climate mitigation objectives.

Nuclear

While technically a low carbon technology, we will discuss the water management implications of this generation technology here because of the similar cooling water requirements relative to fossil fuel based thermoelectric generation technologies and because nuclear power is an established generation technology, as opposed to emerging renewable technologies discussed in the following section. Nuclear power provides around 14 per cent of global electricity supply, with 374 GW of installed capacity in 30 countries at the beginning of 2010 (IEA 2010a). Concerns about overall safety, as well as about the disposal of spent fuel, have long made nuclear power controversial – and led to a strong backlash after the Fukushima disaster in Japan.[6] However, nuclear power is also attractive as a large-scale source of low-carbon electricity.

In terms of water use for fuel production, nuclear power rates relatively well. Drawing on an array of prior analyses, McMahon and Price (2011) estimate that nuclear fuel production consumes 0.004 to 0.022 m^3 per gigajoule (GJ) for raw materials (uranium) and 0.025 to 0.029 m^3 for processing; which compares favourably with coal-to-liquids technology (0.005 to 0.070 m^3 per GJ for raw materials, 0.14 to 220 for processing), oil (0.003 to 0.007 m^3 per GJ for traditional oil, 0.070 to 1.80 m^3 for oil sands, plus 0.025 to 0.065 m^3 for refining), or shale gas (0.036 to 0.054 m^3 per GJ for raw materials alone).

Nuclear power is comparatively water use intensive, however, when it comes to cooling. Nuclear power is a form of thermoelectric power, with the heat provided by a controlled nuclear fission chain reaction, rather than from burning a fuel. Nuclear reactors fall into two main categories: boiling water reactors (BWRs) and pressurised water reactors (PWRs); both systems boil water to make steam (BWRs within the reactor and PWRs outside the reactor). Nuclear reactors use cooling systems similar to those used in fossil-fired power plants, but they require more water per unit of energy, because they operate at a lower temperature and produce less electricity per pound of steam (EPRI 2002). Thus, while a fossil-fuelled plant with once-through cooling will withdraw roughly 76 to 189 m^3 of water per MWh, and consume about 1.1 m^3, a nuclear plant with the same cooling technology will withdraw 95 and 227 m^3 and consume about 1.5 m^3 (ibid.).

The distribution of cooling technologies in nuclear power plants is similar to those in coal-fired plants: 38.1 per cent once-through (vs. 39.1 per cent for coal), 43.6 per cent wet-recirculating (vs. 48 per cent for coal), and 18.3 per cent cooling ponds (vs. 12.7 per cent for coal); dry-cooling systems are used for only 0.2 per cent of coal generating capacity, and in no nuclear plants

5 Throughout this report, all measures given in gallons or litres in the original sources have been converted to m^3.

6 Not surprisingly, nuclear energy production declined somewhat in 2011; see Lucky, M. (2011) 'Global Nuclear Generation Capacity Falls'. *Vital Signs Online*, Worldwatch Institute, Washington, DC, 17 November. http://vitalsigns.worldwatch.org/vs-trend/global-nuclear-generation-capacity-falls.

(NETL 2008). Two factors are cited for not using dry-cooling systems in nuclear power plants: the high cost of operating large dry-cooling fans, and safety risks – since cooling is extremely critical for nuclear power (GAO 2009). It should be noted that in addition to cooling the steam, nuclear power plants also use water in a way that no other plant does: to keep the reactor core and used fuel rods cool. For safety reasons, these systems are kept running at all times, even when the plant is closed for refuelling (UCS 2007).

In the event of a serious accident (e.g. an overheated reactor), nuclear power plants are required by regulation to have an emergency supply of water that can supply cooling and makeup water needs for at least 30 days after the accident. These water sources, called Ultimate Heat Sinks (UHSs), are used to cool the reactor, which will continue to produce heat long after it is turned off. During an accident, a UHS may need to supply 38 to 114 m^3 of water per minute for emergency cooling purposes. A UHS can be the same water source used for power plant cooling (lake, river or ocean) or it can be a separate dedicated water supply (UCS 2007).

WATER USE BY LOW-CARBON TECHNOLOGIES

As the main objective of this report is to explore how a transition to a low-carbon economy in the electricity generation sector could exacerbate or lessen pressures on water resources, this section focuses on the water requirements associated with renewable energy technologies. Specifically, we look at hydropower, wind, solar, geothermal and biomass. As Figure 6 indicates, the use of these energy resources varies widely by region and country.

In 2007, 18 per cent of electricity generated worldwide came from renewable energy sources (IEA 2010b). Renewables' share had declined for several years because fossil-fuelled power grew much more rapidly than hydropower, by far the largest renewable power source (ibid.). However, efforts to mitigate climate change and foster the "green economy" have accelerated renewable-energy deployment in recent years, though in uneven patterns that reflect different countries' policy priorities. Thus, for example, Germany leads the world in solar PV capacity; China is increasing wind capacity faster than any other country, and the USA leads the world in bioenergy (IEA 2011c). Globally, the region with the largest share of renewable energy is Latin America, IEA data show, with 66 per cent of electricity in 2009 generated from hydropower alone (IEA n.d.).

Meeting the IEA's goal of halving global energy-related CO_2 emissions by 2050 would require doubling renewable generation by 2020, with double-digit rates for non-hydro renewables; the IEA scenario calls for wind to grow at an average of 17 per cent per year, and solar power, by 20 per cent – with this trend continuing

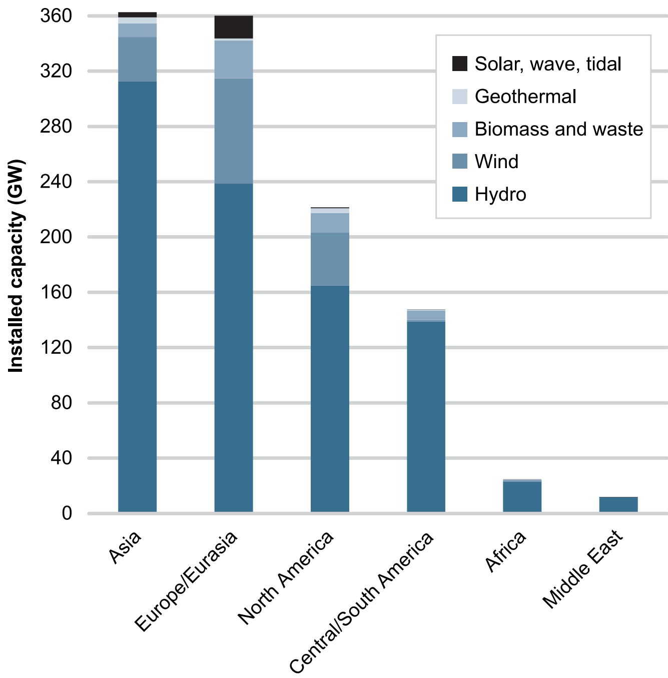

Figure 6: Installed renewable generation capacity by region, 2009

Source: U.S. Energy Information Administration (n.d., accessed April 2012) for many years (IEA 2011c). There is certainly room for growth: in 2009, only 1.36 per cent of the world's electricity came from wind power, only 0.33 per cent from geothermal power, and only 0.10 per cent from solar PV and solar thermal combined (IEA n.d.).

Yet while the climate benefits of low-carbon energy generation are clear, this does not necessarily mean that these technologies have no negative environmental impacts. One of the main areas of concern is water consumption; as will be explored in this section, some renewable energy technologies have water requirements that rival fossil-fuel technologies. Thus the expansion of renewable technologies in water-constrained regions will require careful consideration of the associated water requirements.

Hydropower

Hydropower is by far the most prevalent renewable source of electricity, accounting for 16.5 per cent of global generation in 2009, according to the IEA – more than nuclear energy (13.4 per cent) or wind, biofuels, geothermal, solar PV and solar thermal, waste and tide power combined (3.2 per cent) (IEA n.d.). It is also low-cost and can be adjusted to balance changing demands, which has made it an appealing option for industrialised and developing countries alike. Yet hydropower is unevenly distributed: of an estimated global potential of 16,400 TWh per year, 8,360 TWh is in the top five countries: China, the United States, Russia, Brazil and Canada, and another 2,500 TWh is in the next five countries – Democratic Republic of Congo, India, Indonesia, Peru and Tajikistan (IEA 2010d). Globally, an estimated 19 per cent of hydropower potential has been tapped, but this also varies dramatically by country: from 10 per cent in Russia, to 24 per cent in China, to 88 per cent in Switzerland (ibid.).

Hydropower is a low-carbon energy source, but not emissions-free. In a review of life-cycle emissions for various energy technologies, Weisser (2007) finds most emissions associated with hydropower arise during construction of the plant, especially the dam, though there can also be GHG emissions associated with the decay of biomass that has been flooded, and with land-clearing. Overall, the range of estimated life-cycle GHG emissions for hydropower is 1 to 34 gCO_2e/KWh, compared with 950 to 1,250 gCO_2e/kWh for coal, 2.8 to 24 gCO_2e/KWh for nuclear, 8 to 30 gCO_2e/KWh for on-shore wind, and 43 to 73 gCO_2e/KWh for solar PV.

In terms of water use, hydropower differs from other renewable technologies in that it doesn't consume water as part of the generation process, as thermal power plants do with cooling water. Most of the water that goes through a hydropower generation facility ends back in the river, where it is available to satisfy other uses. Still, hydropower is very disruptive to hydrological regimes, with both of the main approaches, dam-based generation and run-of-the-river generation, modifying river systems in unique ways.

Hydropower plants generate electricity from the energy of water falling from a higher elevation to a lower elevation. To control the flow, a dam is built to hold the water in a reservoir; the water is then released on demand to produce as much electricity as is needed. Dams typically create an on-stream barrier that physically divides river ecosystems, and the storage of water for later release changes natural flow regimes downstream. The volume of water is enormous: an estimated 12 billion m^3 per day flowed through U.S. hydroelectric turbines in 1995 (Solley *et al*. 1998).[7]

Moreover, while most of the water is released, hydropower projects with large storage reservoirs also lose significant amounts to evaporation: an estimated 14.4 million m^3 per day in the USA, or 17 m^3 per KWh (US-DOE 2006); this is 5 to 100 times the water consumption associated with coal-fired power plants (Macknick *et al*. 2011). Hydropower reservoirs often serve multiple purposes, however, such as irrigation, flood control, water supply, and recreation, which means that evaporation losses can't all be attributed to hydroelectric power (US-DOE 2006).

Hydropower technologies also vary considerably. Run-of-the-river hydropower generates electricity by physically removing water from a river, conveying it through a turbine set either in or beside the river, and releasing it back to the river at some distance downstream. A high-profile example is the hydropower operation at Niagara Falls in the USA. These technologies require little to no water storage and thus do not consume water through evaporation (US-DOE 2006); however, they do still substantially alter conditions in the bypassed river. This is one reason why some U.S. states allow only small hydropower (below some threshold) to qualify for contribution to renewable energy portfolio standards.

Hydroelectric plants can affect the temperature, chemistry, silt load and flow characteristics of the water, as well as the landscape through which it flows, affecting

7 This is 2.6 times the average annual runoff in the conterminous United States, Solley et al. note; this is possible because the same water can be used multiple times by successive dams, but each flow is counted towards the total.

the plants and animals that live in and near the river, up and downstream and as far as the deltas where the rivers feed into the sea (US-EIA 2012b). They may obstruct the migration of fish to their spawning areas, and the turbines kill 5 to 10 per cent of fish that pass through them. Reservoirs may displace human settlements and cover natural areas. And large-scale hydropower can sharply increase the risk of disasters, a major concern that has arisen with China's Three Gorges Dam.[8]

In summary, while hydropower will continue to plan and important role in future low-carbon electricity production, likely even expanding in regions where high untapped potential remains, the disruptive nature of hydropower generation means that it likely cannot expand unchecked. In addition, the close link between hydropower and hydrology, and the potential changes which climate change may impose on hydrologic regimes, suggests that hydropower may be exposed to vulnerabilities not associated with other low carbon technologies.

Solar

Solar power accounted for only 0.1 per cent of global electricity generation in 2009 (IEA n.d.), and even in countries that have deployed it aggressively, it provides only a small fraction of total electricity: 3 per cent in Germany, for example, in 2011.[9] However, solar power installations are increasing rapidly in both the industrialised and developing worlds, and the IEA has estimated that, with strong policy supports, solar technologies could provide 20 to 25 per cent of global electricity by 2050.[10]

Solar technologies are classified into two main categories: photovoltaic (PV) and solar thermal (concentrating solar power, or CSP) systems.

Solar PV technology directly converts solar radiation into electricity using photovoltaic semiconductors. At the end of 2010, the IEA estimates, the cumulative installed capacity of solar PV was roughly 40 GW (IEA 2011c); the IPCC has a lower estimate, 35 GW, including 13 GW added in 2010 (Arvizu *et al*. 2011). The solar PV process does not use water, but cleaning PV panels does use a modest amount, about 0.053 m^3 per MWh of electricity produced (Fthenakis and Kim 2010). Macknick *et al*. (2011), meanwhile, find the median water usage for utility-scale PV is 0.098 m^3 per MWh.

Solar thermal systems concentrate solar rays and use them to heat a liquid, solid or gas that is then used to generate electricity. Thus they build on existing knowledge of thermoelectric power; they are also scalable – from tens of KW to multiple MW, and can be combined with thermal storage to provide steady generation and/or adjust to changes in demand (Arvizu *et al*. 2011). The IEA describes solar thermal as a "promising technology for all regions with a need for clean, flexible, reliable power", and notes that because of its characteristics, it can also serve as an enabling technology to help integrate more variable renewable resources on grids (IEA 2010b).

Yet CSP, for all of its potential as a clean electricity generation technology, which is substantial, is likely the low-carbon technology with the most substantial implications for water management. Because solar thermal requires strong direct sun rays, however, it is most viable in very hot, dry areas (IEA 2011c). Only two countries currently have significant solar thermal capacity: Spain (632 MW at the end of 2010) and the USA (473 MW at the end of 2009), but projects are under development in many countries, including Algeria, Egypt, Morocco, Australia, China, India, Israel, Jordan, Mexico, South Africa and the United Arab Emirates (ibid.).

The IEA's CSP Technology Roadmap (IEA 2010b) describes four main types of solar thermal technologies, which are not equal in terms of their water management implications:

Parabolic trough systems, by far the most prevalent technology in commercial use today, consist of parallel rows of mirrors (reflectors) that are curved to focus the sun's rays. Stainless steel tubes filled with a fluid (synthetic oil in all currently used systems) collect the resulting heat and transfer it to heat exchangers, where the heat creates steam to run a turbine. The water used in the process is then cooled, condensed and returned to the heat exchangers. Most existing plants have little or no thermal storage.

8 See UPI (2012) 'China's Three Gorges Dam prompts more evacuations'. UPI, 19 April. Beijing, China. http://www.upi.com/Business_News/Energy-Resources/2012/04/19/Chinas-Three-Gorges-Dam-prompts-more-evacuations/UPI-89201334851239/.

9 See Eckert, V. (2011) 'German solar power output up 60 pct in 2011'. Reuters, 29 December. http://af.reuters.com/article/commoditiesNews/idAFL6E7NT1WK20111229?sp=true.

10 See International Energy Agency (2010) 'IEA sees great potential for solar, providing up to a quarter of world electricity by 2050'. Press Release (10)04, 11 May. http://www.iea.org/press/pressdetail.asp?PRESS_REL_ID=301.

Linear Fresnel reflectors (LFRs) are similar to parabolic trough systems but use long rows of flat or slightly curved mirrors to reflect solar rays onto a downward-facing, linear, fixed receiver. Their simple design lowers costs and facilitates direct steam generation, eliminating the need for heat transfer fluids and heat exchangers. They are less efficient than troughs, however, at converting solar energy into electricity, and cannot incorporate storage capacity as easily.

Parabolic dishes track the sun and concentrate the rays at a focal point above the centre of the dish. Most dishes are fairly compact, typically generating tens of KW or less, so hundreds or thousands would be needed for a large-scale plant. The dishes typically contain their own generator, eliminating the need for heat transfer fluid or cooling water, and offer the highest solar-to-electric conversion performance of any CSP technology.

Solar towers, or central receiver systems, use hundreds or thousands of small reflectors to concentrate the sun's rays on a central receiver on top of a fixed tower. Some use direct steam generation in the receiver; others use molten salts as the heat transfer fluid and transfer medium. The design can produce very high temperatures, increasing efficiency and reducing the cost of thermal storage.

Water consumption estimates by Macknick *et al*. (2011) suggest that along with the power generation technology itself, the cooling technology chosen makes a big impact on CSP systems' water use. They report median water consumption factors ranging from 0.019 m^3 per MWh (for Stirling-brand dishes), to 0.098 m^3 per MWh for towers with dry cooling, to 3.785 m^3 per MWh for Fresnel systems with tower (wet) cooling. One of the challenges with dry cooling is that it is less effective in hot and dry locations – the prime CSP sites – since the ambient air required for cooling is itself very warm, limiting its effectiveness for cooling and reducing the plants' efficiencies.

The U.S. Department of Energy conducted a study in the U.S. Southwest and found that dry-cooled CSP plants would especially be affected at temperatures above 100°F (38°C), where costs increased up to 10 per cent and electricity was reduced by 5 per cent (Carter and Campbell 2009). This means that these plants are less equipped to meet peak power requirements of the middle of hot days, when demand is the highest. In these cases a hybrid cooling system, which uses wet cooling for hot days in parallel with dry cooling, may be most appropriate. This approach limits overall water withdrawals and consumption, but dry cooling and hybrid systems are more expensive than wet-cooling systems (Smart and Aspinall 2009).

Geothermal

Geothermal systems currently produce only a very small portion of the world's electricity, 67 TWh in 2009, or 0.33 per cent of total generation (IEA n.d.). Geothermal energy uses heat extracted from the earth, which can be best accessed in tectonically active regions or "hot spots", such as around the "Ring of Fire" around the Pacific (Indonesia, the Philippines, Japan, New Zealand, Central America, and the U.S. West Coast), and the rift zones of Iceland and East Africa (IEA 2010a). Geothermal energy is immune to the seasons, weather or climate change impacts, and is thus considered a reliable source of baseload electricity in the regions where it is available. Global installed capacity is only 11 GW, but as part of its scenario to halve energy-related emissions by 2050, the IEA proposes near-doubling that by 2020, to 21 GW.

Geothermal power can be produced in steam plants, binary cycle plants or by enhanced geothermal systems. Steam systems use steam from the hot geothermal fluid that comes out of the ground to run a turbine. Binary systems can use lower-temperature fluids (less than 180°C) with a heat exchanger to boil a secondary fluid to drive a turbine. Enhanced geothermal systems circulate water in a closed loop from the surface wells into hot rock farther below (IEA 2010a).

Geothermal power plants have lower thermal efficiencies than fossil-fuel plants due to their lower operating temperatures, and thus have generally higher cooling water requirements per unit of electricity output: as high as 13.63 m^3 per MWh for binary systems with tower cooling, and 18.10 m^3 per MWh for enhanced geothermal systems with tower cooling, per Macknick *et al*. (2011). However, as with solar thermal, the choice of cooling technology can make a big difference: median water consumption with dry cooling is 0.51 m^3 per MWh for binary systems, and 3.22 m^3 per MWh for enhanced geothermal systems.

Biomass

Biomass is widely used for heat production, or for combined heat and power, but it is also used as feedstock for electricity production alone. The use of solid biomass, biogas and renewable municipal waste, and liquid biofuels for power generation has been rising steadily. *Renewable Energy Focus* (Hopwood 2012), extrapolating from Offermann *et al*. (2011), estimates global installed capacity at the end of 2010 at more than 54 GW, including more than 3 GW installed in 2010, and total generation in 2010 at 218 to 342

TWh, or 1.1 to 1.7 per cent of global power production (IEA n.d.). A handful of countries – the United States, Germany, Japan, Sweden, Brazil – are leading the way: among the Clean Energy Ministerial's 23 member countries, which include all the aforementioned, bioenergy power production has risen from about 140 TWh in 2000 to more than 200 TWh in 2009 (IEA 2011c).

Biomass feedstocks for power generation can include agricultural residues; animal manure; wood wastes from forestry and industry; residues from food and paper industries; municipal green wastes; sewage sludge; dedicated energy crops such as short-rotation coppice (eucalyptus, poplar, willow), grasses, sugar and starch crops (sugar cane, corn) and oil crops (soy, oilseed rape, jatropha, palm oil) (IEA 2007). Residues, wastes and bagasse are most commonly used for heat and power generation, but cheap, high-quality biomass could become scarce due to competing uses.

Biomass is considered a low-carbon energy source because the resulting CO_2 is offset by what had been absorbed by the plants (ibid.). It is also considered a water-intensive energy source, however, though water requirements for biomass vary widely based on the type of biomass used for electricity generation, geography, and how the area is irrigated (Fthenakis and Kim 2010). McMahon and Price (2011) find that biofuels production from corn, for example, requires 9 to 100 m^3 of water per gigajoule (GJ) just for the raw materials; sugar cane requires 108 m^3, and soy requires 50 to 394 m^3. (For comparison, coal is found to require 0.005 to 0.70 litres, and uranium, 0.004 to 0.022.)[11]

Wind

Wind is the second-largest renewable source of electricity, after hydropower, with 273 TWh produced in 2010, or 1.36 per cent of global generation (IEA n.d.). Wind capacity is increasing rapidly in Europe – where more wind power was installed in 2009 than any other electricity-generating technology – as well as in the United States, China and India (IEA 2010a). Wind power has grown by an average of 30 per cent per year over the last decade, but to achieve a 12 per cent share of global production, the IEA's target, an average of 47 GW would have to be added each year for the next four decades.

As noted earlier, wind is a very low-carbon power source (8 to 30 gCO_2e/KWh, per Weisser 2007), and can produce electricity on a large scale: the average new grid-connected turbine has a rated capacity of about 1.6 MW, and the largest turbines are now rated at 7 MW (IEA 2010a). Power production rises and falls with the wind, however, so wind needs to be combined with other electricity sources. From an environmental perspective, key issues include the amount of land required for onshore wind farms, noise, and interference with the flight paths of birds and bats (ibid.).

Because wind power uses no water for normal operation, the IEA finds it has a "considerable advantage" over most alternatives in water-scarce regions with ample wind resources (ibid.). Macknick *et al*. (2011) list wind power's water consumption as zero; Fthenakis and Kim (2010) estimate water consumption at 0.015 m^3 per MWh, for blade washing.

11 It should be noted that where rainwater is plentiful, irrigation may not be needed at all; also, use of residues or waste is considerably different, in this sense, from use of dedicated energy crops.

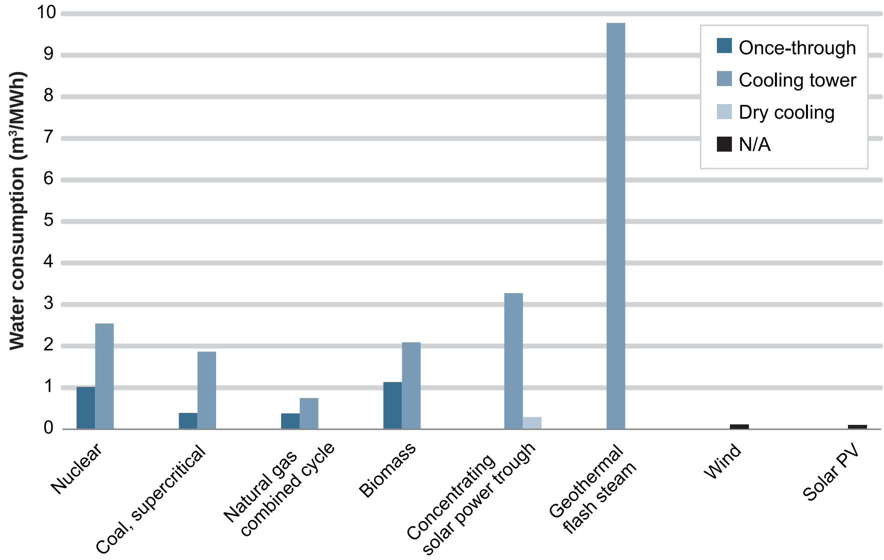

Figure 7: Water consumption by fuel and cooling technology during plant operation

Source: Macknick *et al.* (2011), Tables 1 and 2; values converted by authors from gallons to cubic metres [12]

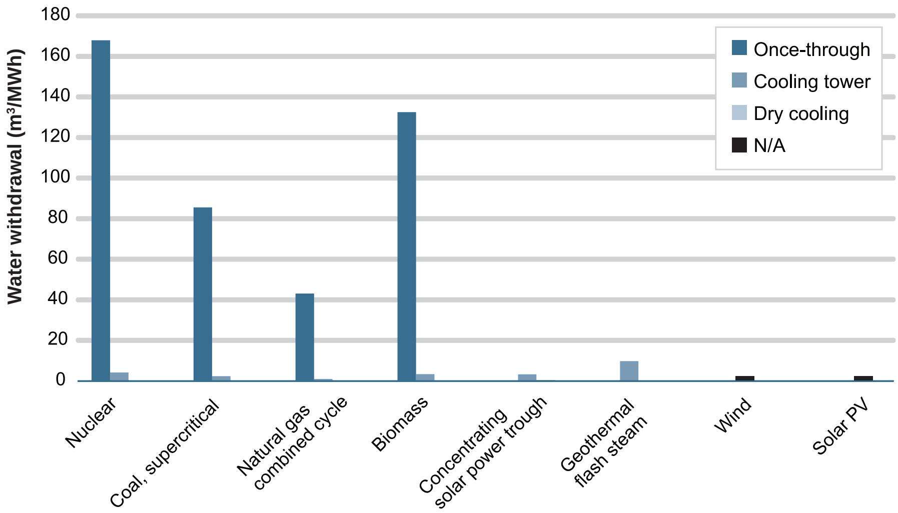

Figure 8: Water withdrawals by fuel and cooling technology during plant operation

Source: Macknick *et al.* (2011), Tables 1 and 3; values converted by authors from gallons to cubic metres. For solar PV, CSP, wind and geothermal, withdrawals are assumed to be equal to consumption

SUMMARY

Figures 7 and 8 show the trade-off between withdrawal and consumption for selected fossil-fuel and low-carbon energy technologies, using different cooling systems (if applicable). As noted before, once-through cooling has high withdrawals and low consumption, while recirculating options (such as cooling towers) limit withdrawals, but increase overall water consumption.

12 Geothermal flash steam systems can use freshwater or geothermal fluids for cooling. This value is for systems using geothermal fluids; the value for equivalent systems using freshwater is 0.04 m^3 per MWh. The emerging binary technology uses 13.63 m^3 per MWh with wet-recirculating systems, and 0.51 m^3 with dry cooling.

CASE STUDY: CALIFORNIA

In order to examine key challenges related to water and electricity tradeoffs, as well as potential solutions, we offer a case study here of the U.S. state of California. California is the country's most populous state, with 37 million residents per the 2010 Census, or 12 per cent of the U.S. population.[13] California also has the largest economy among the states, with a $1.89 trillion gross state product in 2009, or 13.4 per cent of the U.S. GDP; if California were a country, it would be the eighth-largest economy in the world, ranked between Italy and Brazil.[14] Over the past four decades, California has also become a recognised national and international leader in environmental policy, innovating in the arenas of emissions control and proactive research and policy-making on climate change mitigation and adaptation, and renewable energy in particular.

While each setting is unique, we believe that California can provide a useful analogue for other economies moving towards a low-carbon future. One challenge associated with this sort of effort, however, is to define a spatial domain that captures appropriate boundaries for integrated water and electricity analysis. The following sections attempt to provide information useful to the definition of an appropriate case study domain.

ELECTRICITY IN CALIFORNIA

In the electricity sector, California has a long history of supporting renewable energy development through market-based incentives.[15] In 2009, approximately 20 per cent of all electricity generated within California came from renewable resources such as wind, solar, geothermal, biomass and hydroelectric facilities; see Figure 9 for a distribution of California's electricity generation from 1997 to 2010. On average, 70 per cent of the electricity used in California comes from in-state generation, and the remaining 30 per cent is imported from the Pacific Northwest and the Southwest. The California Air Resources Board is in the process of identifying the fuel source of all power imported into California.

The picture that emerges in California is of a region that already relies extensively on renewables, and is in transition towards a lower-carbon future. It is worth noting, however, that natural gas is, and will likely remain, a very important fuel source for in-state generation, and that imports from the Southwest continue to include a great deal of coal-fired power. Thus there is clearly room for additional reductions in GHG emissions associated with electricity consumption in California, both in terms of in-state and imported generation. However, given the complex water management realities in the state, which we describe below, it is important to explore the water resources implications of the various low-carbon options available.

WATER IN CALIFORNIA

The California water system is one of the most extensive and complex in the world, comprising large reservoirs and long canals which serve to smooth temporal and spatial imbalances between water supply and demand. While most of the precipitation in California falls during the winter in the northern half of the state, most of the demand exists during summer months in the southern half of the state. In addition to the substantial development of water within the state boundaries, California also benefits from a substantial input of water from the Colorado River Basin to meet urban and agricultural water demand in its southern regions.

Figure 10 depicts the major features of the California water system, with facilities operated by the federal government shown in yellow, components of the California State Water Project shown in red, and facilities operated by local water management agencies shown in green. One pertinent feature of the California water system, as depicted in Figure 10, is the intersection of water imported into Southern California from the Colorado River and Sacramento/San Joaquin River systems. This intersection links service provision of supplies to several states, major metropolitan areas, vast tracks of irrigated agricultural, major hydropower facilities, and numerous thermal electricity generation

13 U.S. Census Bureau (2012) 'California'. State & County QuickFacts, 17 January. http://quickfacts.census.gov/qfd/states/06000.html.

14 U.S. Census Bureau (2011) *Statistical Abstract of the United States: 2012*. Table 672. Gross Domestic Product by Selected Industries and State: 2009. Washington, DC, US. http://www.census.gov/compendia/statab/cats/income_expenditures_poverty_wealth/gross_domestic_product_gdp.html. For ranking among world economies, see http://econpost.com/californiaeconomy/california-economy-ranking-among-world-economies.

15 See http://www.energy.ca.gov/renewables/index.html for an overview of the state's support for renewables in the past 15 years.

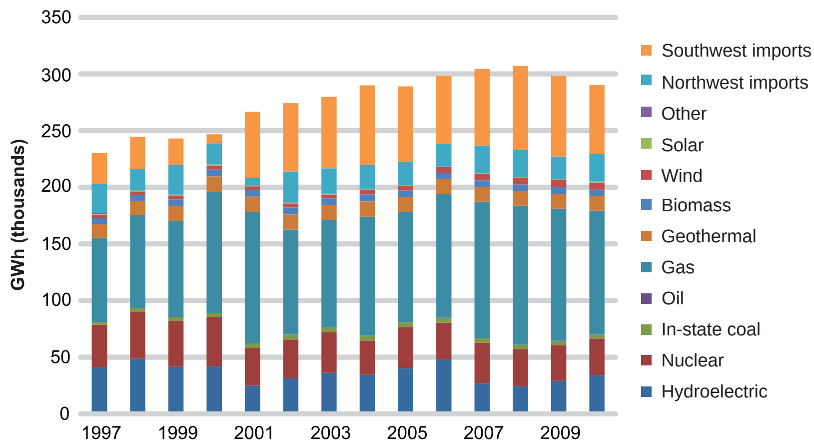

Figure 9: California electricity generation, 1997-2010 *Source: State of California (2011)*

plants. These connections tie California into much broader regional water and electricity considerations, again suggesting that California be considered within a wider regional context.

One major issue that the figure does not convey is California's reliance on groundwater withdrawals to supplement surface water use. In fact, more than half of the Southwest region's current and projected groundwater withdrawals take place in California (Ackerman and Stanton 2011). In terms of water used to generate electricity, power plants in the Southwest region withdraw an average of 370,000 m^3 of groundwater daily, tapping many aquifers already suffering from overdraft (Averyt *et al*. 2011).

California's surface water resources are also under stress. California hydrology can be characterised as Mediterranean and snow melt-dominated, with much of the annual runoff coming from the spring melt of snow that accumulates during the winter in the Cascade and Sierra Nevada mountains to the east of Redding, Sacramento, and Fresno. Over the last 30 years, the region has witnessed changes consistent with the climate change projections described earlier: warmer winters, reduced snowpack, and earlier spring stream flow runoff peaks (Barnett *et al*. 2008; Yates *et al*. 2008). The Southwest and Southern California are already areas of high water stress, and climate change threatens to make the situation more difficult.

WATER AND ELECTRICITY IN CALIFORNIA AND THE SOUTHWEST REGION

There is a growing interest within California – as in several other regions with water concerns – in unravelling the "water-energy nexus" – specifically, the linkages between electricity and water, which can be substantial. For example, the California State Water Project, with a net energy use of 2 million MWh per year (Trask 2005), is the single largest consumer of electricity in California, using the energy to pump water from northern to southern California to supply more than 20 million people and more than 350,000 hectares of irrigated farmland (Klein *et al*. 2005). Competing demands for water (agricultural, municipal, commercial, industrial, ecological and power) drive many of the resource conflicts in California.

In terms of the water required to generate electricity, however, California is a somewhat less precarious situation that other parts of the United States. This is because more than 98 per cent of cooling water used for thermoelectric generation in California is seawater, and a large proportion of that is used for cooling in the state's two nuclear power plants. However, the state may have to reduce its future reliance on sea water due to regulations on ocean thermal discharges. Already California has begun moving to closed-cycle cooling systems in new and repowered power plants to reduce impacts on coastal waters in response to the implementation plan for the Federal Clean Water Act §316(b) Regulation.[16] Moreover, although the proportion of freshwater use is low, the volumes of water in question are still large, more than 1.3 million cubic meters per day in 2000.[17] Thus conserving water in the electricity sector remains an important policy objective – particularly at the basin scale, where water allocations to electricity generation might need to be weighed against other local uses.

16 See http://www.waterboards.ca.gov/water_issues/programs/ocean/cwa316/.

17 See http://pubs.usgs.gov/circ/2004/circ1268/htdocs/table02.html.

Figure 10: The California water system

Source: California Department of Water Resources

In addition, given how California water and electricity management is nested within the wider Southwest regional context, it is important to note that the allocation of water for electricity generation can have significant regional impacts. Thus California has figured prominently in national and regional studies focused on the water-energy nexus (see, for example, Averyt *et al.* 2011; Cooley *et al.* 2011; Fisher and Ackerman 2011). Researchers have developed scenarios to project water usage for electricity in U.S. West and Southwest, and in California in particular, examining the implications of different fuel mixes and cooling technologies.

Cooley *et al.* (2011), for example, examine various options to address the water-energy nexus in the Intermountain West and find that installing dry cooling systems in the region would reduce water withdrawals by 30 to 48 per cent and consumption by 20 to 38 per cent

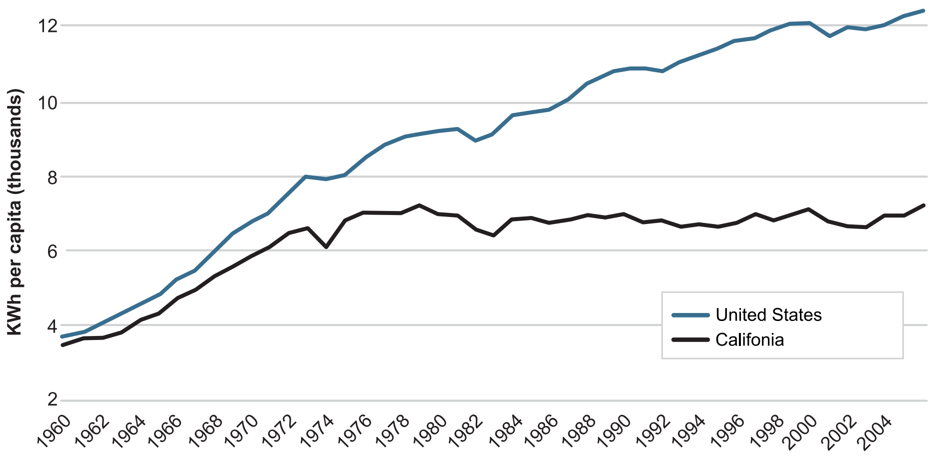

Figure 11: Per capita electricity sales in California and the USA, 1960-2004

Source: California Energy Commission (2007), Figure ES-2

in 2035 compared with 2010 levels, depending on the extent to which dry cooling systems were deployed. The most significant water reductions are achieved by combining dry cooling with changes to the regional electricity generation portfolio (e.g. greater efficiency, less coal, more wind, natural gas and hydropower); this reduces withdrawals by as much as 71 per cent and consumption by as much as 45 per cent below 2010 levels. One common insight from these studies is that it is not safe to assume that renewable energy sources will use less water than fossil-fuel technologies – as our own review of the technologies globally also suggests, some renewables have substantial cooling water requirements.

CALIFORNIA'S RENEWABLES PORTFOLIO STANDARD

It is clear that California is grappling, on a large scale, with many of the issues we identified in our review of water-electricity interactions. Thus its experiences could be instructive for other U.S. states – and countries and regions elsewhere in the world – that may find themselves in similar situations as they pursue low-carbon energy solutions. Another key factor that makes California a valuable case study is that it has adopted a major state policy, its Renewables Portfolio Standard (RPS), to drive emissions reductions in the electricity sector. This provides a very specific study subject with tangible real-world implications. Thus our case study focuses on the projected emissions *and* water use impacts of the RPS. In addition, we investigate the possible impacts of deliberate modifications to the RPS to favour technologies that could conserve water while simultaneously supporting emission reduction efforts.

California has had aggressive energy efficiency and renewable energy policies in place for over 30 years. As a result, California's per capita electricity use has remained relatively stable since the early 1970s, while the national average has increased by 50 per cent (Figure 11). Electricity-related emissions are significantly lower on a per capita basis in California than the U.S. average.

California's policy approach is multi-pronged and cuts across many sectors, with the greatest emphasis on electricity generation and transportation. In 2006, California's Legislature passed the Global Warming Solutions Act, often referred to as Assembly Bill 32 (AB32).[18] AB32 creates a comprehensive, multi-year program to meet a state-wide greenhouse gas emissions reductions goal of returning to 1990 levels by 2020. In 1990, electricity generation contributed 26 per cent of total emissions in California (110.6 million tonnes CO_2e), second only to transportation, which contributed 35 per cent of emissions. In 2004, the electricity sector produced 25 per cent of total emissions, 119.8 million tonnes CO_2e (Rogers *et al.* 2007).

California's RPS programme began in 2002, with the goal of increasing the share of renewable energy in the state's electricity mix. The original RPS required investor-owned utilities (IOUs), electric service providers, and community choice aggregators to increase procurement from eligible renewable energy resources to 33 per cent of total procurement by 2020. With the passage of AB32, California raised its ambitions, and as of April 2011, a 33 per cent Renewable Electricity

18 For the bill text and detailed information about AB32, see http://www.arb.ca.gov/cc/ab32/ab32.htm.

Standard (RES) applies to all electricity retailers in the state, including publicly owned utilities (POUs). The timeline calls for 20 per cent of retail sales to be covered by eligible renewables by the end of 2013, 25 per cent by the end of 2016, and 33 per cent by the end of 2020 (see Figure 12).

Beginning with the original RPS, California's energy policy has followed an electricity "loading order", or a preferred sequence for meeting electricity demands. Further increases in energy efficiency and demand-side reductions are the first response strategy; renewable energy electricity generation is second, and clean and efficient natural gas-fired power plants are third (CPUC and CEC 2008). This policy has a lot to do with the stabilisation of per capita demand, the increasing contribution of renewables, and the prominent role played by natural gas generation in the State.

The RPS defines renewable as "nearly inexhaustible sources" that can quickly be replenished; the California Energy Commission (CEC) certifies which deliveries are eligible according to specific requirements. Certified fuels include biomass, geothermal, landfill gas, solar photovoltaic (PV), solar thermal, wind, and *small* hydroelectric facilities (30 MW or less) (State of California 2007).

CASE STUDY TECHNICAL APPROACH

For this case study, we conducted a scenario analysis using a self-contained model for California created with a software tool developed by the Stockholm Environment Institute: the Long-range Energy Alternative Planning (LEAP) system.

With LEAP, we built an integrated electricity and emissions model, using data on current and recent historical electricity consumption and generation (Kavalec and Gorin 2009), existing power plant capacities and generation by fuel and technology (State of California 2011), and emission inventories from the electricity sector (Rogers *et al*. 2007). We then investigated three scenarios up to 2020, which is the target horizon of the current RPS. The electricity demand module in the model was informed by the California Energy Commission's 2010-2020 forecast (Kavalec and Gorin 2009), which contains historical (1990 to present) and electricity demand projections to 2020. Electricity demand is unchanged across all scenarios analyzed.

Generation capacity by fuel and technology vary among the scenarios as described below. The imported power mix was folded into the total capacity mix, reflecting the fact that the RPS governs all electricity deliveries in the state. This is part of the rationale for the ongoing California Energy Commission effort to produce an inventory of the sources of electricity imports from the wider Northwest and Southwest regions. For each power generating technology, water intensities for withdrawals and consumption were incorporated into the model, using estimates from Macknick *et al*. (2011) and Averyt *et al*. (2011). Figure 13 illustrates median water withdrawal and consumption, by fuel and cooling technology, for the types of power plants now generating electricity for California. Note that these estimates are for total water use, not differentiating between freshwater and seawater.

Scenarios

Under this case study three scenarios are posited. These are based on California's RPS documentation, which

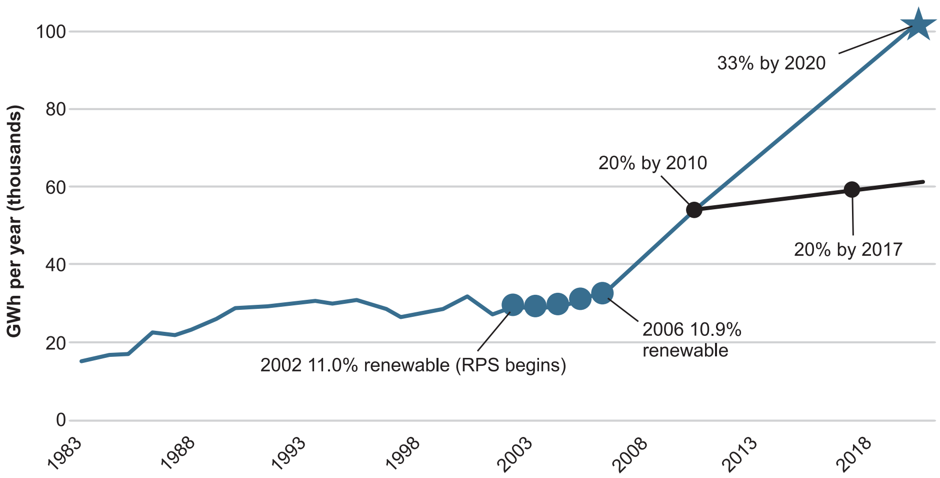

Figure 12: Progress toward California's RPS: Estimated generation from renewables, excluding large hydro

Source: California Energy Commission (2007), Figure 4-3

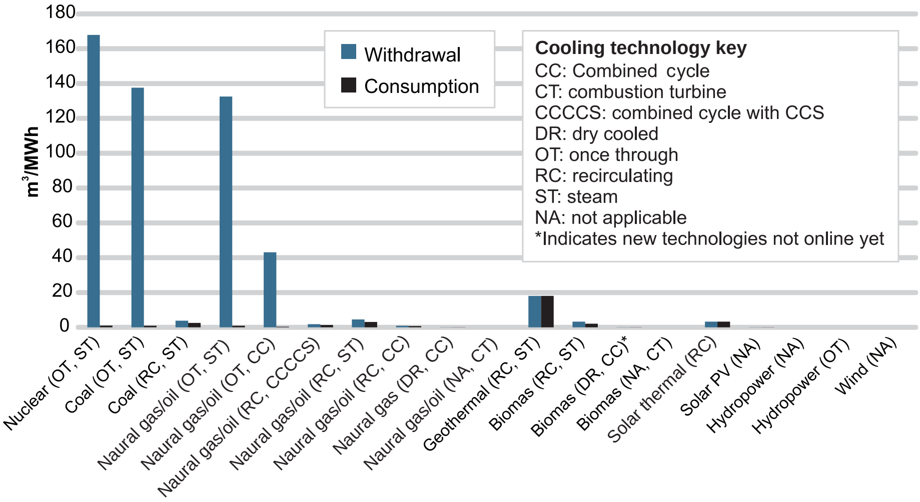

Figure 13. Water withdrawal and consumption rates, by cooling technology, used in model

Sources: Authors' analysis, using Macknick *et al*. (2011) and Averyt *et al*. (2011) water use data.

lays out a reference case – what is assumed would happen without the RPS – as well as the RPS trajectory, each with different assumptions about changes in the power supply mix from the base year (2010) to 2020. Although the RPS is already a legal mandate and thus is technically California's business-as-usual (BAU) pathway, separating the RPS from the reference case makes it easier to understand the implications of the RPS on water and emissions which should be helpful for other jurisdictions considering similar policy initiatives. A third scenario, which we call RPS+Technology, maintains the basic power supply mix, but adds water-saving cooling technologies and other changes that aim to maximise the combined emissions and water conservation benefits. This scenario has been developed primarily to explore the possible future, without extensive focus on what is the most "optimal" future.

The **Business As Usual (BAU)** scenario assumes that the current share of fuel-technology mixes will continue to meet demand through 2020, as demand increases to 316 TWh from 281 TWh in 2010.

In the **Renewables Portfolio Standard (RPS**) scenario, the fuel mix changes gradually from 2010 to 2020 to reflect additional renewable capacity totalling 18.6 GW that utilities have recently contracted to bring on-line in response to the RPS standards.[19] The planned additional capacity includes 12.2 GW of solar power and 5 GW of wind power, with the remainder from biomass, geothermal and small hydroelectric. In the model, these additional capacities come online gradually to 2020, replacing non-renewable sources (coal, natural gas, nuclear and large hydropower).[20] The technologies are assumed to be the same as are currently being used within a specific portfolio category. For example, 70 per cent of current solar capacity in California is from solar thermal technologies that are more water-intensive than PV installations, and under this scenario this share is assumed to remain constant through 2020.

California's RPS program did not explicitly consider water constraints in its formulation. In the **RPS+Technology** scenario**,** we model potential changes to the RPS in response to water constraints that may impose themselves on the system.[21] The basic mix of technologies stays the same, but within individual categories, adjustments are made. In the solar power category, we assume a switch from 70 per cent solar thermal and 30 per cent PV to a 50-50 mix by 2020. Once-through systems are assumed to be incrementally switched to wet-recirculating, and wet-recirculating is incrementally switched to dry-cooling (see Table 2 below). These technology shifts affect power plant

19 See http://www.energy.ca.gov/portfolio/contracts_database.html and http://www.energy.ca.gov/2008publications/CEC-300-2008-005/index.html.

20 Hydropower installations above 30 MW do not qualify under the RPS standards.

21 This is one of only several options to reduce water demand from solar power. As Averyt *et al*. (2011) note that the developer of the 370-megawatt Ivanpah solar thermal project under construction in California's Mojave Desert has chosen to use dry cooling, so the facility will consume 90 per cent less water per unit of electricity than typical wet-cooled CSP plants.

Table 2: Modified technology mix under the RPS+Technology scenario

Cooling Technology/ Fuel	2010 Coal	2020 Coal	2010 Biomass	2020 Biomass	2010 Natural Gas	2020 Natural Gas
Combustion (no-cooling)			50%	50%	20%	10%
Once-through	10%	0%			19%	2%
Recirculating	90%	100%	50%	25%	61%	61%
Dry cooling combined cycle				25%		10%
Recirculating + CCS						17%

efficiency, and the model reflects this. We assume a roughly 5 per cent efficiency loss for switching from recirculating to dry cooling; and about a 7 per cent loss from adding carbon capture and sequestration (CCS) to recirculating combined cycle natural gas plants in California (DiPietro *et al*. 2009). The assumption here is that all CCNG plants in California are equipped with CCS by 2020. Table 2 summarises the changes:

We should stress again that the goal of this case study scenario is to explore interactions between carbon and water considerations, and no claim is made that such an assumption is "optimal" from any economic or financial perspective.

SCENARIO RESULTS

Generation

Figure 14 shows how total generation by fuel type would change from 2010 to 2020 under the BAU and RPS scenarios (note that the RPS and RPS+Technology figures are the same). We assume that the total generation stays the same in 2020; the key difference under the RPS scenario is the additional share of generation from renewables, from 25 per cent in 2010 to 34 per cent in 2020, with concomitant reduction in natural gas, coal and nuclear generation. The major change in the generation mix is the dramatic increase in proportion of solar power in 2020, from less than 1 per cent of total generation under BAU to 8 per cent under the RPS scenario.

Emissions and water implications of California's electricity sector

Under the BAU scenario, by 2020, annual emissions, water withdrawals and water consumption all increase relative to the 2010 baseline (Figures 15 to 17). Annual emissions are 13 million tonnes CO_2e higher by 2020; annual water withdrawals increase by 1422.97 million m^3, while annual water consumption rises by 97 million m^3.

Under the RPS scenario, annual emissions drop by 2 million tonnes CO_2e, driven by reduced generation from fossil fuels and increased reliance on renewables. The decline in emissions is relatively small, however; in essence, the penetration of the low-carbon economy offsets the increased demand from a growing population. Annual water withdrawals, meanwhile, increase by 2.5 million m^3 (Figure 16), driven primarily by the heavy reliance on water-intensive solar thermal generation. Annual water consumption increases even more than under the BAU scenario, by 218 million m^3,

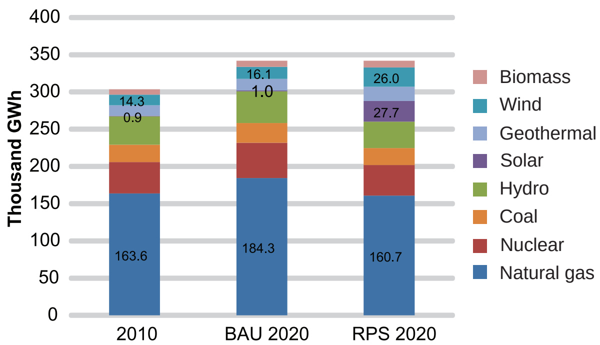

Figure 14: Simulated electricity generation by fuel type for the BAU and RPS scenarios

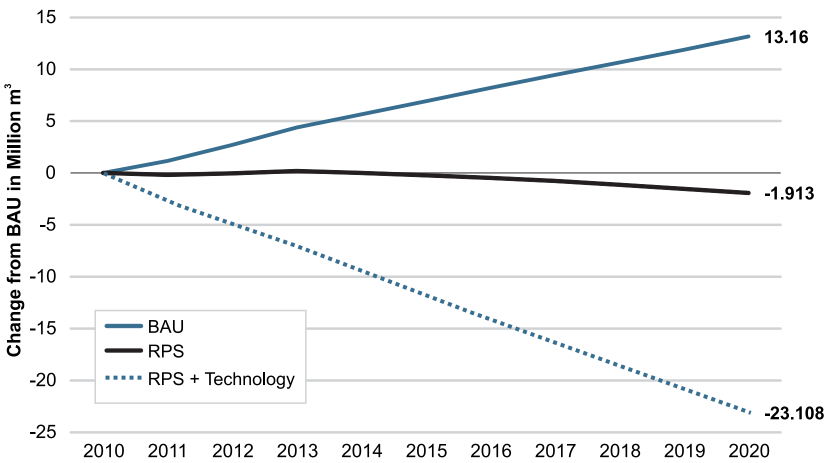

Figure 15: Change in GHG emissions under the three scenarios

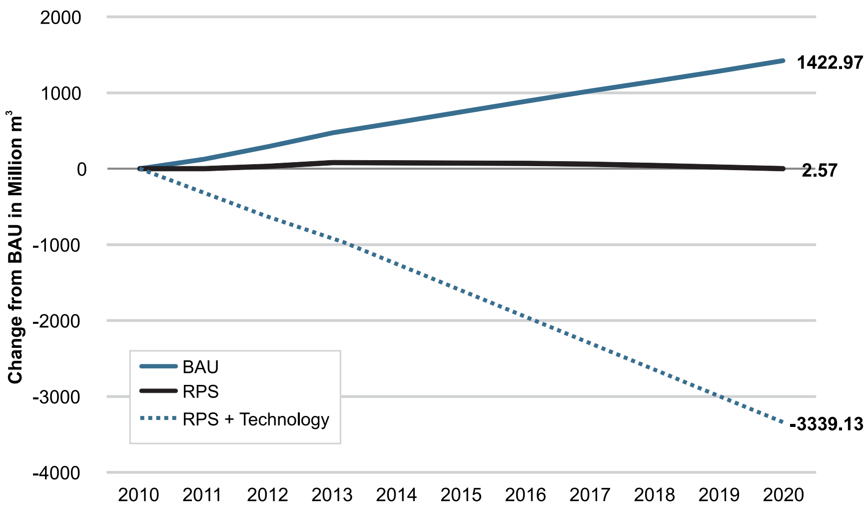

Figure 16: Change in water withdrawals under the three scenarios

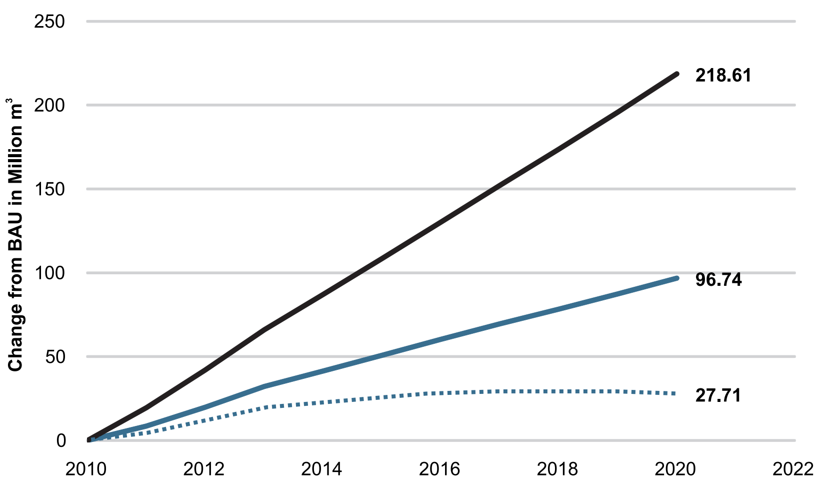

Figure 17: Change in water consumption under the three scenarios

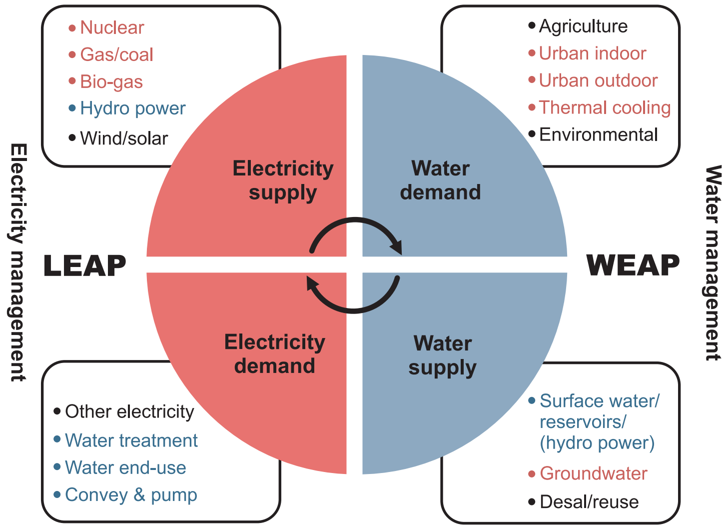

Figure 18: Water and electricity elements represented within the WEAP and LEAP models

given the dominant nature of circulating cooling technologies for solar thermal generation. This result raises an important question. Is it possible to imagine and strategy that would allow for reduced emissions while simultaneously reducing pressure on water resources.

This is the idea we sought to explore under the RPS + Technology scenario, where both emissions and water withdrawals decline considerably compared with BAU, while water consumption rises modestly, comparatively far less than under the other two scenarios. The deep reductions in emissions come about through the introduction of CCS, which captures an estimated 80 to 90 per cent of emissions at CCNG facilities (assumptions follow Thambimuthu *et al*. 2005). Reductions in water use result from the adoption of alternative cooling technologies and through the replacement of solar thermal installations with PV systems. Again, it should be noted that we offer this not as a blueprint for California – or for anyone else seeking to reduce both emissions and water use – but as an illustration of the profound impact of different technology choices in the low-carbon economy. The results are shown in Figures 15 to 17.

DECISION SUPPORT TOOLS FOR WATER AND ENERGY PLANNING

We end this case study with a discussion on the value of the type of decision support tools used in the above analysis. Advanced water and energy decision support tools such as SEI's WEAP and LEAP can be used to robustly investigate the water-energy nexus. These software packages support scenario-based planning and are accessible to a large community of users, with licenses given at no cost to nongovernmental organisations, government agencies, and academic institutions in developing countries. Ongoing technological innovation, focusing on the Southwestern USA, is linking these energy and water tools (Figure 18). The WEAP model will inform water supply availability as driven by hydroclimatology for multiple, competing demand sectors, explicitly including thermoelectric cooling. Innovation within WEAP allows tracking of the electricity demand for the water sector (for pumping, treatment and transport), which is then passed to LEAP. The LEAP model simulates electricity demand, which is met by generation via a mix of fuel types, conversion and cooling technologies, under current and future scenarios. This coupling allows both sides of the water-energy nexus (water intensity of electricity generation as well as electricity intensity of the water sector) to be dynamically evaluated. Add to this LEAP's built-in emissions factors database, and what we have is an integrated water-energy-emissions framework that will be most valuable to planners.[22]

22 To learn more about LEAP, visit http://www.energycommunity.org. To learn more about WEAP, visit http://www.weap21.org.

POLICY AND TECHNOLOGICAL SOLUTIONS

Given the potential exposure of electricity generation to water resource constraints, especially in the context of climate change, and the pressures that energy-sector demand could place on vulnerable supplies, it is important to understand how these conflicts can be minimised. Our case study highlights some options; here we identify some additional strategies, many of which are already built into California's Energy Plan. While the particular set of available strategies will be different in each water management context, many of these options could be applicable in a wide range of settings.

EFFICIENCY IMPROVEMENTS AND DEMAND REDUCTION

One way to decrease water use in the electricity sector is to reduce the overall demand for electricity by improving energy efficiency. There is significant potential in three key areas: devices that consume energy; electricity transmission and distribution systems; and power plants themselves.

The U.S. Energy Information Administration estimates that 86.9 TWh of electricity – 2.1 per cent of the country's total net generation – was saved in 2010 due to demand-side energy efficiency measures (US-EIA 2011a, Table ES1). If you assume this electricity came from coal power (as nearly 45 per cent of the U.S. power supply did in 2010), that translates into 162 million m^3 in reduced water consumption.[23]

After electricity is generated in power plants, it must be transmitted over power lines to be distributed to users. Some electricity is lost in the process of moving electricity over long distances – 6.3 per cent in 2010 in the USA (US-EIA 2012a, Table 10); 4 to 8 per cent in 2009 in much of Europe; 5 per cent in China and Japan; but as much as 15 per cent in Argentina and Turkey, and 24 per cent in India.[24] Clearly there would be great benefits from decreasing these losses. Even greater power savings could be attained by deploying "smart grids" to monitor and manage the transport of electricity and coordinate the needs and capabilities of generators, grid operators and end-users for maximum efficiency. The IEA estimates smart grids could reduce projected peak demand increases by 13 to 24 per cent from 2010 to 2050 (IEA 2011a) – and in the process, reduce water demand for electricity generation.

Improving power plants' thermal efficiency could also reduce water demand – although the relationships are complex. All else being equal, a more efficient plant will require less cooling, because more of the energy produced during combustion goes to powering the turbine, and less into waste heat. But the technologies used also make a difference – so, for example, Macknick *et al*. (2011) find that supercritical coal-fired plants have slightly higher median water consumption and withdrawal factors than less-efficient subcritical plants (1.87 vs. 1.78 m^3 consumed per MWh, and 2.31 vs. 2.01 m^3 withdrawn). And cooling technologies that save water can also reduce plants' efficiency, especially in hot, dry climates. These trade-offs will have to be carefully weighed in order to find the best solution for each site.

RECYCLING AND RE-USE

The U.S. Geological Survey (Kenny *et al*. 2009) estimates that 71 per cent of water withdrawals for thermoelectric generation in 2005 were freshwater, and the remaining 29 per cent, saltwater (mostly sea water, but also some saline groundwater). Saline water withdrawals declined by 4 per cent from 2000, while freshwater withdrawals increased by 7 per cent. Yet with growing concerns about freshwater shortages, saltwater use may need to increase.

Saltwater is used mainly for once-through cooling systems in coastal areas. Seawater is an abundant resource, but with coastal real estate in high demand, it is becoming more difficult to access. In addition, much like freshwater once-through cooling technologies, these saltwater systems can have significant environmental impacts, killing small aquatic organisms that are carried by the cooling water into the power plant, trapping larger organisms against the intake screens, and further harming sea life when the heated water is discharged again. A California Energy Commission report has warned that millions of aquatic organisms could be harmed each year, including fish, fish larvae and eggs, crustaceans, shellfish, sea turtles, and marine mammals (Ferry-Graham *et al*. 2008).

23 Assuming 493 gallons per MWh, per the Macknick *et al*. (2011) estimate for supercritical coal with wet-recirculating cooling, which is roughly the mid-range for coal power.

24 Per World Bank statistics; see http://data.worldbank.org/indicator/EG.ELC.LOSS.ZS.

Unlike once-through systems, wet-recirculating systems recycle cooling water, so they don't have the same environmental impacts and also do not have to be sited next to the water source. In the USA, the use of recirculating systems has been rising, driven by regulations promulgated under a Clean Water Act section that requires that "the location, design, construction and capacity of cooling water intake structures reflect the best technology available for minimizing adverse environmental impacts" (US-DOE 2010b). This also applies to systems using saline water, and a study for the California Energy Commission (Maulbetsch and DiFilippo 2010) found that recent installations of mechanical-draft cooling towers using high-salinity water "operated satisfactorily, with no extraordinary operating and maintenance problems". However, they also found accelerated corrosion of unprotected metal surfaces in nearby buildings, and they estimated a 4 to 8 per cent performance penalty and a 35 to 50 per cent cost penalty compared with towers using freshwater.

Saltwater is only one of several options, however. There are many types of wastewater that are currently being explored for use in power plant cooling, including municipal wastewater, produced water from oil and gas extraction, and agricultural runoff. Treated municipal wastewater, also called grey water, is a huge unclaimed water resource in the United States. An Electric Power Research Institute review (Barker 2007) notes that of the 121 million m^3 of municipal wastewater treated every day, only about 8 per cent is reused. Some U.S. power plants have successfully used grey water for decades, in several states; in Arizona, thermoelectric plants used about 223,000 m^3 per day of reclaimed wastewater in 2005 (Kenny *et al.* 2009). Because the water has already been treated in the public facilities, it is of relatively high quality (EPRI 2007), though it may still need additional treatment to remove dissolved metals and chemicals. The Palo Verde nuclear plant in Arizona, for example, pumps grey water from Phoenix, runs it through filters and clarifiers, then adds chemicals to reduce the level of calcium carbonate (Barker 2007).

Another option is using wastewater from oil and natural gas production, or from mining. Large volumes of such water may be available, but they also require significant pre-treatment, at a cost of more than $1,000 per m^3 (EPRI 2007). Water pumped from spent coal mines has high acidity, for example, and "produced water" from oil and gas operations can have high levels of salts, silica, and hardness (ibid.). Other future options are wastewater from industrial processes and agricultural runoff. These are not commercialised processes, but if put into place would likely require additional treatment to extract metals and organic material from the water before use in a power plant cooling system (Barker 2007).

RENEWABLE ENERGY STORAGE TECHNOLOGIES

Energy storage technologies such as pumped hydro and compressed energy storage system (CAES) offer the largest and most economical grid-scale energy storage options. Both technologies have been used to help with load smoothing and to enable coal and other fossil-fuel based plants to operate at maximum efficiency. Energy storage is critical to a low-carbon energy future, and in the following sections we explain how pumped hydro and CAES are coupling with renewable energy technologies

Wind powered pumped hydro storage system

In conventional energy systems, plants are designed to cover demand fluctuations. Plants generating sufficient electricity to meet base demand are combined with "cyclical plants" during periods of peak demand. This combined generating system is due, in part, to the ongoing challenge of electricity "non-storability", wherein electricity must be produced at the moment of consumption given technological limitations in storing electricity. Pumped hydro storage systems are increasingly become an attractive "cyclical plant" option because they offer storage by pumping low-altitude water to higher elevations at periods of low energy demand, then releasing it to produce hydroelectricity for consumption during peak demand periods; thus the generation potential is stored for when it is needed.

Hydroelectricity can be produced almost instantaneously, and its flexibility makes it an important contributor to load smoothing and system reliability (Crampes and Moreaux 2010; Bueno and Carta 2006). The alternative for meeting peak demand is often to generate extra power from fossil-fuelled plants (Crampes and Moreaux 2010). Thus pumped hydro can be a cost-effective and pollution-reducing way to smooth loads by using cheap thermal electricity during periods of low demand to restore water resources that would then be used to generate electricity at periods of peak demand.

However, pumping the water uses a large amount of energy as well, so the source of that energy – and of the electricity that would otherwise be produced to meet peak demand – is an important consideration. Bueno and Carta (2006) and Dursun and Alboyaci (2010) suggest employing wind-generated electricity to restore water for pumped storage in the Canary Islands and Turkey, respectively, where wind energy is generated but not consumed during periods of low demand.

Various projects that add wind energy to existing hydroelectric power stations or for small hybrid systems have already been proposed in the USA, Europe and Asia (Bueno and Carta 2006; Bueno and Carta 2005). One analysis of pumped hydro storage in Germany found that "introducing storage smoothes market prices and increases consumer rent and overall welfare"; the paper goes on to suggest an important role of pumped storage for expansion and grid-integration of intermittent renewable electricity sources such as solar and wind (Schill and Kemfert 2011).

Compressed energy storage system

Similar to pumped storage, CAES plants store off-peak power when it is not needed (and least expensive) and return energy to the grid at peak demand. During times of excess energy production, air is compressed and stored, and when power is needed, it is run through a turbine. CAES allows plants to operate closer to full load and at peak efficiency when demand drops. Few such plants have been built so far, because it is challenging to find a storage container large enough to hold enough compressed air to produce a useful amount of energy. Because of the risks involved, it can take several years to find, regulate and build a compressed air site, which could explain why after 30 years, there are still only two CAES plants online: one in Germany and one in the USA.

The first CAES plant was established in 1978 in Huntorf, Germany, above salt domes. And since the early 1990s, PowerSouth in Alabama has been using CAES in underground salt caverns with large enough gas-tight volumes store compressed air for its base-load coal-generating plant (PowerSouth 2011). Some researchers warn of inefficiencies in CAES, noting that 1 KWh of natural gas is needed for every 3 kWh generated from a CAES system (Westervelt 2010). These two first generation CAES plants have remained the only demonstrations, globally, until interest in renewable energy in the last 10 years. New CAES2 technology is more flexible and a cost-effective solution, especially when coupled with renewable energy load management (De Biasi 2009).

The U.S. states of Iowa and Arizona and large utilities such as New York State Electric & Gas (NYSEG) and California's Pacific Gas & Electric (PG&E) are already exploring and testing potential CAES sites which include leasing depleted metal mines, using depleted gas-storage facilities, salt caverns, or aquifers (PowerSouth 2011; Westervelt 2010). In Arizona, the proposed CAES would also use solar energy to heat the air when it is released, allowing more energy to be extracted from the stored air than the energy required to compress it.[25] The Iowa Stored Energy Park, NYSEG and PG&E all plan to integrate off-peak grid electricity, existing and new wind farms and CAES. ISEP is expected to be commercially viable by 2015, and NYSEG by 2014 (ISEP 2010; US-DOE 2010a).

25 See Blute, V. (2011) 'UA looking at air-storage system as alternative green-energy source'. *Arizona Daily Star*, 9 April. Environment. Tucson, AZ. http://azstarnet.com/news/science/environment/ua-looking-at-air-storage-system-as-alternative-green-energy/article_c3643dbf-6b03-5531-881c-94d9b21827cd.html#ixzz1kJmmGy8s.

CONCLUSIONS

Though there is uncertainty about when and how low-carbon development will happen for the energy sector, we can be sure of some of the implications for water. Constraints on available water are expected to affect electricity generation, further straining thermoelectric technologies.

Thermoelectric renewables such as solar thermal and geothermal steam technologies are arguably at a higher risk than conventional thermoelectric power plants, as they must be sited near solar and geothermal resources, respectively. These areas are typically arid, warm and far from water sources, leaving only wet-recirculating and dry-cooling options available. Though dry cooling may seem like the obvious choice, as we noted earlier, the plants' thermal efficiency is reduced, and the cost of dry cooling and hybrid systems is considerably higher.

This challenge highlights once again the motivation for this report. Developing and expanding the use of low-carbon electricity generation technologies will be an essential component of any creditable effort to reduce GHG emissions and avoid the most harmful impacts of dramatic climate change, including those related to water resources management. Indeed, the management of water resources, already a challenge in many parts of the world, could become increasingly problematic should the global climate regime shift substantially. This fact, however, could constrain the available options related to renewable electricity generation expansion, particularly for those low-carbon technologies with high water demands. This circular argument looks all too much like a vicious circle.

Yet as demonstrated in our case study, using reasonable generation and water use numbers, there are ways that generation, cooling and carbon management strategies can be assembled such that emissions can be controlled while minimising additional pressure placed on water resources. These are not policy prescriptions, which would require much more detailed analysis informed by the particular water and energy context within which decisions are being made – analysis which will surely need to consider important financial and economic factors. The point is that these heretofore independent policy domains, energy and water, are linked in ways that cannot be ignored. It is our hope that this report will have demonstrated that point convincingly, so that the hard work of managing defining sustainable future electricity generations and water management pathways can be undertaken with the knowledge that it is necessary. This would be a virtuous outcome.

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