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Introduction

The tradeoffs between energy and water have been gaining international attention in recent years as demand for both resources mount and governments continue to struggle to ensure reliable supply to meet sectoral needs. As almost all energy generation processes require significant amounts of water, and water requires energy for treatment and transport, these two resources are inextricably linked. This relationship is the energy-water nexus.

As population and economies grow many regions of the world experience water and energy security challenges that must be addressed now. During the next 20 years, cities in developing countries will have to meet the demand of 70 million more people each year. Recent FAO estimates show that by 2050, feeding a planet of 9 billion people will require a 60 percent increase in agricultural production and a 6 percent increase in already-strained water withdrawals (FAO, 2012). Further, over 1.3 billion people worldwide still lack access to electricity; most of them reside in sub-Saharan Africa and East-Asia (IEA, 2012). About 2.8 billion people live in areas of high water stress and 1.2 billion live in areas of physical scarcity. It is estimated that by 2030, nearly half of the world's population will be living in areas of high water stress affecting energy and food security (WWAP, 2012). According to recent estimates from the World Energy Council, emerging economies like China, India, and Brazil will double their energy consumption in the next 40 years. By 2050, Africa's electricity generation will be seven times as high as it is today. Similarly, in Asia, primary energy production will almost double, and electricity generation will more than triple by 2050. And in Latin America, increased production will come from non-conventional oil, thermal, and gas sources and the amount of electricity generated is expected to increase fivefold, tripling the amount of water needed (World Energy Council, 2010). The increased demand for energy will put additional pressure on already constrained water resources.

Mitigating the challenges presented by the nexus will be made more difficult by climate variability and related extreme weather, which are already causing major floods and droughts and putting populations, livelihoods, and assets in danger. Climate change will increase the vulnerability of countries as rising temperatures accelerate evaporation and precipitation. In addition, rain patterns will shift and intensify, thereby enhancing uncertainty in energy development. In some cases future water scarcity will threaten the viability of projects and hinder development. The power sector is vulnerable to increased water temperature and diminished water availability. Several power plants

have already been forced to shut down in the United States, India, France, and other countries due to lack of water or high water temperatures compromising cooling processes. Thermal power plant projects are being re-examined due to their impact on regional water resources and their vulnerability to climate impacts. More recurrent and longer droughts are threatening the hydropower capacity of many countries, such as Sri Lanka, China, and Brazil.

Those involved in the energy sector recognize the magnitude of this issue. Last year (and for the first time since it was first published in 1994), the International Energy Agency's World Energy Outlook report included a special section on the water needs and the possible future water constraints of the energy sector. The report concluded that "constraints on water can challenge the reliability of existing operations and the viability of proposed projects, imposing additional costs for necessary adaptive measures." Most recently, General Electric's Director for Global Strategy and Planning stated that expansion plans for coal power plants in China and India could become unfeasible due to water scarcity. A World Resources Institute report assessed existing and planned power plants in India and Southeast Asia and concluded that more than half are in areas that will likely face water shortages in the future. The 2012 UN Water Report surveyed more than 125 countries on this topic and found that the problem of water for energy was high or very high on the list of priorities in 48 percent of the countries surveyed.

To address these challenges, the World Bank has launched a new global initiative entitled "Quantifying the Tradeoffs of the Water and Energy Nexus" that is a joint effort of the energy and the water groups. The goal of the initiative is to generate innovative approaches and evidence-based operational tools to assist developing countries to assess and quantify the economic, environmental, and social tradeoffs of water constraints in energy security and power expansion plans. In addition, the initiative will demonstrate the importance of integrated planning of energy and water investments to sustainable economic growth. As part of this initiative, the World Bank will produce technical and policy-oriented material to support its client countries as they address this challenge. This document is the first report in this series and focuses on an introduction of the nexus (in particular on water for energy) and examines the water requirements of power generation. As such, it is not meant to be a technical piece, but rather, its aim is to raise awareness in both the energy and water sectors of the linkages and complexities of the challenge. Section 1 of this paper examines the existing models, literature, and management frameworks on the nexus, as it seeks to determine what gaps exist. Section 2 describes the water demands of power generation in order to identify potential areas of future uncertainty and delineate areas where integrated energy-water management may improve the reliability of operating power plants and the viability of proposed schemes. Section 3 describes possible solutions that may alleviate challenges resulting from the link between energy and water by improving energy efficiency and integrating water resources management into energy planning.

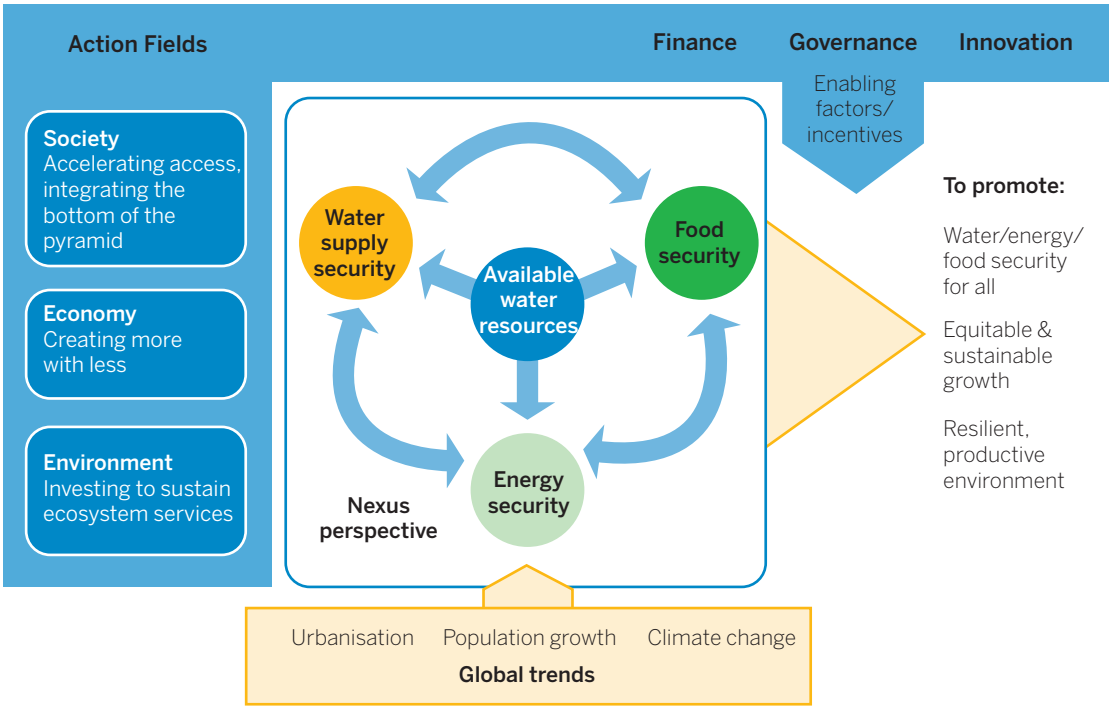
Section 1

The Global Challenges in Energy and Water

The Energy-Water Nexus

The interdependence between water and energy is growing in importance as demand for both water and energy increases. Almost all energy generation processes require significant amounts of water, and the treatment and transport of water requires energy (mainly in the form of electricity). This tradeoff between energy and water resources is the energy-water nexus. Integrated planning is vital to ensure future social, political, and economic stability and to avoid unwanted and unsustainable scenarios (IAEA, 2011; Olsson, 2012; Sandia Labs, 2011; WEF, 2008). As shown in figure 1, water resources greatly determine food and energy security. Continued investment and research into interactions

Figure 1: The Nexus Framework (SEI, 2011)



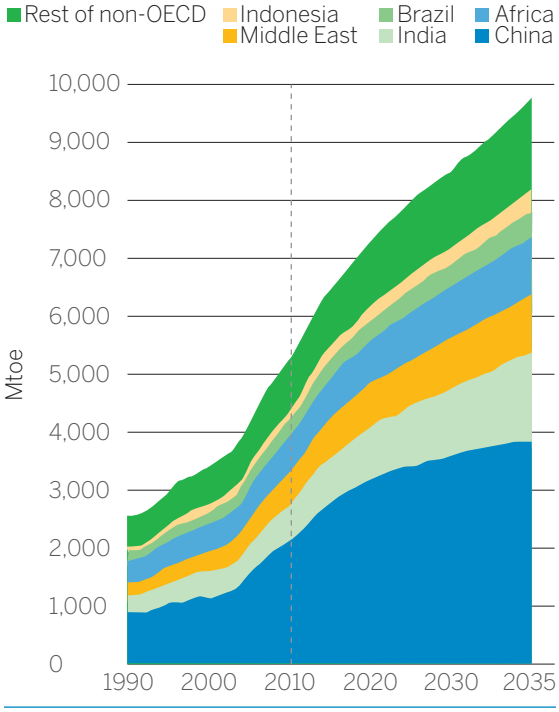
within the nexus are critical for smart climate and infrastructure planning and to ensure a sustainable future.

Population and economic growth are expected to increase demand for food, energy, and water. Global economic growth is being driven largely by emerging markets. Over the medium term, it is estimated that economic growth will average 6 percent in the developing countries compared to 2.7 percent in higher-income countries (World Bank, 2011). Yet, currently 783 million people lack access to clean drinking water and 2.5 billion people remain without sanitation. Growing stresses such as rapid urbanization and climate change are affecting all water uses. During the next 20 years, cities in developing countries will have to meet the demand of 70 million more people each year. Recent FAO estimates show that by 2050, feeding a planet of 9 billion people will require a 60 percent increase in agricultural production and a 15 percent increase in already-strained water withdrawals (FAO, 2012). Further, over 1.3 billion people worldwide still lack access to electricity with most of them residing in sub-Saharan Africa and East-Asia (IEA, 2012). Closing the energy gap could have negative implications on water resources because water is needed for fuel extraction, cooling thermal power plants, and to turn hydropower turbines.

Water scarcity is increasing. About 2.8 billion people live in areas of high water stress and 1.2 billion live in areas of physical scarcity. It is estimated that by 2030, nearly half of the world's population will be living in areas of high water stress affecting energy and food security (WWAP, 2012). Worldwide, decreasing water quality also impacts growth as it degrades ecosystems; causes health-related diseases; constrains economic activities such as agriculture, energy generation, industrial production, and tourism; affects the value of property and assets, and increases wastewater treatment costs.

Global energy consumption will increase by nearly 50 percent by 2035 (IEA, 2012) and most of this increase will happen in non-OECD countries (see figure 2). According to recent estimates from the World Energy Council, emerging economies like China, India, and Brazil will double their energy consumption in the next 40 years. By 2050, Africa's electricity generation will be seven times as high as it is today. In Asia, primary energy production will almost double, and electricity generation will more than triple by 2050. And in Latin America, increased production will come from non-conventional oil, thermal, and gas sources and the amount of electricity generated is expected to increase fivefold in the next 40 years, tripling the amount of water needed (World Energy Council, 2010). The increased demand for energy will put additional pressure on already constrained water resources.

Figure 2. Non-OECD primary energy demand by region; Mtoe stands for million tons of oil equivalent (IEA, 2012)



Climate change is exacerbating energy and water insecurity, due to extreme weather conditions, such as prolonged drought periods and major floods, which will put populations, livelihoods, and assets in danger. The number of people affected by climate-related disasters doubled every decade in the last 40 years. The effects and intensity of climate change will vary regionally, as populations experience a change in average precipitation, surface runoff, and stream flow, deviation from rainfall averages, and increased probability of extreme events, such as intense storms, floods and droughts. Altered precipitation and evapotranspiration patterns are predicted to reduce runoff in southern Africa, the Mediterranean basin, Central America, the southwestern United States and Australia, among other places (FAO, 2008). This is likely to increase competition for water across sectors, such as agriculture, energy, water supply and the environment.

The combined effects of population growth, climate change, and increasing hydrological variability will result in a heightened reliance on energy-intensive water supply options, such as water transport or desalination plants to supplement urban water supply. Moreover, as temperatures rise, more water will be needed by the energy sector to meet both its own demand for water for cooling per unit of energy produced, and also to meet increased energy demands for the cooling of houses, offices, and factories. Climate change will also impact the energy sector through changes in energy demand, and through the need to transition to energy supply options involving low or zero greenhouse gas emissions.

As economic development at the household level depends on access to basic energy and water services, economy-wide growth and poverty reduction depend on water and energy systems to provide reliable and affordable services. Growth in electricity demand, as well as demand for motorized transportation are hallmarks of the transition to higher-value-added, more diversified and integrated economic activity. Similarly, as economies grow and diversify, competing demands for water broaden to include more intensive municipal and industrial uses, as well as increased demands for agriculture. Environmental considerations also come into play: increased demands for potable water and air pollution control increase energy use; expansion of renewable energy utilization increases the need to consider the water requirements of diverse technologies from traditional hydropower, to renewable thermal power, to biofuel feedstock production.

Water is needed in almost all energy generation processes. Most thermal power plants require large quantities of water, primarily for cooling purposes. Water drives energy production in hydropower generation and is also critical in energy development (such as coal, oil, and gas extraction and refining). Only wind (which requires virtually no water) and photovoltaic (which requires a small quantity of water to wash the panels) have negligible impacts on the water and energy nexus. Both energy and water are used in the production of crops and some crops are used to generate energy through biofuels.

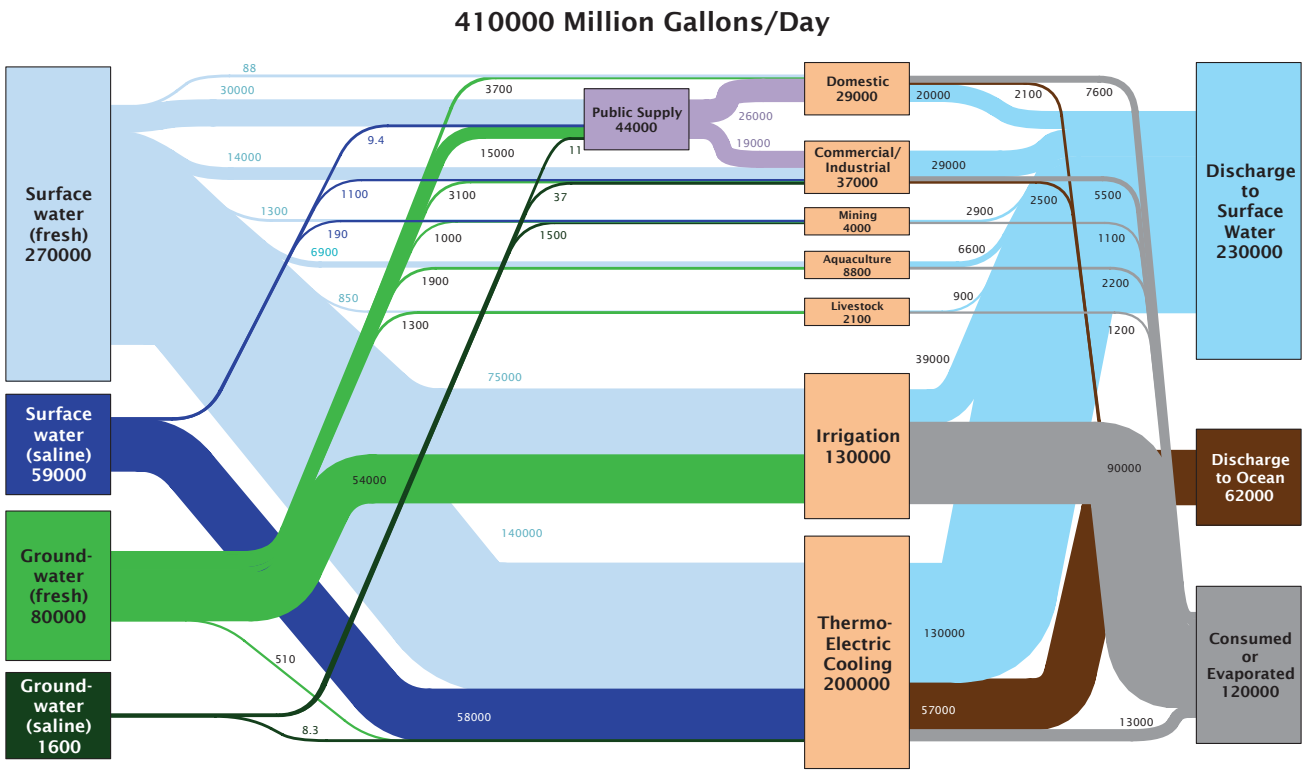
Determining energy-water tradeoffs is a complex matter. Energy development requires varying quantities of water by resource and defining water use by the energy sector is challenging because not all uses are the same. Water and energy managers must consider the water requirements in energy development in order to ensure the long-term viability of operations. In such an analysis, the water requirements are usually broken down into water withdrawal, water consumption, and discharge. Withdrawal is defined as the amount of water taken from a water source (lake, river, ocean, aquifer, etc.). Consumption is the water that is lost from the total water withdrawn. Discharge is

the amount of water that is returned to the water source in a different state. Therefore, the water consumed is equal to the water withdrawn minus the water discharged to the environment.

These requirements can differ dramatically depending on the type of process or technology employed. For example, hydropower requires the availability of large quantities of water, but the water is only diverted and can be used downstream by other sectors, such as agriculture. In biofuels, most of the water is consumed through irrigation and a reduced amount is returned to the system. In thermal power plants, large quantities of water are withdrawn for cooling purposes, but most of the water is returned to the freshwater source (see figure 3). Conversely, while mining and energy development do not require large volumes of water at the national level (see figure 3), resource development requires large volumes during extraction, transportation, and processing. As a result, it can dramatically affect water availability regionally, both in time and place. The vast differences in water demand in the energy sector, imposes an important challenge when analyzing and quantifying potential water constraints.

Visualization tools, such as the one depicted in figure 3 allow resource managers to better project water and energy needs and determine if supplies will be adequate. Using data from the United States, figure 3 illustrates how water resources are withdrawn, discharged

Figure 3: Estimated Water Flow in the United States in 2005



Source: LLNL 2011. Data is based on USGS Circular 1344, October 2009. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. All quantities are rounded to 2 significant digits and annual flows of less than 0.05 MGal/day are not included. Totals may not equal sum of flows due to independent rounding. Further detail on how all flows are calculated can be found at http://flowcharts.llnl.gov. LLNL-TR-475772.

and consumed by different sectors. In the United States, the withdrawal rate for thermal power plant cooling processes is almost as much as the withdrawals for agriculture, which consumes water for food and biofuel production. While most of the water in the energy sector is not consumed and is returned to the source, the large volume of water withdrawn by the power sector greatly impacts the ecosystem and the water resources of a region.

In 2010, water withdrawals for energy production were estimated at 583 billion cubic meters (bcm), of which 66 bcm were not returned to the water body (IEA 2012). Water withdrawal is predicted to increase by 20 percent by 2035, with consumption increasing by 85 percent. This increase in consumption is mostly due to a shift from once through cooling to closed loop cooling systems, which withdraw less water, but consume most of it, and also due to the expansion of crop production for biofuels. Water withdrawals are typically greater than consumptive use and are, therefore, considered the limiting factor for energy production in locations where water is a constrained resource. Even if water use for electricity generation is non-consumptive, the timing of water releases and water quality issues can have material impacts on other sectors, giving rise to tradeoffs and potential conflicts with other water uses, particularly in water scarce regions and basins.

Expansion of many forms of renewable energy could increase accompanying demands for water (e.g., in solar thermal, biofuels feed stocks, geothermal, and hydropower). In the coming decades the energy demand and greenhouse gas emissions are estimated to triple under a business-as-usual scenario (IAEA, 2011). One of the proposed solutions is the substitution of fossil energy sources with renewable low-carbon sources, such as hydropower, wind, solar-thermal, geothermal or biomass. Nuclear energy has also been advocated for in many countries. Most of these solutions are thermal power plants, and due to their lower efficiency compared to conventional fossil fuel power plants, they usually require larger amounts of water for cooling purposes. Non-thermal renewable generation technologies such as wind and photovoltaics consume negligible amounts of water. However, they provide intermittent service. Thus, without the existence of large scale electricity storage, it seems inevitable that thermal power plants will continue to be used as base-load and dispatchable power. Pressures for adoption of low carbon sources of energy can be expected to increase the demand for investment in the development of hydropower in ways that may change the timing and delivery of water to other users. Policy choices are further complicating addressing the energy-water nexus as people select more water-intensive energy and more energy-intensive water sources to meet demand (WWAP, 2012).

The competition between water and energy is asymmetrical. Water scarcity threatens energy production, and energy is also needed for water production, yet water availability is not threatened by energy scarcity. Water consumption for energy generation contributes to water scarcity; as more energy is generated significantly less water may be available. On the other side of the equation, the energy use for the treatment, transport and pumping of water can be significant, but it is not seen as a major determinant of energy scarcity. This study focuses on addressing this imbalance; in particular, the tradeoffs between these resources, by proposing solutions that emphasize their common dependence given that they are inextricably linked. This interdependence is already critical in many regions, and the resulting stresses are compounded as demand grows from emerging economies and "graduating" countries. The impact of climate change on water and energy

resources is also a factor. Projected consequences of these factors are alarming enough to require the urgent development of more accurate integrated planning tools.

Existing Efforts in the Energy-Water Nexus

A review of the literature shows a consistent theme of water stress and scarcity as well as the expectation that these will increase over time. The impact of cross-sector competition on the energy-water nexus highlights the need for a more integrated approach to energy-water planning. There are several components of integrated energy-water planning that should be addressed, both systematically and over long planning horizons. The major planning aspects relate to technical, policy, and socioeconomic factors. Specifically, there are political and institutional barriers that affect energy-water planning because these resources are very profitable. Thus, entrenched political and economic interests may prefer that resources and data sharing remain separate. The literature also reveals that while many organizations examine the water and energy nexus, most of the existing analysis deals primarily with physical and technical variables. Few analysts are trying to quantify the tradeoffs.

Despite growing concerns over these trends, decision makers are often ill-informed about what drives the trends, their possible outcomes, and the merits of different technical options. The study of growing water and energy needs often occurs in isolation from plans for expanding the provision of these resources. For example, research on siting for a solar thermal plant may take into account the availability of water for cooling at specific sites, but the systemic implications of solar thermal versus other technology choices receives less attention. Energy planning is often made without taking into account possible changes in water availability due to climate change or other competing uses. Water resources planning rarely takes into account the energy used to pump, treat, and desalinate the water, which in turn has an impact on the water used by the power sector. Assessment of a large hydropower project for electricity generation may not sufficiently consider that the agricultural value-added of using that water for irrigation may be greater than using alternative groundwater sources for food production.

Currently, the majority of integrated energy-water planning efforts are specific to the United States and many of the programs are in pilot and research stages. Developing countries have limited literature on energy projections and associated water consumption. Late last year, and in an effort to quantify the challenges facing the nexus, the IEA World Energy Outlook included a section on the possible future water constraints in the energy sector for the first time in its 19-year history (IEA, 2012).

The issue of water scarcity at the basin level is less well understood and illustrates one of the gaps in planning in the energy-water nexus. Water scarcity is typically analyzed on a high-level conceptual approach that is supported by the data that is available. This gap illustrates an area where the conceptual programming of energy-water tradeoffs could be applied to provide real-time data and feedback through a basin study focused on a region with electricity generation needs that may compete for water resources with other sectors, such as industry, municipalities, agriculture, and the environment.

Energy and water policies are disjointed, with many federal, state, and local decision makers but few mechanisms to coordinate action. This lack of integrated planning, management, and regulation has already had an impact in the power sector. In the United States, power plant permits have been rejected due to water

concerns (US Department of Energy, 2006). Yet, there are technologies and policy approaches that could be adopted that would improve a country's position with regard to energy, water, and climate security, if only the means of coordination were in place.

Water allocation modeling does not adequately address scale and time in energy modeling from planning to operation. Water supply planning generally uses a fairly broad spatial scale (river basin) and a fairly coarse time scale (months or weeks). Energy operational models generally run on a more refined time scale (minutes or hours) that are not necessarily concerned with the spatial component or supply limitations evidenced with the underlying hydrologic systems.

A better understanding of the cross-sectoral implications and the potential magnitude of water and energy stresses for the energy sector is needed for climate-smart and inclusive green growth planning. The need to understand the interactions between energy and water use is growing, and in addition to energy and water, planning and development challenges are likely to involve land use, food production, urbanization, demographics, and environmental protection. A number of modeling platforms have been developed to support an assessment of energy sector development under different economic and environmental policy conditions, and to support integrated resource development in the water sector. The water models take into account water use for hydroelectricity expansion versus other uses; and some energy models include calculations of water requirements for different technology investments. Typically, however, the models are designed for different purposes and the linkages between energy and water sector development are limited. Moreover, the level of technical detail and complexity in the models can preclude their application for upstream sector strategy development, a crucial analytical need in development planning. The converse is also true for the needs at the river basin or sub-basin level, when models are too general and do not include the necessary level of detail.

Despite the importance of energy and water, and their interconnectedness, funding, policy making, and oversight are scattered among many agencies. Practitioners also often manage these resources broadly, including land and food in their management approach. The current internal incentives system still favors independent sectoral outcomes over cross-sectoral results.

Section 2

Water Demands of Power Generation

Introduction

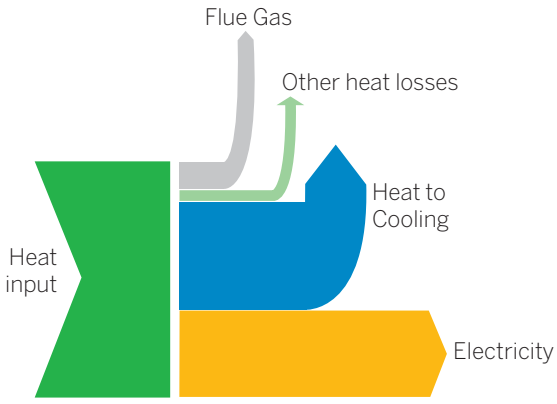
Water is required in almost all types of electricity generation. The most obvious and well-known is hydropower. However, most thermal power plants, which produce most of the electricity in many regions of the world, also require large quantities of water for their operation. Thermoelectric power plants account for 39 percent of annual freshwater withdrawal in the United States (USGS, 2005) and 43 percent in Europe (Rubbelke and Vogele, 2011). Only open cycle power plants, which require no water for cooling, and energy from wind and photovoltaics have a negligible impact on the water and energy nexus.

Thermal Power Plants

Thermal power plants generate around 75 percent of the electricity produced in the world (IEA, 2012). Most of these plants require large quantities of water, mainly for cooling purposes.

Thermal power plants convert heat into power in the form of electricity. The heat is generated from a diverse range of sources, including pulverized coal, natural gas, uranium, solar energy, and geothermal energy. Most of these thermal power plants, including coal power plants, geothermal, solar thermal, biomass, nuclear, and in part, natural gas combined cycle power plants use steam as the prime mover. In these plants water is heated and turned into steam. The steam spins a turbine which drives an electric generator. After passing through the turbine the steam is cooled down and condensed to start the cycle again (closing the so-called steam cycle). In other words, all the heat put into the plant that is not converted into electricity is "waste heat" and has to be dissipated into the environment. Most of this heat (blue arrow in figure 4) is rejected to the environment through

Figure 4. Simplified Visualization of Heat Balance of a Fossil Fuel Power Plant



Source: Delgado, 2012.

the cooling system, which usually uses water as the heat transfer medium (UCS, 2011).

As power plants become more efficient, less waste heat needs to be rejected (yellow arrow becomes bigger and blue arrow smaller), which diminishes the cooling requirements per kWh produced. Therefore, more efficient new natural gas combined cycle power plants (around 50 percent efficient) require less water than a new coal power plant (38 percent) or a solar thermal power plant (25 to 40 percent) and much less than an old coal power plant (efficiencies could be as low as 25 percent) or new coal power plants with carbon capture (33 percent).[1] On the other hand, open-cycle gas turbines, which are usually used as peaking power plants, have no steam cycle and thus do not require water for cooling.

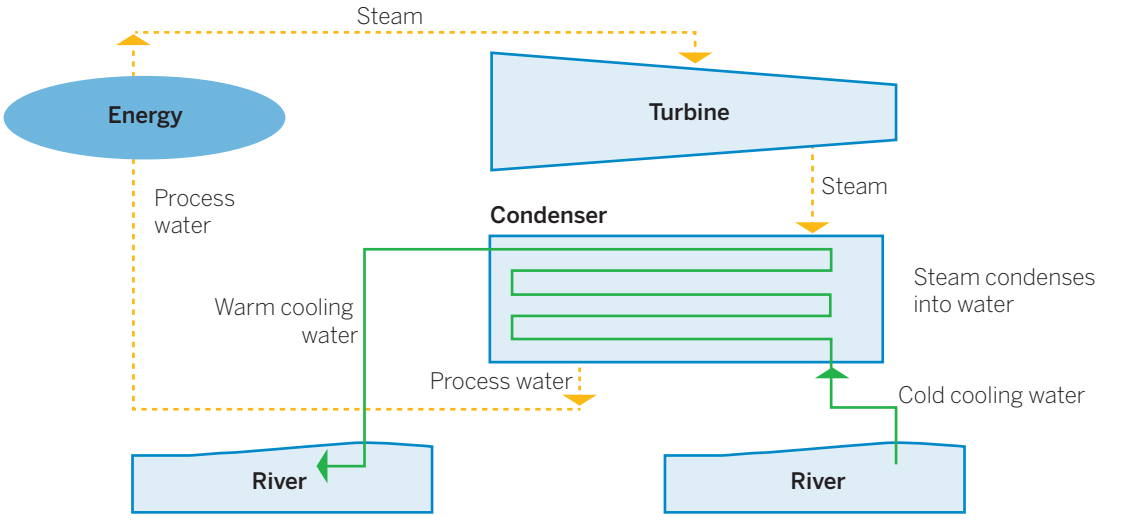
The amount of water required for cooling is highly dependent on the type of cooling system used in the plant. Although water is also used in smaller quantities for steam generation and in other processes, such as ash handling and flue gas desulfurization, most of the water is used for cooling purposes. In a coal plant with cooling towers, it is estimated that 90 percent of the water is used in the cooling system and the other 10 percent is used in other processes (DOE, 2009). Therefore, the choice of cooling system should take water requirements into account in order to minimize environmental impacts.

There are four types of cooling systems, and water withdrawn and consumed is highly variable depending on the system implemented: once-through cooling systems, closed-loop or wet-recirculating systems, dry cooling systems, and hybrid cooling systems.

- **Once-through cooling** systems are the simplest method of cooling steam that is exhausted from the turbine. This system requires withdrawing large quantities of water from a water body, but returns all the water to the source once it has passed through the heat exchanger and condensed the steam (see figure 5). Although the power station does not consume any water, the increased temperature of the returned water means that a small

[1] See Annex 2 for a discussion of the effects of carbon capture and storage on water resources.

Figure 5: Diagram of Once-Through Cooling System

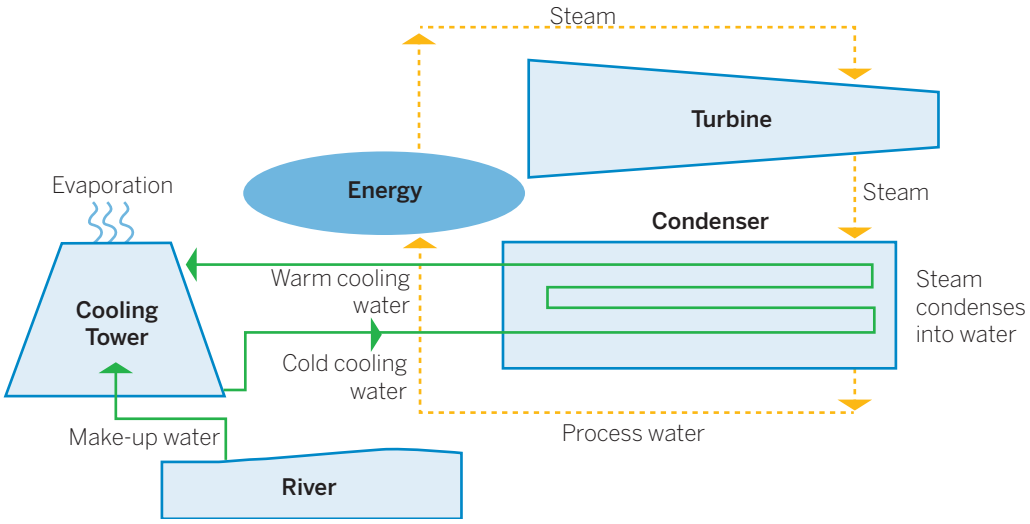


Source: FAO, 2011.

percentage (around 1 percent) of it evaporates downstream. Moreover, the warm water may cause thermal pollution of the environment and have an adverse impact on ecosystems.

- **Closed-loop or wet-recirculating systems** include wet cooling towers and cooling ponds. Both cooling systems use a recirculating loop of water. Wet cooling towers are the most common systems used. After the water goes through the steam condenser and removes the waste heat, it is sprayed down the cooling tower while air comes up from the bottom of the tower and goes out into the environment. This process exchanges heat from the water to the air, cooling the water. Some water is lost due to evaporation. The remaining water is then collected at the bottom of the cooling tower and reused in the steam condenser of the power plant, closing the recirculating loop (see figure 6). Although this cooling system withdraws far less water than once-through systems, water consumption is higher due to evaporation; around 85 percent of the water withdrawn is consumed.
- **Dry cooling systems** use air instead of water to cool the steam leaving the turbine, and therefore can decrease the power plant's water consumption by more than 90 percent. (UCS, 2010). Compared to the other cooling systems, dry cooling systems have minimal environmental impacts. However, since air is not as efficient as water in heat transfer, dry cooling systems require a greater surface area to dissipate waste heat to the environment. Therefore, dry cooling is two to four times more expensive than an equivalent wet tower cooling system. Moreover, since dry cooling is less efficient than water cooled systems, it affects the efficiency of the plant, so these systems are used in extreme situations of water scarcity, although in ambient temperatures of above 100 degrees Fahrenheit, it is much less effective than other systems. (UCS, 2010).
- **Hybrid cooling systems** combine wet and dry cooling approaches. Although

Figure 6. Diagram of Closed-Loop Cooling with Cooling Towers



Source: FAO, 2011.

there are different types of systems, they still fall between wet and dry in terms of cost, performance, and water use.

The cooling system employed by the power plant has an impact on power plant efficiency, capital and operation costs, water consumption, water withdrawal, and total environmental impacts. Therefore, tradeoffs must be evaluated case-by-case, taking into consideration regional and ambient conditions, and existing regulations. It is also important to note that there is a wide range of operational consumption for the same type of system, reflecting local conditions in particular areas and countries and depending on the efficiency of the power plant (see annex 1). Any assessment must clearly identify and quantify the tradeoffs between cooling systems in terms of water use, costs, and efficiency (see table 2).

Thermal electric power plants can also have an adverse effect on water quality. Once-through cooling discharges alter the water temperature and cause thermal pollution and changes in oxygen levels in the surrounding environment. Air emissions from fuel combustion in thermal power plants can contain mercury, sulfur, and nitrogen oxides, among other chemicals, which can have an impact on the water quality and aquatic ecosystems downwind. In wet cooling towers, smaller amounts of water, known as "blowdown," are purged from the cooling water circuit to avoid the buildup of harmful contaminants and concentration of dissolved and suspended solids. These streams of water contain several pollutants and should be treated before being returned to the water source or sent to holding ponds. Fossil fuel power plants also require greater volumes of water for processes, such as flue-gas desulfurization, coal washing, and dust removal. This water must be treated before it is discharged because it could pollute surrounding water resources with toxic chemicals.

Hydropower

While there is abundant potential hydropower in developing countries, it has not yet been harnessed. Unexploited hydropower potential amounts to 93 percent in Africa, 82 percent in East Asia and the Pacific, 79 percent in the Middle East and North Africa, 78 percent in Europe and Central Asia, 75 percent in South Asia, and 62 percent in Latin America and the Caribbean (WBG, 2009).

Hydropower is also a water intensive source of energy, although there are different water concerns in the electrical generation processes. In hydropower plants, most of the water is not consumed but diverted to generate electricity. As a result, it can be used downstream of the dam for other purposes, such as irrigation and for urban use. In a world of severe energy shortages and increasing water variability, hydropower and its multipurpose water infrastructure will play an expanding role in providing electricity and allocating scarce water resources.

Table 2: Cooling System Tradeoffs

Cooling Type	Water Withdrawal	Water Consumption	Capital Cost	Plant Efficiency	Ecological Impact
Once-Through	intense	moderate	low	most efficient	intense
Wet Cooling Towers	moderate	intense	moderate	efficient	moderate
Dry Cooling	none	none	high	less efficient	low

Source: modified from Delgado, 2012.

Hydropower plants consume water through evaporative losses from the reservoir and through seepage. Consumption varies greatly depending on site location and design. In an arid environment, where reservoir storage is very large, evaporative losses can be significant compared to run-of-the-river hydropower plants, which store little water, and therefore have evaporative losses near zero. However, a run-of-the-river site cannot be used for water storage, nor can it control the efficient generation of the electricity when needed (for peak loads, for example).

Hydropower plants impact the land and water. Hydropower plants change the hydrogeology of an area because they convert a free-flowing river into a reservoir, thus altering the timing and flow of the water. This impounded water affects water quality and aquatic life, as rivers and lakes can fill with sediment and baseline nutrient levels can be altered. Water rushing through the turbines can increase the presence of dissolved oxygen in the water, affecting aquatic life. Ecosystems and water quality are further affected by the dam because hydropower plants may slow the river's flow, thus potentially increasing the temperature stratification of the water body.

Present and Future Challenges

Although the water-energy nexus varies by region, challenges in securing enough water for energy and energy for water will increase with population and economic growth. In addition, competition for water resources will intensify and climate change will compromise solutions. Recently, General Electric's director of global strategy and planning stated that water scarcity made expansion plans for coal power plants in China and India unfeasible (BusinessWeek, 2012). The 2012 UN Water Report surveyed more than 125 countries and found that 48 percent of nations rank the importance of water for energy as a high or very high problem, while only 9 percent of the countries surveyed did not view it as a problem (UN 2012). A recent World Resources Institute report assessed existing and planned power plants in India and southeast Asia and concluded that over half are located in areas that will likely face water shortages in the future (Sauer, 2010).

Climate change will increase the vulnerability of countries, as rising temperatures accelerate evaporation and precipitation. Also, rain patterns will shift and intensify, thereby increasing uncertainty in energy development. Power generation faces two main risks: increased water temperatures for cooling (van Vliet, 2012), and decreased water availability. There have already been some repercussions on the energy sector (USC, 2011) as power plants have been forced to shut down due to lack of water for cooling purposes or due to high water temperature. In addition, questions are being raised about solar thermal power plant projects because of their impact on the water resources of particular regions. Moreover, sea level rise could adversely impact coastal energy infrastructure and power plant operations, and climate change will also affect the energy sector through varied energy demand, especially for cooling homes, offices and factories as temperature increases. Integrated planning will serve as adaptation and mitigation measures to improve resilience to climate change impacts.

Future water scarcity can threaten the viability of projects and hinder development. Market analysts are predicting that energy supplies may be threatened by water scarcity. A recent report by the IEA (2012) concluded that water constraints might compromise existing operations and proposed projects, and increase operational costs when adaptive measures have to be put into place.

Thermal power plants can become stressed in regions with low water availability

due to their large water requirements. In order to reduce vulnerability to water scarcity, power plants will most likely employ closed-loop cooling systems. While this may reduce water withdrawals, water consumption could significantly increase (IEA, 2012). There are many alternatives to address the water-energy nexus in power generation, such as better cooling system technologies. However, many current options are less efficient and more costly, so operators prefer conventional systems until regulation or pricing dictates otherwise.

Thermal power plant operations can also be threatened by increased water temperatures. Increased water temperatures are correlated with rising air temperatures (Stewart et al., 2013) and can prevent power plants from cooling properly, causing them to shut down. These concerns will become increasingly important as companies consider alternative technologies (such as dry cooling), and governments study the placement of power plants along rivers, ensuring the plant's sustainable future operation under increased energy demand and potentially warmer climate. Due to these risks, governments must re-examine where thermal power plant projects are located. Figure 6 depicts the risks assessed by a study done by the World Resources Institute (WRI) for Southeast Asia. The impact of climate change and population growth in the region will increase water stress on power plant operations. The map at the top reveals the baseline[2] water stress[3] conditions in Southeast Asia, and the map at the bottom depicts water stress power plants will face in 2025. The maps show that 19 percent of the design capacity of power plants in southeast Asia is located in areas of "medium-high,[4]" "high," or "extremely high" baseline water stress, and that by 2025 (map on the right), 55 percent of these plants will have "significantly worse,"[5] "extremely worse," or "exceptionally worse" water stress. As climate change impacts manifest themselves and global resources are placed under additional pressure, it is critical that governments prepare to ensure the security and stability of their countries.

A changing climate and increasing water variability will also affect hydropower as flows shift due to changing precipitation. In addition, glaciers that feed hydropower plants may disappear, thus jeopardizing the ability of nations to generate power. Compounded uncertainty due to changes in surface water temperature, flows, and availability are forcing companies to develop more sustainable practices to ensure the long-term viability of their operations and infrastructure.

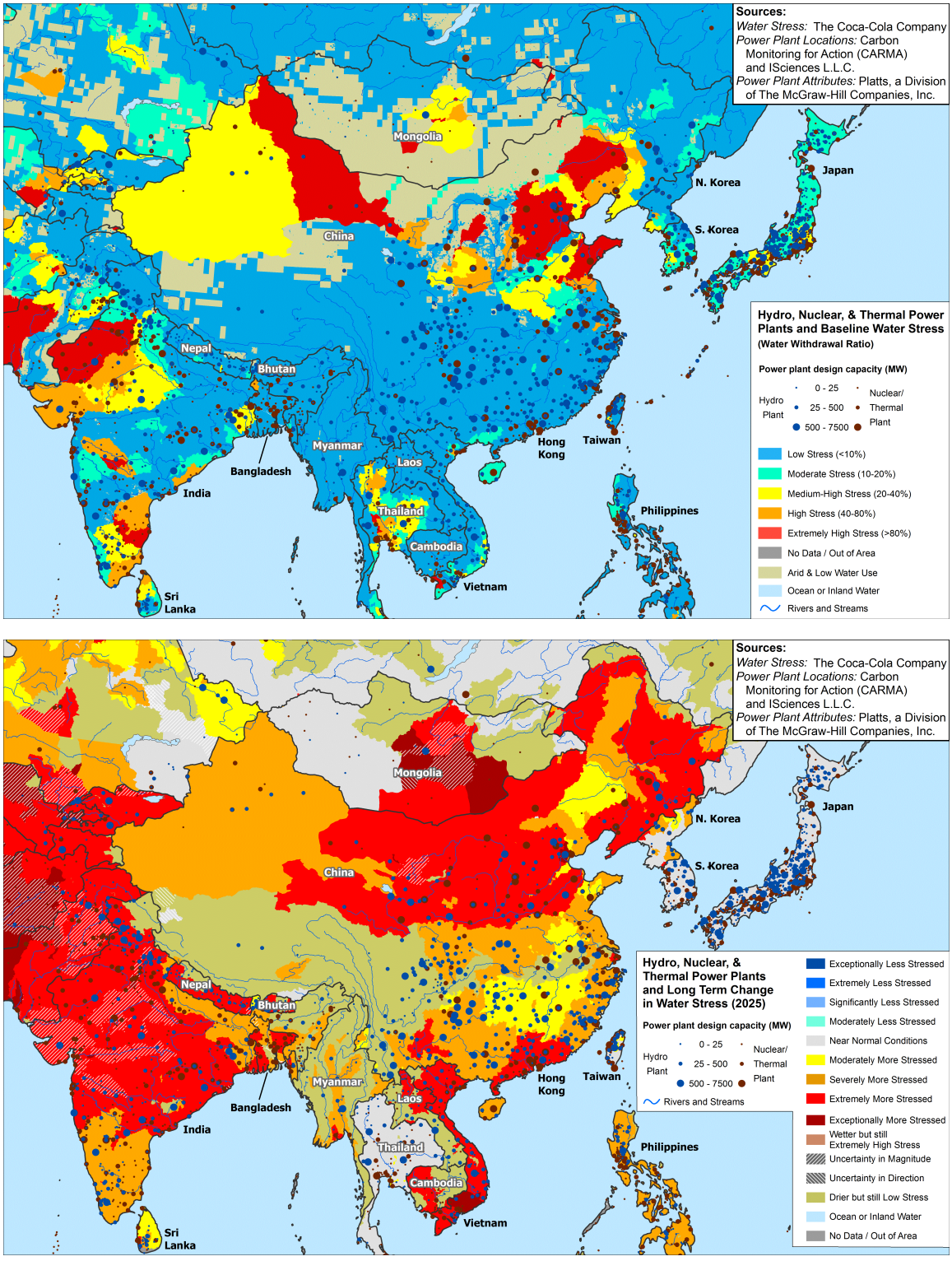
[2] The baselines water stress is defined as the ratio of total annual freshwater withdrawals for the year 2000, relative to expected annual renewable freshwater supply based on 1950–1990 climatic norms. This ratio provides an assessment of the demand for freshwater from households, industry, and irrigation agriculture relative to freshwater availability in a typical year.

[3] In this study, water stress is defined as the ratio of water withdrawal to renewable supply.

[4] 'Medium-high' corresponds to a ratio of 20 to 40 percent of available freshwater used; 'high' corresponds to a ratio of 40 to 80 percent of available freshwater used; and 'extremely-high' corresponds to a ratio of more than 80 percent of available water used.

[5] WRI defines "significantly worse" as 2 to 2.8 times worse than baseline conditions; "extremely worse" means 2.8 to 8 times worse than baseline conditions; and "exceptionally worse" means more than 8 times worse than baseline conditions.

Figure 7: Southeast Asia, Baseline Water Stress and Power Plants (top) and Long Term Change in Water Stress and Power Plants, 2025 (bottom)
(WRI, 2011)



Section 3

Towards Potential Solutions: Improved Management of the Nexus

Opportunities for Synergies in Water and Energy Infrastructure

Although the link between water and energy is now evident, these two sectors have historically been regulated and managed separately. The complexity of the system requires a more systematic approach that takes into account all the existing interactions and relationships between sectors and explores the strategic complementarities and potential synergies among infrastructure sectors, as well as with other sectors. Energy and water planning must be integrated in order to optimize investments and avoid inefficiencies. Similarly, cross-sectoral implications need to be better understood. In addition to taking water constraints in the energy sector into account when undertaking power expansion plans, there are also many opportunities for the joint development and management of water and energy infrastructure and technologies, maximizing co-benefits and minimizing negative tradeoffs. When assessing the needs of the energy sector, water planners and decision makers must fully understand the requirements of electricity generation technologies and their potential impact on the resource. Similarly, energy planners and investors must take into account the complexities of the hydrological cycle and other competing uses when assessing plans and investments. One way of ensuring robust planning efforts is by implementing technical approaches and reforming governing institutions. Specifically, technical approaches may include employing co-production synergies, such as developing combined power and desalination plants, and using alternative sources of water for thermal power plant cooling processes. Institutional reform will require integrated planning and cross-sectoral communication to bolster efforts to mitigate the energy-water nexus, and must be achieved before technical solutions can be successfully adapted.

An integrated energy and water planning approach can ensure that both resources are developed sustainably as well as explore synergies more effectively. It is important to create innovative approaches that encourage cross-sectoral cooperation and assess water and energy tradeoffs at the regional and national levels, thereby ensuring that future demands will be met.

Technical Opportunities

There is an array of opportunities and technical solutions to reduce water use in power plants and to exploit the benefits of possible synergies in water and energy. Given the different uses of dams, hydropower sustainability can be improved through integrated water and energy planning and management

(see next section). For other power technologies, the shift towards those that require no water, such as wind and solar photovoltaic, could reduce both water requirements and greenhouse gas (GHG) emissions by the power sector. Since most of the water used by thermal power plants is for cooling purposes, the focus there should be on technical solutions that decrease freshwater needs. This can be achieved by a) using cooling systems that require none or very limited amounts of water, b) decreasing the waste heat of the plant and, as a result, decreasing the cooling needs, and c) using alternative water sources, therefore displacing freshwater needs. These options are described in the sections that follow.

Alternative Cooling Systems

Since the amount of water required depends on the cooling system used in the power plant, the use of alternative cooling technologies, such as dry cooling or hybrid cooling systems, can significantly reduce the power sector's water needs. Dry cooling uses air instead of water as the main heat transfer, and therefore does not consume nor withdraw water. This type of cooling system is suited for water scarce regions and is currently being used in South Africa as well as in several solar thermal power plant projects in arid areas. Hybrid cooling uses a combination of dry and wet cooling systems, thus consuming and withdrawing less water than conventional systems. However, regulations or policies are needed to encourage alternative cooling systems because they are often more expensive and less efficient than conventional ones. These systems allow for the location of power plants away from water sources but could result in more costly investments.

Decreasing Waste Heat in Power Plants

Another way to minimize water use in power plants is by reducing the amount of heat that is dissipated through the cooling system. This can be done by improving the efficiency of the fleet or by reusing some of the heat that is being lost. Some options for reusing the waste heat are: combined power and desalination plants, and combined heat and power plants.

Combined Power and Desalination Plants

Combined power and desalination plants, or hybrid desalination plants, can simultaneously produce drinking water and electricity. This solution is especially suited for extreme arid areas such as the Middle East, where there is almost no water available and where desalination will likely be implemented. Desalination is more energy intensive than traditional water treatment. However, in some regions of the world it might be the only alternative available to meet the growing demand for water. Hybrid desalination plants use an innovative process to integrate desalination with thermal power generation, which improves the efficiency and lowers the electricity cost of desalination processes. The waste heat from the power plant is used as the heat source for the desalination process.

Integrated water and energy production has several benefits: a) the waste heat becomes a resource, thus decreasing the volume of water required for cooling purposes, b) the cost of desalinating water decreases, so the option becomes more economically attractive,[6] and c) the integrated system is more efficient than the stand-alone option (a separate power plant and a separate desalination plant). The disadvantage is that the integrated system is harder to operate due to seasonal variability. During winter, demand for electricity can decrease; however, demand for water can remain constant all year long. This demand variability can be managed, but implies that when the two demands are not constant, the

[6] Some studies argue that this is the most feasible way to meet both electricity and water demand in arid areas (Pechtl, 2003).

system is running below its possible efficiency. There are different hybrid desalination plants in the world. Examples include the Fujairah hybrid plant in United Arab Emirates and the Shoaiba power and desalination plant in Saudi Arabia.

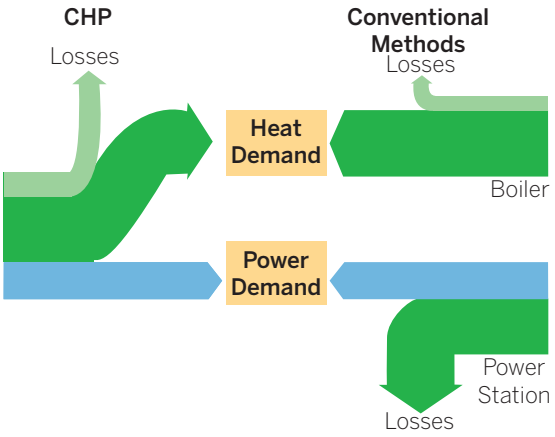
Combined Heat and Power (CHP) Plants

CHP plants (or cogeneration plants) integrate power and usable heat production in a single process. Whereas in conventional power plants, half or more of the heat produced gets lost as waste heat (dissipated into the environment through the cooling system), in CHP plants the heat is used for district heating as steam or hot water (see figure 8). Therefore, the amount of cooling water required by the power plant decreases substantially and the efficiency of the overall process increases. CHP plants can be implemented with any fuel source, but efficiency of the plants will vary.

An important advantage of CHP plants is that an integrated power and heat generation process is more efficient than the two stand-alone processes, thus decreasing greenhouse gas emissions and diminishing water requirements. The combined efficiency of the heat and power processes (total energy output by energy input) can reach as high as 90 percent (IEA, 2008). CHP plants rely on existing technologies and are in use in many parts of the world. In Denmark about 50 percent of the total power generated is produced in CHP plants (IEA, 2008). CHP plants are more efficient when they are located near the demand for heat and power, such as a city or industrial complex. If the heat has to be transported far from the production site, a significant percentage gets lost and the efficiency of the process drops considerably, and costs can also be higher. Thus, CHP plants are often well suited as decentralized forms of energy supply.

On the other hand, CHP plants require higher initial capital investments compared to conventional power plants. Although CHP plants are more economical in the long term due to the energy savings, the payback time is usually quite long. As with combined desalination and power plants, another disadvantage of CHP is the seasonal variations that affect the performance of the plant. Meeting the demand for heat and power adds additional complexity to plant operations. During the summer, it can become challenging to deal with the extra heat.

Figure 8. Sankey Diagram of CHP and Conventional Power Plants



Source: UK Department for Environment, Food and Rural Affairs.

Alternative Water Sources

Alternative, non-freshwater sources, such as brackish water or seawater may be used as cooling water for thermal power plants. Although using alternative water sources can be challenging, and costs vary depending on the location of the source and water quality, alternative sources may reduce freshwater demands and use. One solution widely employed in some parts of the world is the use of sea water. However, this is only feasible if the power plant is located near the coast.

Treated wastewater can be an attractive cooling water alternative. However, there are several issues that must be addressed. Wastewater usually contains polluting substances. As a result, the water must be treated in order to avoid

corrosion and other undesired effects in the cooling system, which can be expensive. Moreover, in most countries the use of treated wastewater requires that power plant operators obtain additional permits, resulting in higher administrative costs. However, in those same countries, wastewater treatment plants are often required to pre-treat municipal water to at least secondary treatment standards before discharging it back to the source.

A major advantage of wastewater is that it is a source available in mostly every country, particularly in large cities. Securing wastewater from a nearby wastewater treatment plant could reduce future uncertainty and ensure a reliable and continuous water source for the power plant. This integrated solution is already being employed in some countries; in the United States, wastewater is used for cooling purposes in 50 power plants. Perhaps one of the best-known cases is Palo Verde in Arizona, which is the largest nuclear power plant in the United States. This plant uses wastewater as the sole source for cooling. The wastewater is piped in and re-treated onsite before it is used. Once it runs through the cooling system, it is transported to a pond where it evaporates. The power plant has recently secured 26 billion gallons of wastewater a year until 2050 (UCS, 2011). An important barrier to implementing this solution worldwide is that many developing countries lack sanitation infrastructure. However, this option presents a great opportunity to plan integrated water and energy infrastructure in the future and avoid the lock-in inefficiencies of developed countries.

Institutional Reform and Integrating Models for Planning and Design of Investments

Decision makers are often ill-informed about the source of problems in the water-energy nexus, what the merits of different technical options are, or the possible outcomes. Existing publicly available models[7] lack the capacity to address issues surrounding the value of different energy investments given likely or potential future water constraints and competing trends. Available models also lack the ability to address the wider social, economic, and environmental impacts of the energy-water nexus, and are unable to identify the implications of potential water and energy policies and investments intended to address water constraints. These challenges and complexities can no longer be addressed in the conventional way, with each sector taking decisions independently, with separate regulations, and different goals.

The Conventional Approach in Water and Energy Models

Currently, the primary concern in managing water resources is the distribution of water over space and time in order to meet specific objectives or demands. Most water allocation modeling often assumes adequate energy supplies will be available to divert, pump, and treat the water. Few, if any, of the water allocation models quantify the energy consumed in different water demand scenarios. This isolated assessment of water resources does not reflect the dynamic interplay between energy and water, especially due to the large energy demands required to transport and treat water to meet an end use.

Water models typically require a high level of hydrologic detail on a particular watershed, making them data-intensive as well as complex. Models can provide great detail of information

[7] There are several private and commercial models available that are more sophisticated. However in order for them to be useful for support developing countries, models and tools must be available at no/low cost. At current prices, the models are not able to provide a sound basis for national energy and water policy and investments.

on water circulation in the watershed, such as stream flows, evapotranspiration, return flows, exchange between surface and ground water. Yet, scaling up models to assess national water budgets is data intensive and often too detailed for first level resource assessments. In addition, while economic parameters can be combined with hydrological modeling to analyze the costs and value of output for a new hydroelectric investment, economic analysis of water allocation at a national level requires more economic detail on competition among alternative water uses.

Similarly, energy planning is primarily concerned with siting and cost requirements for energy generation in the context of transmitting the produced energy to population centers. Except for systems dominated by hydropower, the supply of water necessary for power generation at the upstream planning stage is typically assumed to exist and is often not considered to be a limiting factor in operations (although it is accepted that potential constraints will be an important factor). Models do not consider dynamically the use of water to generate the energy required by water infrastructure. In these situations, there is an inherent multiplier on both energy and water demands that may be overlooked when employing the traditional approach to modeling and analysis. While this effect may be quite marginal in regions with ample supplies of both water and energy, it could become a central cross-sector constraint in regions with resource scarcity and will require accurate evaluation and analysis.

Although energy models mainly focus on generation, they have advanced significantly over the last 40 years, incorporating estimates of water demand for energy production through simple coefficients of water utilization per unit of output.[8] Several energy systems models have been specifically developed to assist resource managers to develop water and energy resources in a sustainable manner. A wide range of models are available, from fairly basic electricity capacity expansion models to detailed electricity network models to economy-wide general equilibrium models with representations of various types of energy supply and demand. However, the energy models do not address total water availability and its dynamic nature or tradeoffs among water uses. In some advanced models water availability and variability are taken into account mainly as they affect hydropower production. The links between water availability and variability and other sectors are usually handled by incorporating exogenous constraints or parameters into the energy models (e.g. minimum environmental or navigation outflows, quotas for irrigations, among others). The Long Range Energy Alternatives Planning system (LEAP) is a widely used energy model because it provides a simple accounting framework, although it has limited optimizing capabilities. Other more sophisticated models, such as MESSAGE and MARKAL/TIMES, apply least-cost optimization that addresses the complexity of all technology options, especially for full-sector models that include end-use technology options. These models allow for the assessment of a wide variety of policies and technology options, and provide a consistent framework for assessing their costs and benefits (annex 3 provides a detailed assessment of different publicly available models).

Projected climate change and impacts on water availability are not commonly factored into conventional energy planning and operations. Global warming will likely cause increased competition for water resources from sectors such as agriculture and water recreation. The usual methodological approach to assess climate impacts on hydropower resource endowments consists of translating long-term climate

[8] Mainly for electricity, but can include water for biofuels, mining, and refining as well.

variables into runoff, although this involves great uncertainty.

Integrated Energy-Water Planning Approach

The tendency for traditional planning is to be narrowly focused and exclusionary (Grigg, 2008). Risk avoidance and control of resources is a paramount consideration in traditional planning for electrical utilities and water resources, but successful planning requires that government agencies and stakeholders participate in making decision through a coordinated process that includes conflict resolution. Integrated resource planning of the energy-water nexus often emphasizes the importance of establishing a more open and participatory decision-making process and coordinating the many institutions that govern water resources. Therefore, the energy-water planning approach encourages the development of new institutional roles and processes in addition to strengthening existing planning and analytical tools. It also promotes consensus building and alternative dispute resolution over conflict and litigation.

Due to the lack of integrated planning around energy-water management, an integrated energy-water modeling framework needs to address the shared needs of energy and water producers, resource managers, regulators, and decision makers at the federal, state, and local levels. Ideally, the framework should provide an interactive environment to explore tradeoffs and potential synergies, and also evaluate alternative energy/water options and objectives. In particular**,** the modeling framework needs to be flexible in order to facilitate tailored analyses over different geographical regions and scales (e.g., national, state, county, watershed, interconnection region).[9]

There are three possible approaches to address the nexus: a) incorporate water resources and uses into existing energy modeling frameworks, b) incorporate energy production and uses into existing water resource modeling frameworks, or c) build a new integrated framework. Of the existing modeling frameworks and current approaches to modeling energy and water, it appears that the most promising model is a nested approach that incorporates water resources and uses into existing energy modeling frameworks. This conclusion is further supported by the fact that energy system planning models currently exist in many developing and emerging economies.

There are several publicly available modeling frameworks under development that aim to provide an integrated energy-water planning capability. One such model is the integrated LEAP-WEAP model. The linkages between the two models allows planners to track water demands for the energy sector as defined by LEAP, and allows LEAP to track energy demands for various water processes (drinking water, agriculture, etc.) as outlined in WEAP. The priority for water lies within WEAP, which will "inform" LEAP when water availability is not sufficient for LEAP's proposed energy pathway. The program will then have to iterate until a balance is reached. While the combined WEAP-LEAP model represents each sector in detail, the model must overcome several differences in order for the systems to be dynamically linked. First, LEAP must be modified to include water demands for energy processes, and WEAP must be modified to include energy demands for water processes. Secondly, WEAP and LEAP must produce results for identical time steps. To achieve this LEAP was recently updated to include daily, weekly, monthly, and seasonal time slices. Additionally, WEAP and LEAP must agree on the spatial boundary for the model. WEAP applies primarily to watershed boundaries, while LEAP deals mainly with political boundaries.

[9] Annex 3 discusses the requirements of an energy-water integrated model in more detail.

WEAP also deals with specific power plants at a specific location (i.e., a point along a river), while LEAP deals generally with "types" of power plants.

When the differences between the two models are resolved, the combined model will allow integrated energy-water policy analysis for a broad range of energy-water options. Potential applications of the model include evaluating water needs for hydropower, cooling systems for thermal plants, tar sands mining, and biofuel production, as well as tracking energy requirements for water pumping, treatment, and other water processes. The main drawback of the WEAP-LEAP combined model for policy analysis is that the user must specify the development pathways of the energy and water systems, requiring iterations to evaluate alternative scenarios until the desired outcome is produced. There is no least cost optimization capability. However, the level of detail supported for the water system provided by WEAP and the lower initial data requirements are strengths that makes the model flexible and readily available. Other models are being developed that will provide planners with a complete view of energy and water demand from resource extraction to end use, across sectors.

Case studies are needed to demonstrate the importance of, and apply the existing tools to, an integrated energy-water planning process. The water and energy nexus is a very broad topic. As a result, case studies or pilot projects are required to illustrate different types of situations that are most relevant for client countries. There are many potential typologies for cases. Examples include a case where thermal generation will increase the demand on water resources; a case where renewable energy plans could be hindered by the need for water for new technologies, and where perhaps combining energy production and water could be the best strategy, and so on.[10]

Strengthening modeling framework and capacities will require a more robust treatment of risk and uncertainty. Resource cost and availability are typically defined by supply-cost curves, which are inputs to the model. Uncertainty in the cost or availability of specific resources is traditionally handled through scenario or sensitivity analyses that can determine different model results when these parameters are changed. Examples of when it is important to investigate uncertainty in this area include situations where the energy system is dependent on a significant amount of imported fuels, or where environmental or technological concerns may significantly alter the cost or availability of extracting or processing certain resources, and where weather/climate unpredictability may have extreme impacts on water for power generation.

Uncertainty in demand projections is typically only investigated through scenario analyses, where specific changes in future energy demands are postulated based on specific changes in underlying assumptions behind the original demand projection, such as a change in gross domestic product (GDP) or population growth rates. The introduction of water into energy models introduces new areas of uncertainty. The biggest of these is the variable nature of the underlying weather data projection and its correlation to the energy service demand projection. Energy system models do not normally deal with this kind of variability. Water models are often used to determine the resilience of the water system to weather extremes. Energy system models are more often used to identify economically optimal investments out of a large variety of possible options. Integrating water systems

[10] Other examples are: a case where existing thermal capacity could be facing challenges resulting from climate change impacts and where the future plans in the sector need to consider that effect; and a case where the impacts of climate change could radically change the expectations regarding hydropower production and where alternative designs or adaptation strategies need be pursued, and so on.

into energy optimization models will require careful design of the input data sets to avoid or minimize inconsistencies. Precipitation levels and temperature data are primary drivers of water availability, and they also directly affect the levels of energy services required for space heating and cooling as well as many other energy services. Integrated models will require the development of a coherent set of weather and energy demand projections.

The proposed modeling framework must incorporate the long-term effects of climate change. Climate change has an impact on both the energy and the water sector. Moreover, some mitigation policies may exacerbate challenges presented by the nexus in the future. Increased energy demand may occur with decreasing water resources (due to climate change and other social and environmental pressures). In combination, this may be a serious problem that planners are not adequately considering today. There is a need to explore the potential technological, social, political, and economic shifts involved in achieving different global climate trajectories and account for the potential impacts of climate change in the water and energy sectors.

The issue of agriculture, in particular food production is an integral part of the nexus. Water and energy are required in the agriculture sector, and some crops are used for the production of biofuels, which compete with food crops for water and land. However, bringing food into the mix adds several complexities to the modeling framework (e.g., modeling biofuels), which make such an approach extremely difficult to address. One possibility is to incorporate agriculture indirectly by adding the water demand of the sector (and other competing uses of water) into the modeling exercise.

Addressing the water and energy nexus will require the capacity and modeling tools to understand the advantages of different energy investments given the potential future constraints and the wider social, environmental, and economic implications of potential water and energy policies, **including investments intended to address water constraints.** Existing models do not provide the capacity to address these questions, and so are not able to provide a sound basis for national energy and water policy and investments. This is of particular concern for countries with strong energy demand growth, or significant declines in per capita water supply.

Addressing these shortcomings is not simply a matter of integrating physical water use into energy models. Economic analysis is necessary when assessing tradeoffs. Water and energy are crucial inputs into economic production. Tightening constraints may introduce the potential for reductions in economic activities. Increasing water demand and scarcity may increase market prices for water and energy and lead to the redistribution of these increasingly scarce resources. In the case of water, increasing scarcity in one area is likely to result in the increased purchase of food products from another area. When this occurs, significant structural adjustments can take place. These adjustments need to be managed with sensitivity in order to forestall short-term increases in overall economic activity and employment. Actual outcomes will depend on the capacity of a community to adjust; the rates of technological progress in water efficiency in energy and food production; and knowledge provision, institutional, governance, and planning arrangements to facilitate efficient investment and synergies in water and energy planning. One of the more difficult issues to manage is the fact that the economic value of water to the energy sector, at the margin, will generally be greater than its economic value to agriculture, while the implicit political power of the agricultural sector can sometimes be greater than that of the energy

sector. This implies that the energy sector will generally be willing and able to pay more for water than competing agricultural uses. The risk associated with this is that some agricultural groups may seek to use their political power to redress this difference in economic power, such as by portraying the energy sector as damaging agricultural interests and threatening food security. The output from the different energy and water planning models will be then incorporated into an economic model that will make it possible to look at different policy options.

Section 4

Conclusions and Recommendations

ntegrated energy-water modeling allows resource planners to consider whether water supply today and in the future will be sufficient to meet the cooling requirements of different power plants. Today, most of the energy-water planning efforts are specific to the United States, and the initiatives are in their pilot and research stages. Developing countries lack detailed energy studies and projections, limiting their capacity to fully assess energy-water impacts. There is scant literature regarding energy projections and associated water consumption for developing countries. If an analytical modeling framework is to be employed, several additional steps must be taken, including data collection, model(s) development and verification, and stakeholder involvement. The tools must be reviewed by stakeholders and need to clearly identify the tradeoffs associated with different operational and policy decisions. Finally, a decision making process must be developed that incorporates all of the above in order to have practical, real-world applications.

Modeling for integrated energy-water planning and water allocation must have a solid basis for identifying current and future levels of water availability. The models must incorporate accurate projections for water demands and consumptive use for all sectors: energy, agriculture (including biomass), public water supply, and the environment. Accurate projections for water supply (not availability, but natural water supply) are also needed. The models must address variability in scale to ensure results are congruent with respective water basin and the corresponding political/administrative control of the basin/region. Climate change's impact on supply and demand should also be considered.

Improved modeling will ensure that power plants are more strategically located and that they implement technologies that increase energy efficiency. Examples include hybrid desalination plants, which produce drinking water while generating electricity; combined heat and power plants that integrate power and usable heat production into one process; and water energy recovery from sewerage that captures methane and carbon dioxide in the waste to generate energy. Such integrated technologies have several benefits, including that they turn waste products, such as heat, into an input for another process. Moreover, energy and water planning that optimizes both resources will result in a more diversified energy mix, including renewables that consume almost no water, such as

wind and solar photovoltaics. Also, shifting from old (coal) power plants to newer, more efficient plants, such as natural gas combined cycle power plants would significantly reduce water use in the power sector.

Comprehensive approaches that consider the diverse set of factors that influence energy and water demand and incorporate those issues into solutions will provide a robust management framework for the energy-water nexus. Management capacities will be strengthened by integrated modeling approaches that allow governments to adapt to change, such as population and economic growth. This will enhance a nation's resiliency in the face of uncertainties brought on by climate change.

Integrated planning will require regulatory and political reform. Currently, laws and regulations governing water use vary, some are quite complex, while others are vague and inconsistent. Determining what laws govern water can be expensive and time consuming, thus preventing certain stakeholders from acquiring all the information they need or understanding their full implication. In addition, laws determining water rights may further complicate matters as some may govern an entire region, while others are basin specific. Certain groups hold special privileges of prior appropriation, recognizing their "first right" to water withdrawals. Thus, in basins where water rights are fully allocated, transferring water rights could be difficult or expensive.

The energy-water nexus will be addressed more effectively through enhanced stakeholder collaboration. Integrating policy to respond to challenges presented by the energy-water nexus will be a difficult. Through the incorporation of energy and water policy, existing synergies may be exploited more effectively. If policymakers improve coordination, the uncertainties brought on by climate change and the nexus may be made more manageable. If not, then they will be forced to address scenarios with policies that have cross purposes and deal with crises that could have been mitigated (Faeth, 2012).

Sustainable solutions require that issues not be addressed in isolation but through a systems approach of integrated solutions. Such solutions can only be achieved if there is communication between engineers and scientists in different disciplines as well as with technical experts and professionals in the social sciences, and economic and political decisions makers (Olsson, 2012). Cooperation is also a key element in integration, whether by formal or by informal means.

It is critically important to involve the public affected by the development and maintenance of a project. Therefore, the recording and collection of data, and the development and application of models at the basin level are needed to illustrate the benefits of bottom-up (versus top-down) approaches to integrating energy and water resources planning. Focusing on smaller basins will help member states benefit from understanding the impact of their planning and actions at the local level. The lessons learned from energy-nexus planning and implementation will carry these efforts forward on larger scales, such as regions.

To enhance these efforts and provide additional solutions and recommendations, the World Bank will continue to work with client countries to develop integrated water and energy management strategies through a series of case studies. Different tools and approaches will be developed and implemented that will enable countries to address and quantify the impacts of water constraints on the energy sector and the potential tradeoffs with other economic sectors. Thus, the initiative will demonstrate the breadth of benefits that the

integrated planning of energy and water investments has on a nation's long-term economic stability and well-being. This is the first introductory report of the initiative. Findings from the case studies will be disseminated to promote best practices in integrated water and energy planning, and means of mitigating pressures brought on by the nexus.

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ANNEXES

Annex 1

Water Withdrawal and Consumption by Power Plants[11]

To understand the order of magnitude of the water requirements of power plants, figures 1.1, 1.2, and 1.3 summarize the current knowledge that describes water withdrawals and consumption for different types of power plants and cooling systems. These figures exclude hydropower. However, it should be noted that given a type of cooling system, the amount of water required will mostly depend on the efficiency of the power plant (and not so much on the fuel type) and to a lesser extent on other factors such as climatic conditions. This also accounts for the disparity in outcomes among the same power plant technologies and using the same cooling system as seen in the graph below. For example, in the category "coal generic" there is a large range due to different power plant efficiencies: older coal power plants can have efficiencies as low as 25 percent whereas newer power plants can reach 40 percent efficiency.

Once-through cooling technologies withdraw 10 to 100 times more water per unit of electric generation than cooling tower technologies, yet the latter usually consume at least twice the volume of water as once-through cooling technologies, depending on climatic conditions. Water consumption for power plants using dry cooling is an order of magnitude less than for those same plants using recirculating cooling.

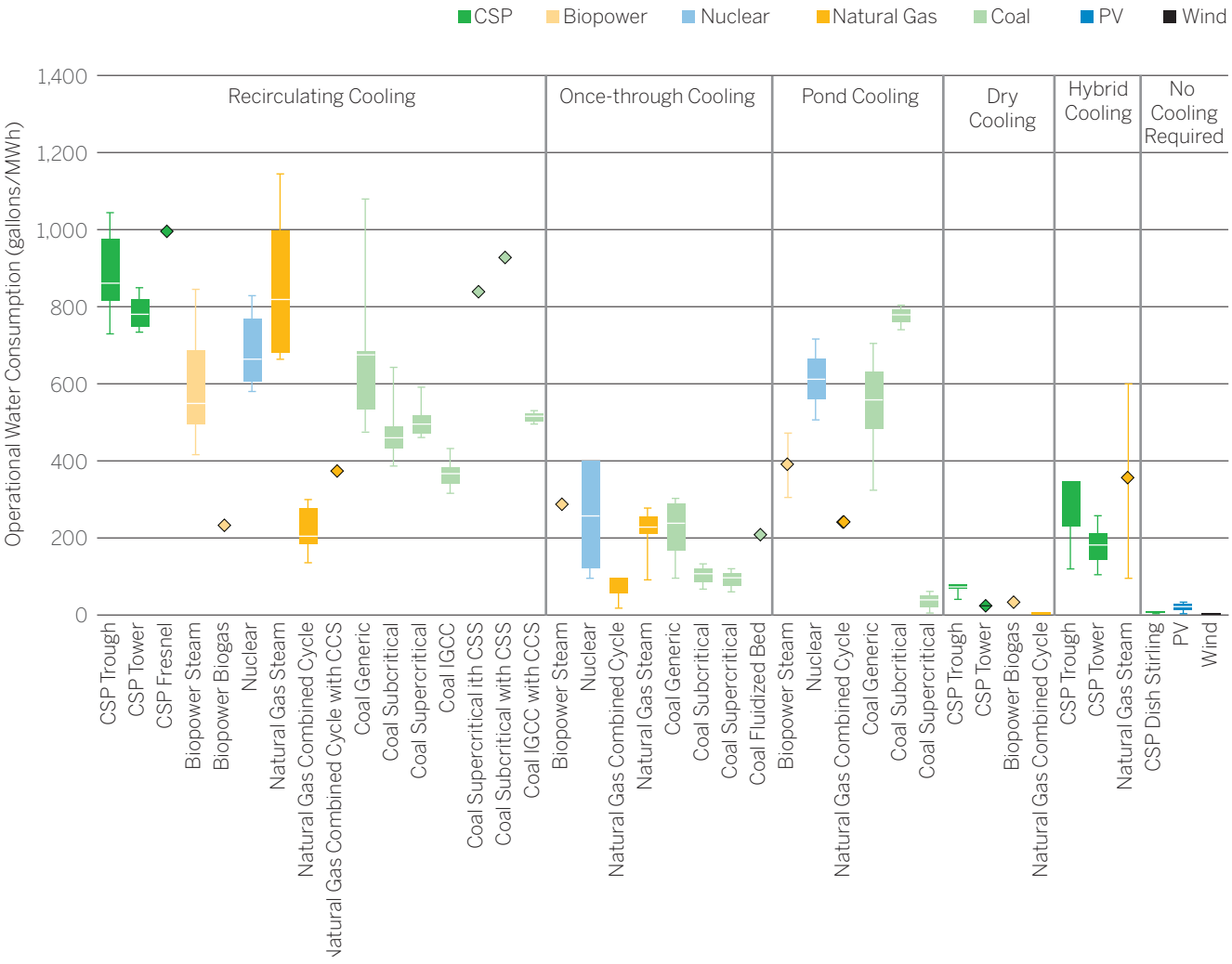
Water consumption factors for renewable and non-renewable electricity generating technologies vary substantially within and across technology categories, mostly due to their difference in efficiency. The highest water consumption factors for all technologies result from the use of evaporative cooling towers. Less efficient power plants such as pulverized coal with carbon capture and CSP technologies utilizing a cooling tower represent the upper bound of water consumption, at approximately 1,000 gal/MWh of electricity produced. The lowest operational water consumption factors result from wind energy, PV, and CSP Stirling solar technologies because none of them require water for cooling, and all the technologies using dry cooling systems. It should be noticed that natural gas combined cycle power plants have low rates of consumption and withdrawals in all types of cooling systems. Water

[11] This annex is based on the work done by Macknick, J., Newmark, R., Heath, G. and Hallet, KC. 2011. "A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies," Technical Report No. NREL/TP-6A20-50900. U.S. DOE National Renewable Energy Laboratory, Boulder, CO..

withdrawal factors for electricity generating technologies show a similar variability within and across technology categories. It is important to note that it is the efficiency of the technology that is the metric that must be assessed.

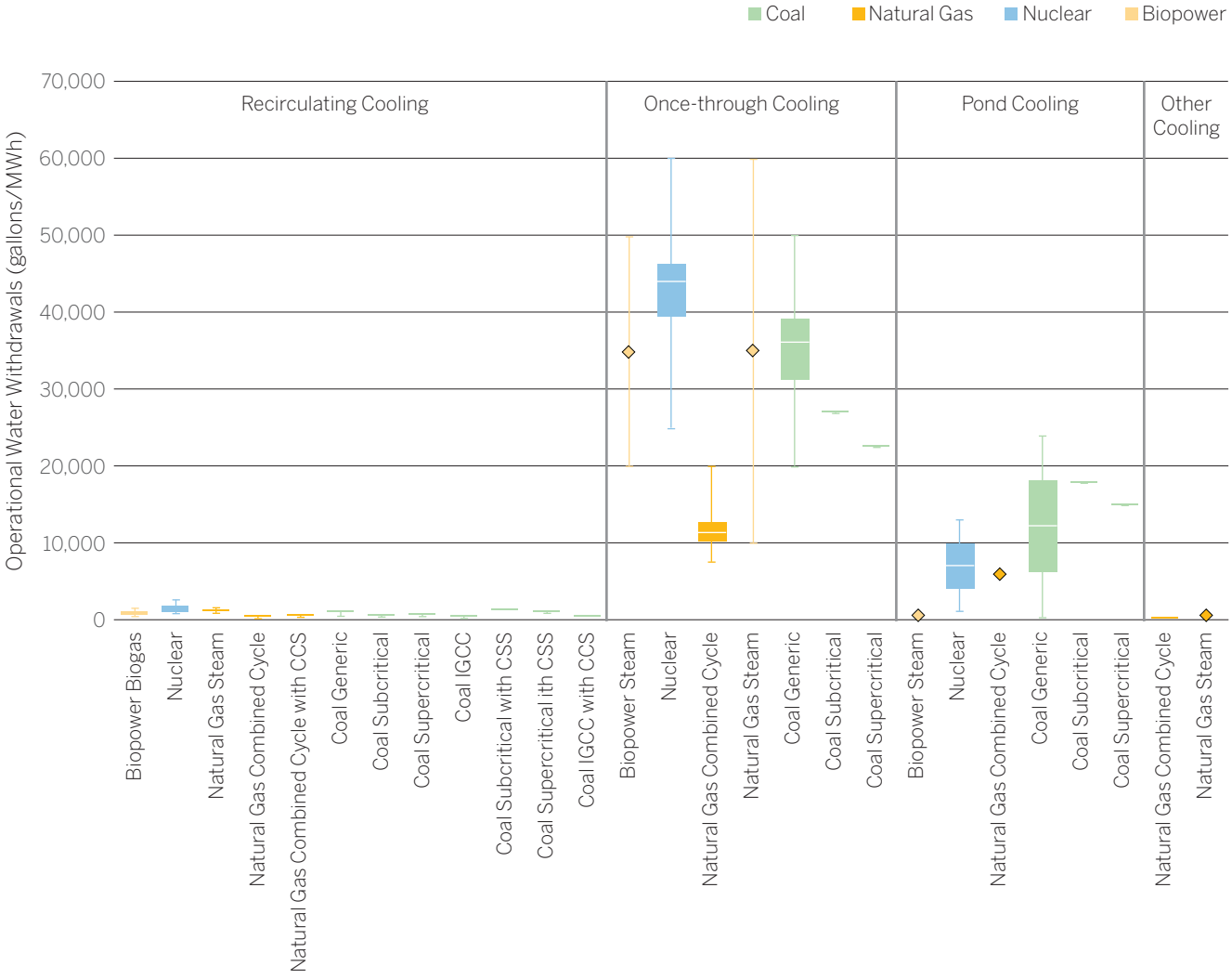
Taking the example of CSPs, Macknick et al. (2011) conclude that switching facilities from wet cooling to dry cooling results in reductions in output of 2 to 5 percent and increases the levelized cost of electricity by 3 to 8 percent (depending on local climatic conditions). In addition to the losses in efficiencies and the increases in costs of production, the choice of cooling system can have environmental impacts on the water resources.

Figure Annex 1.1. Operational water consumption factors for electricity generating technologies



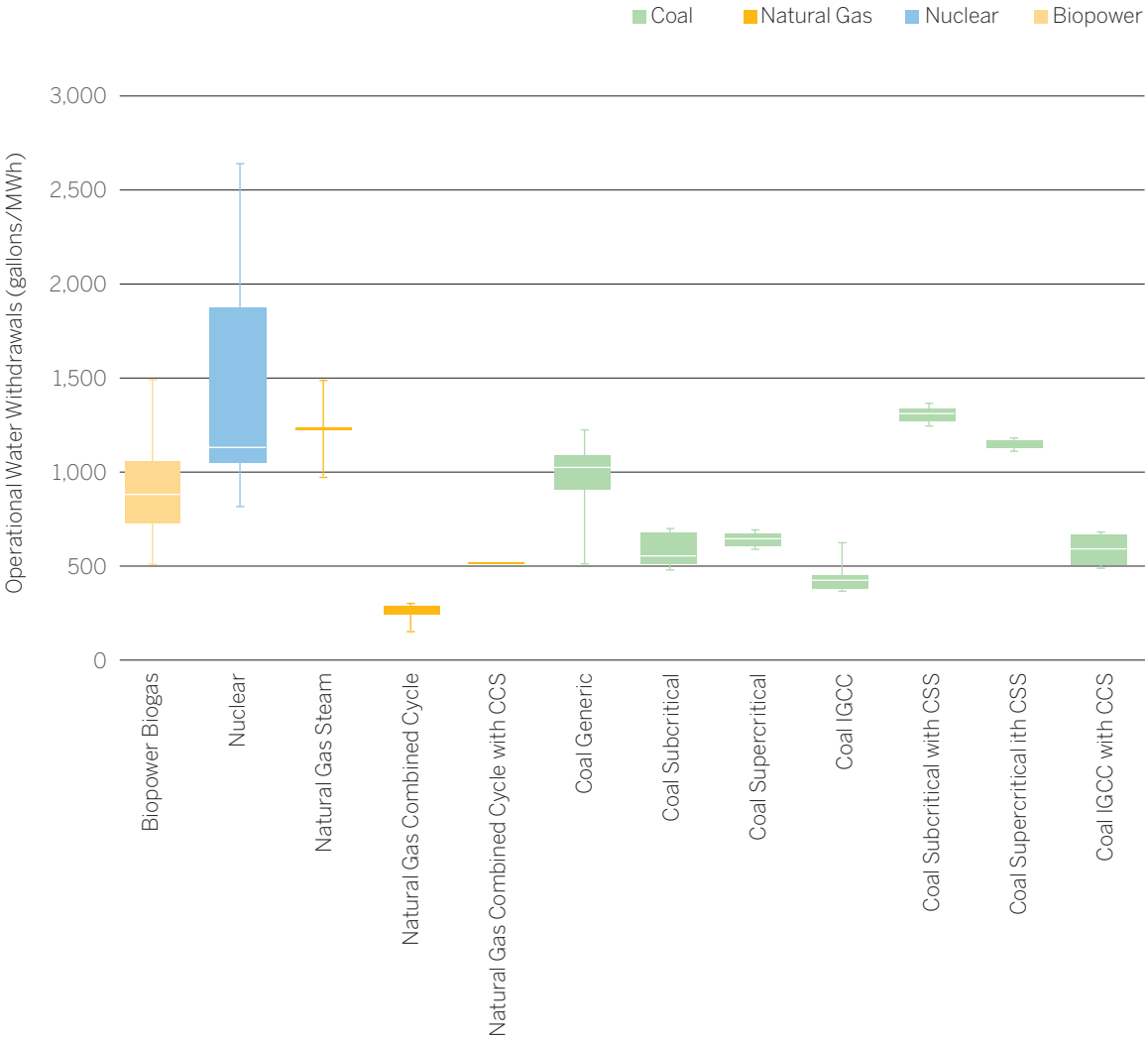
Source: Macknick et al., 2011.

Figure Annex 1.2. Operational water withdrawals for electricity generating technologies



Source: Macknick et al., 2011.

Figure Annex 1.3. Operational water withdrawal factors for recirculating cooling technologies (*zoom-in from previous figure*)



Source: Macknick et al., 2011.

Carbon Capture and Storage

Carbon capture and storage (CCS) involves capturing carbon dioxide from large point sources (e.g., fossil fuelled power plants or other industrial sources) before they are emitted to the atmosphere, transporting it to the injection site and injecting it into deep geological formations for storage. There has been considerable interest in CCS as a supply-side management tool to dramatically reduce greenhouse gas emissions with the continued use of fossil fuels (IPCC, 2005; IEA, 2008). In fact, the EIA suggests that the power sector must rapidly adopt CCS over the next 30 years to achieve a 50 percent reduction in GHG emissions by 2050.

Although carbon capture technology is commercially available today (IEA, 2009), there are currently no large-scale commercial CCS power plants projects in operation. This is, in part, due to the high capital costs of the technology and sustained operating costs. However, as of January 2013, sixteen large-scale integrated CCS projects are considered "active," that is, they are being implemented or have secured a positive financial decision to proceed to construction. Of these, 12 percent are in the power sector and 88 percent are in industrial applications (Global CCS Institute, 2013). There are 75 projects identified around the world, of which seventeen are in developing countries (Global CCS Institute, 2013).[12] The first two commercial large-scale CCS-fitted power stations will begin operating in Canada and the United States in 2014 (Sweet, 2012).

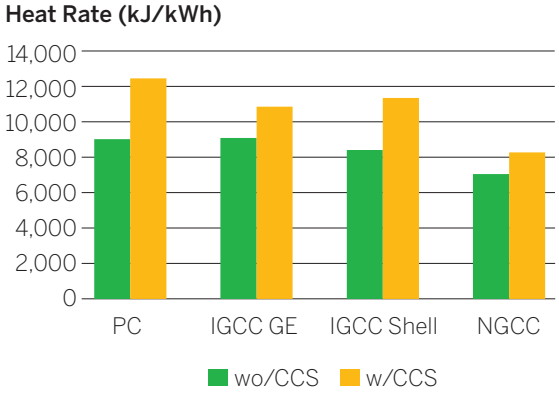
However, CCS presents new water challenges, both in the electricity generation process and in the injection of CO_2. Understanding these potential impacts and the conditions under which they arise is important to ensure the sustainable development of these projects. There are three categories of carbon dioxide capture processes from power production: (1) flue gas separation; (2) oxy-fuel combustion in power plants; and (3) pre-combustion separation. Each technology has energy and economic costs (Herzog and Golomb, 2004), and affects water resources.

[12] Eleven projects are in China: seven power plants and four industrial projects.

Water Usage

Current forms of conventional thermal electricity generation with fossil fuels use water for fuel extraction, generation, and cooling. Adding CCS technology to power stations increases water requirements, qualified by capture and power station specifications (DOE, 2009). Power plants with CCS necessitate additional water for the carbon capture processes, especially in IGCC plants. However, most of the increased water requirements are for cooling purposes. Carbon capture reduces substantially the efficiency of the power plant (heat rate increases: see figure 2.1). In post-combustion carbon capture, efficiency is affected as a result of the extracted heat from the steam electric cycle that is used to heat the solvent (amine) and release the captured CO_2. In addition, efficiency suffers when electricity is used to run auxiliary equipment such as pumps, fans, and compressors for the CO_2 capture stream. Thus, more fuel inputs are required to achieve the same electricity output, resulting in additional amounts of cooling water per kWh generated. This increase in water needs could more than double water requirements for CCS power plants compared to the non-CCS ones with the same cooling system.

Figure Annex 2.1. Comparison of Heat Rates (HHV) with and without CC



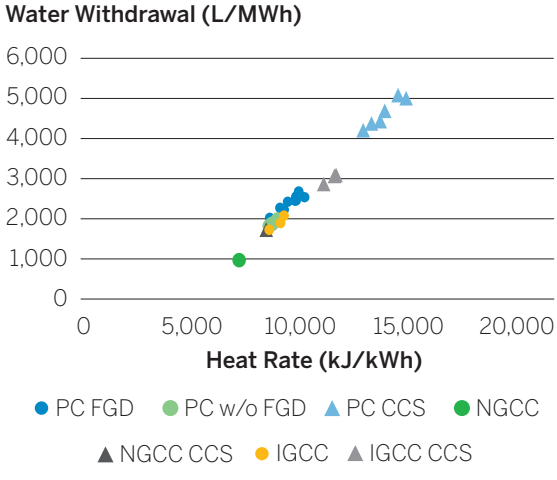
Source: DOE/NETL, 2010.

Analyses of the performance of power stations with CCS have been frequently overlooked water use. Nevertheless, some detailed estimates of the water withdrawal and consumption needs of electricity generation with CCS have been prodbuced, notably by the US Department of Energy and the National Energy Technology Laboratory (DOE/NETL, 2009). Figure 2.2 compares water withdrawal requirements for power generation with and without CCS (with cooling towers).

It can be observed that water requirements increase substantially with CCS, more than doubling in some cases. Moreover, this graph also shows the relationship between heat rate and water needs. The more efficient is the plant (lower heat rate), the less waste heat and the less water it requires

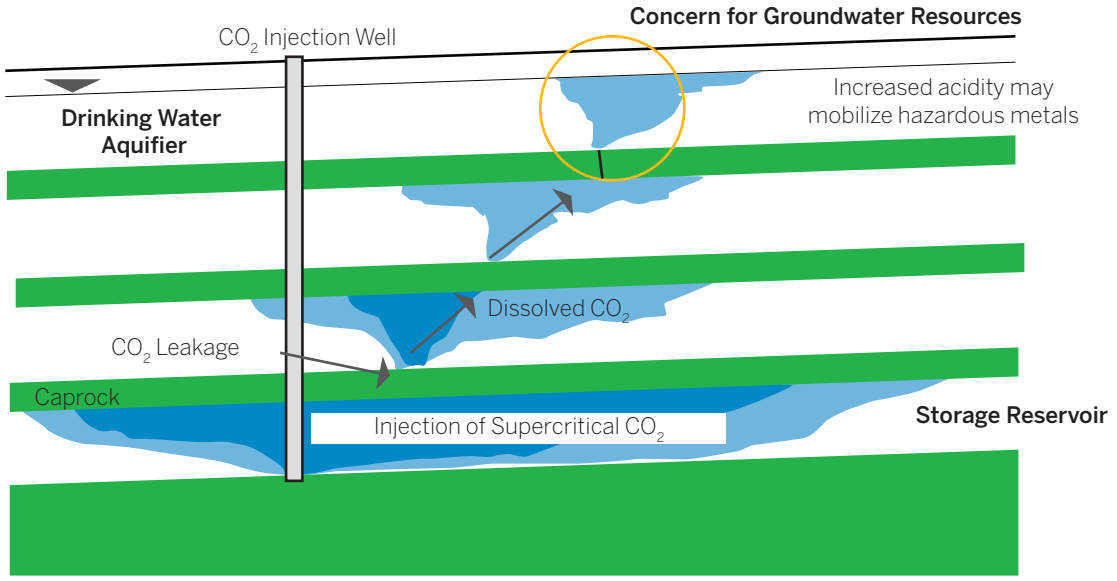
The use of water in electricity generation with CCS varies according to the efficiency of the power station, its cooling system, and the CCS technology in place. However, most of the water requirements are for cooling purposes, which accounts for 71 to 99 percent of the total water

Figure Annex 2.2. Comparison of Water withdrawn of CCS vs. non-CCS power plants with wet cooling towers



Source: Delgado, 2012.

Figure Annex 2.3. Leakage of CO_2 from storage reservoirs into potable aquifers and its impact on the water quality is a potential concern.



Source: Xu et al., 2007.

needs of the plant with CCS (Newmark, 2010). The type of cooling system used will determine most of the water requirements of the plant. The Tenaska Trailblazer Post-Combustion CCS Power Plant being developed in Texas will use dry cooling systems to reduce the water requirements of the plant by 90 percent (Tenaska Trailblazer Partners, 2011).

Adding CCS to a power plant can increase the water requirements per kWh up to 100 percent in some cases (depending on the cooling system used). This could be an issue for local water resources, especially in areas where the impacts of climate change could decrease water availability or increase water temperature (Naughton, 2012). This impact could be mitigated through the installation of a dry cooling system, but these systems are more capital intense than the wet counterparts and affect the efficiency of the plant. In order to ensure sustainable growth, the water aspects of CCS cannot be overlooked and must be incorporated into decision-making processes.

Water Quality

Carbon dioxide leakage is a particular concern with CCS (see figure annex 2.3), which is exacerbated due to higher withdrawal and consumption rates. The primary concern regarding the leakage of CO_2-rich fluids into groundwater is the potential mobilization of hazardous inorganic constituents (including lead and arsenic) due to the increased acidity these fluids generate, which could exceed maximum concentration limits under some conditions (Newmark et al., 2010). However, there is general agreement that the operational risks of CO_2 leakage due to CCS would be no greater (and likely lower) than the oil and gas equivalents because CO_2 is not flammable or explosive. The wealth of experience accumulated by the natural gas storage and oil industries can be harnessed for CO_2 storage and risk mitigation. The inherent risks associated with CO_2 injection and storage can be managed. A crucial element is assessing and identifying an appropriate injection site based on criteria for

capacity, injectivity, and effectiveness. Appropriate monitoring of the site will be important to detect and mitigate any potential leakages.

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Assessment of Energy Models

Review of Energy Models

While there are many energy models available, particularly in the private power sector (such as SDDP, Ventys, Promod, which are used for investment planning), this section focuses on only those models that are publicly available.

All the models discussed in this section are built on the principle of the Reference Energy System (RES), which identifies technologies and process as nodes in a network connected by energy flows. The models also include material flows that meet demands for energy (and material) services, while tracking emissions and other commodities based upon how the RES configured over time. This entire class of models is considered "bottom-up" technology-rich frameworks.

LEAP

The Long Range Energy Alternatives Planning system (LEAP) is an accounting and simulation-based framework in which the user defines the evolution of an energy system under various policies. It is developed and maintained by the Stockholm Energy Institute (SEI). The analyst must provide the allocations at each point in the energy system, indicating the levels of competing technologies and thereby the flow of energy throughout the system. The user must continually refine these assumptions until the desired results are reached. An intuitive user-friendly interface makes the model relatively easy to use. However, since it is an accounting framework, the user must provide "the answer" at each decision point in the model. Hence, LEAP currently cannot be used to determine the least-cost optimization of an energy system across policy goals. In addition, LEAP is not meant to handle very large, complex energy systems.

In attempting to address these shortcomings, an experimental optimization feature was introduced in the 2011 version of the model, which calculates the least-cost reduced form power sector capacity expansion scenario, with or without emissions constraints. This feature works with the Open Source Energy Modeling System (OseMOSYS) developed by SEI, IAEA, and others. The OseMOSYS project has resulted in a usable but limited representation of the power sector that can be subject to optimization. Comprehensive full sector (multi-objective) optimization could be brought to LEAP by constructing a bridge to TIMES. This would result in a way to introduce full sector optimization to LEAP users. LEAP is the most widely available energy planning tool and thousands of users have been exposed to it. All components of LEAP and OseMOSYS are provided

at no cost to nonprofit organizations, nonprofit governmental agencies, and universities based in developing countries.

ENPEP (BALANCE)

The Energy and Power Evaluation Program[13] (ENPEP) is a data intensive, complex energy modeling framework. It is an equilibrium simulation model that requires the placement of elasticities at every node in the network. The energy sector is treated as consisting of autonomous producers and consumers of energy, each seeking to optimize their own profits (or reduce costs). This approach is different from that of optimization models such as MESSAGE and MARKAL/TIMES (see below), which aim to optimize the entire energy system while achieving a set of user-defined policy goals. Policy analysis is difficult when using ENPEP because there is no easy way to formulate and evaluate alternative scenarios. The model is difficult to use because of a bulky user interface that is made more complex because of the numerous model components required. Thus ENPEP is a complete, comprehensive energy system model but one that is very difficult to use and maintain. ENPEP used to be provided by the International Atomic Energy Agency (IAEA) to member countries. However, due to the complexity of working with the model, the agency no longer promotes its use.

MESSAGE

The Model for Energy Supply Strategy Alternatives and their General Environmental Impacts[14] (MESSAGE) is an energy systems optimization model capable of scenario and policy analysis. It was developed and is used by the International Institute for Applied Systems Analysis (IIASA). It is similar to MARKAL/TIMES, but has some disadvantages. Most notably there is a very weak user interface and it uses a general purpose solver that can take hours to solve, particularly for large systems. Users familiar with MESSAGE and either MARKAL/TIMES or LEAP consistently prefer the latter alternatives. Therefore, it is not as widely used as the other modeling platforms.

MARKAL/TIMES

MARKAL/TIMES is the product of over 30 years of development and use under the auspices of the International Energy Agency's Energy Technology Systems Analysis Programme[15] (IEA-ETSAP). The modeling framework enables a wide range of users to employ least-cost optimization as an integral part of their planning process. It is a well-established model in use in over 70 countries and 200 institutions world-wide. The MARKAL/TIMES modeling framework allows users to specify policy and resource constraints as an input, and the model determines the optimal make-up of the energy system to meet that outcome (as is the case with MESSAGE). A typical national model can solve in seconds to a couple of minutes. In addition to its long-standing track record and ongoing development and support by IEA-ETSAP, a major advantage of MARKAL/TIMES is the very powerful model support systems available that oversee seamless management of all aspects of working with the model. Another advantage is the ability to link input and output data to Excel workbooks, resulting in a "report ready" format. Only LEAP can boast similar capacities.

MARKAL/TIMES is available through the IEA-ETSAP at no cost. The GAMS programming and model management software systems essential to effectively work with the tool are available from their developers, at a cost dependent upon the nature of the institution (e.g., academic, donor/research, commercial).

[13] See http://www.dis.anl.gov/projects/Enpepwin.html.
[14] See http://www.iiasa.ac.at/Research/ENE/model/message.html.
[15] See www.etsap.org.

Typical Inputs and Outputs of Energy System Models

The energy system models described above utilize information about both the current and possible future components of the energy system as well as demographic and economic information on resources and energy utilization needed to forecast future supplies and demands. The key types of inputs and outputs for an energy system model are summarized in figure 3.1.

Summary of Energy System Models

LEAP is a strong entry-level modeling framework that works well in developing countries with relatively simple energy systems. It is available at no charge and many developing countries are using it. However, LEAP is primarily an accounting framework with limited optimization capability, and the user must provide "the answer" at each decision point in the model. Therefore, LEAP is not suitable to handle large, complex energy systems.

MESSAGE is an energy systems optimization model capable of scenario and policy analysis. It has a very weak user interface and uses a general purpose solver that can take hours longer to solve large models than MARKAL/TIMES. Therefore, it is not as widely used as the other modeling platforms.

MARKAL/TIMES is used widely by agencies that employ least-cost optimization as an integral part of their planning process. MARKAL/TIMES has a very powerful user interface that supports data entry, scenario management, and results analysis. The IEA-ETSAP operating agreement sponsors the ongoing development of the

Figure Annex 3.1. Typical Energy System Model Inputs and Outputs

INPUTS	OUTPUTS

• Characterization of the current stock of existing technologies
• Resource supply (step) curves, and cumulative resource limits
• Characterization of future technology options
  • Fuels in/out, efficiency, availability, technical life duration
  • Investment, fixed and variable O&M costs, and "hurdle" rates
  • Emission rates
  • Limits on technical potential
  • Performance degradation (e.g., efficiency, maintenance costs)
• Demand breakdown by end-use
  • Demand for useful energy
  • Own price (and income) elasticities
  • "Simplified" load curve
• Discount rate, reserve margin
	• Total Discounted Energy System Cost
	• Resources levels and marginal costs, if constrained
	• Technology
	  • Level of total installed capacity
	  • Annual investments in new capacity and expenditure
	  • Annual fixed and variable operating and fuel costs
	  • Annual and season/time-of-day (for power plants) utilization
	  • Marginal cost, if constrained
	• Energy consumed by each technology (sector), and marginal price (by season/time-of-day for electricity)
	• Demand marginal costs and change in levels, if using elastic MARKAL
	• Emission level by resource/sector/technology for each period, and marginal costs, if limited

framework and supports a broad user community. MARKAL/TIMES is available through the IEA-ETSAP at no cost, but the GAMS programming and model management software systems are available at a cost from their developers. Because of its complexity, the IAEA no longer promotes ENPEP.

Least-cost optimization is a modeling methodology often used in the energy sector because it can handle the complexity of the possible options, particularly in the case of full-sector models that include end-use technology options. It allows for the assessment of a wide variety of policies and technology options, and provides a consistent framework for assessing their costs and benefits. However, energy sector actors do not always make decisions based on least cost principles, and a variety of modeling approaches are used to compensate for this fact. Most models are not intended to predict the future. Instead, they provide a consistent framework for examining the costs and benefits of alternative policies, strategies, technology options, and environmental constraints relative to a reference scenario, which represents a likely future projection of the energy system under current business-as-usual practices and policies.

Review of Energy-Water Models in Development

EPWsim

This section explores efforts to develop modeling frameworks that better integrate energy and water issues into planning models. EPWsim Sandia National Laboratories developed the Energy Power Water simulation[16] (EPWsim) tool in 2009 as a product of the Energy-Water Roadmap exercise. This prototype model has a modular architecture and is based on the commercial systems dynamic platform, PowerSim Studio Expert. The model currently supports several prototype modules for calculating thermoelectric power demand and related water use, water demand from competing use sectors, surface and groundwater availability, and an energy for water calculator.

An ongoing project being conducted by Sandia and partners aims to expand upon the existing modules and develop additional ones that would be able of providing planners in the Texas and western interconnects with a decision support system to analyze the potential impacts of water stress on transmission and resource planning. Among the new modules envisioned is an environmental controls model, climate change calculator, water cost calculator, and a "water stress" calculator. The new and expanded modules will provide a complete view of the power and water systems, from resource extraction to end use, and will allow the user to explore how the two systems interact and are affected by economic and environmental uncertainties (such as climate change and population growth). The model allows for a flexible definition of the "water stress" indicator, which is calculated by taking into account factors such as water availability, water demand, water cost, and institutional controls (water rights). The user chooses how to weight these factors. This "water stress" indicator is then factored into future investment decisions.

An optimization feature is anticipated that will tell the user the optimal sites for future power plants, when to construct them, as well as the optimal energy portfolio. These calculations will take into account cost, water availability, emissions, and so on. For example, the model may decide that a future power plant should be sited in an area with less stringent institutional controls in order to reduce cost. To determine this, the model has two ways of defining water availability. "Wet" water is water that is physically available in the region, while "paper" water is water which is available after institutional controls have been applied.

[16] See http://energy.sandia.gov/?page_id=4458.

The goal of the model is to explore the shared needs of energy and water producers, managers, regulators, and government decision makers to determine the "best alternatives" from a wide range of power-water options. The analysis can be tailored to different geographic boundaries and scales (national, state, county, watershed, interconnection) and can model results from a year to decades in the future. This spatial flexibility allows the model the potential to be applied in many different countries and regions around the world.

The challenges involved in expanding the EPWsim model stem from the integration of a wide array of data sets and modeling tools that all are based on different software platforms. The current project will create an overarching model architecture that integrates all of the components together into one user-friendly interface. The model will also have extensive reporting capabilities, creating customized charts, tables, and maps using GoogleEarth.

While the current state of EPWsim is not yet suitable for final policy analysis, Sandia's project is expected to result in a decision-support system that provides full sector representation of the energy and water systems and can optimize future pathways of development to ensure adequate water and energy supplies for all.

MARKAL-Water

Another result of Sandia's Energy-Water Nexus Roadmap was a pilot study undertaken by the Brookhaven National Laboratory (BNL) to develop and demonstrate an integrated energy-water decision support tool for planning in New York City (NYC). Although 57 percent of NYC's freshwater withdrawals are for thermoelectric power production, water supply for energy production is less of a concern to the city than its ability to provide adequate energy for future water and wastewater processes.[17] As such, the development of the model placed greater emphasis on defining the energy needs of the water and wastewater sectors, while still tracking water and wastewater flows to evaluate the impact of water conservation initiatives.

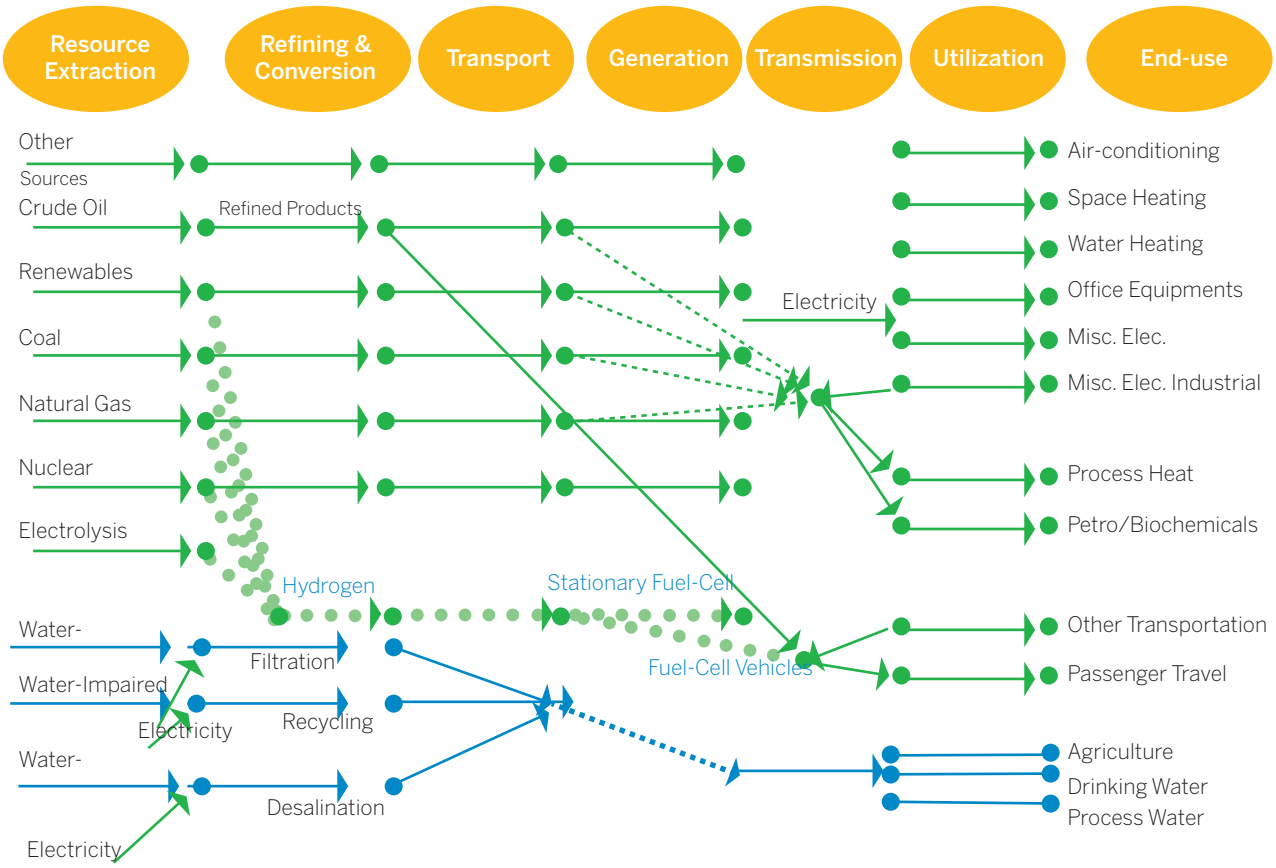
The study determined that a decision-support tool could most easily be created by expanding upon MARKAL, which is the existing energy modeling framework. In the pilot study, an existing MARKAL model of the NYC energy system was expanded to include the water system, creating a Reference Energy Water System (REWS). The REWS models water and wastewater (impaired water) from the source (freshwater, groundwater) to processing (treatment), transmission (conveyance systems), and through to end-use. The three water service demands included in the preliminary model were those for agricultural, drinking water, and processed water. Water flows for thermoelectric power production and steam generation are also tracked. The simplified REWS from this study is shown in figure 3.2.

Each node in the REWS represents an energy or water technology with associated energy and material flows. As with a typical MARKAL model, the parameters of each energy and water technology are the inputs (e.g., investment cost, operating cost, lifetime, efficiency). The level of detail for the water technologies were limited compared to the energy technologies for this preliminary model. The costs for every component are evaluated because the demand for both energy and water are optimized simultaneously to configure the least-cost REWS, subject to resource limits and policy constraints.

The ultimate goal of the MARKAL-Water model is to provide a widely available, user-friendly integrated decision support tool. However, the modeling of the system at the watershed level was not included beyond basic

[17] Brookhaven National Laboratory, 2008. http://www.bnl.gov/isd/documents/43878.pdf

Figure Annex 3.2. Example Reference Energy-Water System



resource supply curves (a series of quantities of water at incremental costs), and will require further development or linking to other modeling programs. The impact of climate change scenarios on the water supply system was not captured in the model but could be handled by means of sensitivity analysis (on assumed supply and demand levels). The effect on hydropower, which presents unique energy-water-climate challenges, can be addressed in MARKAL by applying stochastics to the reservoir and water supply. The NYC MARKAL-water model demonstrates that the integrated platform is viable. Yet, further work is still needed to improve the dynamics of water supply, perhaps by linking to a water basin model for a particular area of study.

WEAP-LEAP

The Stockholm Environment Institute (SEI) is working on an integrated energy-water decision support system that integrates their WEAP and LEAP modeling frameworks.[18] This combined model matches the energy system planning capabilities of LEAP with the water system detail and planning capabilities of WEAP. Both of these programs are well-established, accounting and simulation-based models suitable for policy analysis in their respective sectors. Both models have a wide user base and friendly user interface, and both come with extensive default

[18] See http://www.sei-us.org/media/SEI-Symposium-2010_Heaps_Sieber.pdf

datasets to lower the initial data requirements. To date, WEAP-LEAP integration is still in the beta testing stage, and data exchange has to be performed manually. However, SEI is developing a new version to allow for the two programs to run in concert, in an iterative manner.

The linkage between the two models will allow WEAP to track water demands for the energy sector as defined by LEAP, and LEAP to track energy demands for various water processes (drinking water, agriculture, etc.) as outlined in WEAP. The priority for water will lie within WEAP, which will "inform" LEAP when the availability of water is insufficient for LEAP's proposed energy pathway. The program will have to iterate until a balance is reached.

The advantage of the combined WEAP-LEAP model is that each one represents its respective sectors in detail. However, in order to link them dynamically, several differences between the models must be overcome. First, LEAP must be modified to include water demands for energy processes, and WEAP must be modified to include energy demands for water processes. Secondly, WEAP and LEAP must produce results for identical time steps. To this end, LEAP was recently updated to include daily, weekly, monthly, and seasonal time slices. Additionally, WEAP and LEAP must agree on the spatial boundary for the model. WEAP applies primarily to watershed boundaries, while LEAP deals mainly with political boundaries. WEAP also deals with specific power plants at a specific location (i.e., a point along a river), while LEAP deals generally with "types" of power plants.

When the differences between the two models are resolved, the combined model will allow integrated energy-water policy analysis for a broad range of energy-water options. Potential applications of the model include evaluating water needs for hydropower, cooling systems for solar thermal plants, tar sands mining, and biofuels production, and tracking energy requirements for water pumping, treatment, and other water processes.

The main drawback of the WEAP-LEAP combined model for policy analysis is that the user must specify the development pathways of the energy and water systems, requiring their iteration to evaluate alternative scenarios until the desired outcome is produced. There is no least cost optimization capability. However, the level of detail supported for the water system provided by WEAP and the lower initial data requirements are strengths that makes the model flexible and readily available.

A WEAP-LEAP beta test project is currently underway at Lawrence Berkeley National Laboratory to model energy water use in the Sacramento, California, area.[19] Energy-water sector linkages include power generation, water utilities, cooling and water heating for residential, commercial and government buildings, agriculture irrigation and water pumping, and industrial heating and cooling. The study is focused on understanding potential climate change impacts and the effectiveness of adaptive management strategies. A WEAP-LEAP model was developed for the American River basin and Sacramento Municipal Utility District. The study is still ongoing.

[19] SEI, 2010. http://sei-us.org/media/SEI-Symposium-2010_Dale.pdf.

Summary of Characteristics of Existing Energy Modeling Frameworks

Characteristic	LEAP2011	ENPEP-BALANCE	MESSAGE	MARKAL/TIMES
Developer/ Support Group	SEI	Argonne/IAEA	IIASA/IAEA	IEA/ETSAP
Home Page	www.energycomunity.org	www.dis.anl.gov	www.iiasa.org / www.iaea.org	www.etsap.org
Methodology • Model Type • Solution Algorithm • Foresight	• Accounting/Simulation • Limited optimization solver added late 2011 • Not Applicable	• Equilibrium Simulation • Non-Linear Programming, Iterative • Myopic	• Optimization • Linear Programming • Perfect or Myopic	• Optimization • Linear Programming • Perfect or Myopic
Solution Goal	• Simulate effects of user-defined expansion pathways by adding flows through a rigid network • Optimization tool will allow option to calculate least cost energy system over entire time period.	• Simulate response of various segments of the energy system to changes in energy prices and demand levels • Calculates equilibrium price for intersection of supply and demand	Minimize total system costs under constraints imposed on the energy system	Maximize consumer/ producer surplus while minimizing overall total system costs
Data Requirements	Medium: Typically 1 to 6 months of effort depending on the size and complexity of the energy system	Medium-High: Typically 6 to 12 months of effort depending on the size and complexity of the energy system	Medium-High: Typically 6 to 12 months of effort depending on the size and complexity of the energy system	Medium-High: Typically 3 to 9 months of effort depending on the size and complexity of the energy system
Default data included	• Technology Energy Database (TED) with costs, performance, and emissions factors (IPCC) • National Level "Starter" Data Sets for 104 developing countries: IEA energy balance data, IPCC emissions factors, UN Population projections, WB development indicators, non-energy sector GHG sources/sinks from (WRI), energy resource data (WEC).	• IPCC Emissions Factors • Technology cost and performance data	• CO_2DB with ranged values for technologies • IPCC emissions factors	Global models from the IEA, EIA, and ETSAP provide a repository of existing data for technologies and emissions
Time Horizon	User Controlled Annual Results	Up to 75 years. Annual Results	Up to 120 years. 5 to 10 year time steps	User controlled, any number of years
Other model features	New optimization tool links to OSeMOSYS to calculate least cost energy system. Not suitable for final reports or analysis.	Links with MAED demand services projection module, plus WASP power expansion module, and impacts, requiring additional information	• Links with MACRO model to determine impact of policies on energy costs, GDP, and energy demand.	Integrated MACRO nonlinear programming version allows for coupling with the economy, without iteration

(*continued on next page*)

Summary of Characteristics of Existing Energy Modeling Frameworks *(continued)*

Characteristic	LEAP2011	ENPEP-BALANCE	MESSAGE	MARKAL/TIMES
Other model features *(continued)*			• Expanded to include endogenous learning of technologies and include all six Kyoto GHG's	
Current Representation of Water Use	Water requirements can be externally specified for each technology as a form of environmental loading. In the same way that emissions are specified as kg/GJ of energy consumed, water can be specified as liters/GJ.	Water consumption can be entered as an "environmental parameter" such as gal/kWh or gal/kBOE. This information is entered into each node in the network. A price may be placed on the water ($/gal), however, there is no overall constraint for an environmental parameter	Water use is externally estimated. Exact mechanism is unknown.	Water can be modeled as a material flow linked to the energy system, and can be calculated and used as constraints on the energy system solution
Data/Results Handling	Full importing and exporting to Microsoft Excel, Word, and PowerPoint. Flexible reporting in charts, tables, and maps.	Manual data input/ Analysis module supporting reporting graphs, tables	ASCII tables and manual input. Standard set of results tables and graphs.	Integrated "smart" Excel input workbooks. Allows full customization of analysis tables, and intelligently links to Excel to automatically update presentation tables/graphs
Representation of policies	Policy analysts must create and then simulate alternative scenarios to determine marginal effects of new policies, or combined effects of multiple policies over time horizon. Optimization tool will allow policies to be represented in form of constraints: • Max annual emissions • Min, Max capacities for certain plant types	Policy analysts must create and adjust assertions as to how the system will develop over time and review the results, tweaking the assumptions until the desired results are reached.	Policies can be tried by means of constraints in the form of: • emissions targets on the overall system • Fuel • Export • shares for renewable energy	Policies can be introduced by means of flexible user-defined constraints in the form of: • emissions targets (on plant types, sectors, system) • energy security goals • shares for renewable energy • imposing efficiency standards

(*continued on next page*)

Summary of Characteristics of Existing Energy Modeling Frameworks *(continued)*

Characteristic	LEAP2011	ENPEP-BALANCE	MESSAGE	MARKAL/TIMES
Expertise Required	Low: Default data sets available, no optimization and relatively intuitive user interface.	High: Limited default data sets, limited elasticity data, difficult user interface	High: Limited default data sets, poor user interface with lots of manual data handling	Medium: Limited default data sets, clear and friendly user interface, Smart spreadsheets and results analysis tools.
Level of training required	Low-Medium: One to 2 weeks of training and most energy experts are able to build/use a simple model	High: 2 to 6 months of training and familiarization before most energy experts are able to build/use a model	High: 2 to 6 months of training and familiarization before most energy experts are able to build/use a model	Medium-High: 1 to 3 months of training and familiarization before most energy experts are able to build/use a model
How Intuitive? (matching analyst's mental model)	High, owing to its flexible graphical user interface	Low, owing to its bulky nature and complex user interface	Low, owing to its very poor user interface	Medium, owing to its powerful user interface with embedded modeling assistance features, as well as its dynamic linkage with Excel
Reporting Capabilities	Advanced	Basic	Basic	Advanced
Data management capabilities	Advanced	Basic	Basic	Advanced
Software requirements	Windows, executable	Windows, executable	Windows, executable. MESSAGE IV uses UNIX operating system	Windows, model source code, GAMS/solver, user interface executable
Software cost	Free to NGO's, government and researchers in developing countries	Free to Everyone	Free for academic purposes. Free to NPT states through IAEA	$8,500-$15,000 (including GAMS, solver & VEDA interface)
Typical training support & cost	Phone, email, or web forum. Regional workshops	5 day training session, $10,000	2 week session, free to NPT states	8 days, $16,500–$22,500
Technical support & cost	Phone, email, or web forum. Free limited support.	IAEA no longer promotes ENPEP	Phone, email. Free limited support to NPT	Phone or email. $500-$2,500 for one year
Reference materials	Manual & training materials free on web site.	Manual available to registered users	Manual provided with training	Manual available free on website
Languages	English, Spanish, Chinese, French, Portuguese, Italian, Indonesian	English	English	English, customizable

Annex 4

Requirements for Integrated Energy-Water Modeling Framework

One of the main challenges to integrating energy and water system planning models is their fundamental differences.

Watershed models are primarily dynamic simulations of a natural watershed and its interaction with man-made systems over an extended period given actual (and projected) precipitation and weather patterns. These models are driven by physical principles, such as soil permeability, to track the interactions between surface water and groundwater. They track water additions, withdrawals, and consumption across multiple interconnected basins from the system entry to the system exit. **Simulation models** are used because the objective is to meet water demands (physical and legal/institutional) under the most extreme conditions expected. The models determine the impact on future water availability and quality based on investment and management options.

Energy system models are also based on physical principles such as conservation of energy and materials, conversion efficiencies, and operational limitations. However, energy systems are driven by societal demands for energy services, which are related to standards of living and overall economic activity and growth. Within energy systems there are usually multiple energy carriers and technologies that compete to provide the many requirements. Therefore, **optimization models** are most often used, and most energy system models look to compare the optimal investment strategies for new energy technologies under a business as usual scenario and under alternative scenarios representing policy or technology options and choices. The models provide a quantitative measure of the relative costs and benefits for each option or choice.

Geographic and Temporal Requirements

The geographic nature of water and energy systems differ in that energy systems are typically delineated along political boundaries or interconnect regions, while water systems are generally outlined by watersheds and river basins. Location is more critical to water, as the majority of the resource supply is local. However, in order for an integrated energy-water model to be effective, the capability must exist to model the water system along boundaries typical to energy system models. Most energy models currently constructed were created to model geopolitical boundaries, and range from single nation to multinational and even global models. One approach to creating common assumptions on study

area boundaries is to construct an overlapping water model inside an existing energy model, such as in the BNL MARKAL-Water study for New York City. In this approach, the processes of the energy model would have to be spatially linked to the water supply locations from which they withdraw water.

In addition to agreeing on the spatial boundary of the model, an integrated energy-water model must also produce results for each system in identical time steps. Currently, many energy models produce results on time increments of one to five years, and analyze policies and options with model planning horizons of 20 to 50 years or more. Water models such as WEAP are able to generate sub-annual results (i.e. monthly), with WEAP being able to model time steps as small as one day. Since seasonal variability can have a large impact on water supply, it is important that the energy system can be modeled in sub-annual time steps. LEAP, in the ongoing effort to link it to WEAP, has been given the capability to model time slices of days, weeks, months, and seasons. MARKAL/TIMES also contains the ability to model these time slices, and both models provide additional differentiation between day and night and weekday versus weeknight. With an integrated energy-water tool that models each system across identical time steps and planning horizons, the analyst will be able to evaluate the temporal aspect of how the two systems interact with each other.

Another difference between energy models and water models is that water models use variable time series data on precipitation, which is their main driver. However, energy models usually assume relatively smooth changes in energy service demands and resource supply costs. Because most energy models are used to analyze relative changes from a reference scenario, weather-induced and other variability in these inputs does not add to the analysis. However, when water is added to energy models, the link between the projected future precipitation/weather patterns could be correlated with the energy service demands to better model the synergies.

Data Requirements for Incorporating Water into Energy Planning Models

After defining the model structure, one of the biggest challenges to creating an integrated energy-water model is gathering all of the data required to incorporate the water system into the model. The data collection may be time intensive, particularly in developing countries where it is not as readily available. There may also be legal and proprietary obstacles that require additional time to overcome. Sufficient lead time should be allowed to establish data sources and compile the required information. The types of data required for an integrated model include water consumption and withdrawal data from the energy sector, non-energy water demands, and water availability data, including knowledge of the local regulations and controls governing water use.

Water Consumption Data for the Energy Sector

Water consumption is present in virtually every stage of the energy system, from resource extraction, transportation and processing, to final conversion. Water intensity differs in each of these stages depending on the type of fuel and the technologies and methods used. The term "water intensity" is used to define the volume of water required per unit of energy produced (or potential energy in terms of resource extraction). This becomes useful when comparing the

water requirements for different technologies and methods with the same output goal (i.e., the difference in gallons of water consumed/MWh of electricity produced between a coal plant with open-loop cooling and one with closed-loop). While region-specific data should be used whenever available, there are numerous publications that contain averaged water use statistics for a variety of energy system processes. A number of agencies in the United States, including the Department of Energy and several national laboratories, have produced scientific reports on the water use of the U.S. energy system. One study from the Belfer Center for Science and International Affairs at Harvard University builds on work done by the USDOE, USGS, and multiple independent studies to create a detailed look at the use of water in each stage of the energy system. That information is a good data source for modeling water consumption.

Non-Energy Water Demand Data

Reliable projections of non-energy-related water demands, such as agricultural and municipal uses, are essential for incorporating the entire water system into the model. For each study area, the key indicators of future water use will be its population growth, GDP growth, and historical water use trends. Data for population and GDP growth projections are widely available through international agencies such as the IMF and UN. The availability and reliability of data on historical water use trends vary by country. However, agencies such as the UN FAO provide water profiles by country that detail water withdrawals per sector as well per source type.

Data concerning the breakdown of non-energy water sector demands is critical to modeling of future demand trends and to modeling of possible conservation measures. The UN FAO breaks down these sectors into domestic, agricultural, and industrial (including water for power plant cooling) uses.[20] As the goal is to track energy-related water use separately from competing demands, water demands for energy should be removed from the industrial or any other sector of which it is a part. Depending on the level of data available, additional non-energy demand sectors, such as mining and livestock, could be defined separately from agriculture. Further definition of the non-energy water demand sectors should be determined in accordance with the design and objective of the model.

The integrated model should be able to evaluate the impacts of end-use water conservation measures in the non-energy sectors. Data needed to accomplish this include information on the current stock of end-use water technologies as well as the costs, performance, and availability of future technology options. One way to model end-use conservation in the water sector is to establish water-independent parameters that separate the service demands from the technologies used to meet them. Parameters for the domestic sector may include "minutes per shower" or "flushes per year", while the technologies meeting these demands (showerheads, toilets) would require parameters such "gallons per minute" or "gallons per flush." Conservation initiatives may then be modeled by evaluating the impacts of incorporating more water-efficient technologies into the system. Additional examples might include the introduction of more water-efficient irrigation technologies in the agriculture sector.

Water Availability Data

Data on water resources by type (surface water, groundwater, non-potable) for the present

[20] UN-FAO. http://www.fao.org/nr/water/aquastat/main/index.stm.

and the future will need to be generated in a watershed model and aggregated for use in the energy model. The energy system model may span a single water basin or include two or more basins. Each water basin will have its own set of water supplies, withdrawals for energy and non-energy uses, and water reclamation. The data must be region-specific, and the availability and accuracy of the data may vary widely by country.

Average annual rainfall values provide a picture of the mean freshwater input to the system per year. Data on surface water entering the system may be obtained from stream gage measurements translated into historical average daily and yearly flows. Knowledge of locations of these measurements is important to determine the effects of upstream activities on future flows. In addition to average flows, data on extreme years of low flow will be needed to determine how the system is affected by periods of diminished supplies. Groundwater availability modeling requires a tremendous amount of detailed information about the aquifers in the region. Each aquifer will first need to be defined by its hydrogeological characteristics, water quality, and its connection to the environment and existing river systems. Then extensive amounts of data will be required concerning water levels, pumping rates, recharge rates, and other hydraulic properties. This data is likely to come from a wide variety of sources such as well owners/operators, regional planning groups, local water utilities, and governmental agencies.

Finally, defining the supply of non-potable water resources will require examining the potential uses of reclaimed wastewater, agricultural runoff, saline groundwater, produced water, and other industrial waste streams. Data regarding water quality, quantity, acquisition costs, and regulatory issues will be needed to determine the available supplies of these resources. The required water quality for compatibility with different cooling systems and other technologies should also be investigated to determine the need for additional treatment. Data on wastewater effluent quality and quantity should be obtained from local wastewater treatment plants. Information on other non-potable water sources may not be as widely available and may require consulting industry owners, farm owners, and other sources. Water availability is affected not only by the total supply of water, but also by local regulatory issues that determine how the water can be used. Acquiring knowledge of the local regulations regarding water use can be accomplished by consulting the local government. This information will allow the model to represent the true volume of water that is actually available for the energy sector.

User-friendly Interface

The user interface of the integrated model must be flexible and easy to use to allow for a wide range of users. A graphical, GIS-based interface is desirable to make it easy to enter region-specific data into the model. This allows for things such as the actual physical placement of not only the water sources, but the water and energy processes that utilize those sources. Links can then be made between the various processes in their respective locations. The model should have an interactive interface which allows direct control of the model and access to results displayed in charts, tables, and geospatial maps that are "report ready." A scenario generator is also needed to allow the user to create and evaluate multiple scenarios, and should allow clear control of the scenario make-up and criteria. Should the model be of modular architecture or require linking to other models, the user-interface should provide the seamless integration of all necessary models.

Impact of Water Constraints on Energy Sector Investment

Even in developed countries such as the United States, water constraints have already caused disruptions to energy investment plans. Recently, Idaho placed a 2-year moratorium on new coal-fired power plant construction because of concerns over the impacts to water supplies. And in other areas of the world, such as Latin America, worry over decreased precipitation levels and retreating glaciers due to climate change have caused concern over production from hydropower plants. Glacier retreat has already affected the output of hydropower plants in areas of Bolivia and Peru. As these trends continue, water availability and costs will act as constraints that affect the way investment decisions are made for many energy system processes, such as power plant selection, resource extraction, biofuels production, and resource processing.

In an integrated energy-water model, selection of the type and location of new power plant construction must factor in the consumptive water use requirements for cooling systems. Water requirements must then be compared to the available water supply in the area the plant is to be sited. If water availability is a constraint, several alternatives may be evaluated based on the severity of the supply shortfall. Changing the proposed cooling system to a dry cooling technology or hybrid technology will alleviate the requirements for water but will decrease plant efficiency. Utilizing different fuel types and generation technologies may also decrease the need for water, but will have an impact on plant performance as well as costs. Finally, relocating the power plant to an area without water constraints or constructing alternative supply infrastructure may prove to be cost-effective. The costs and availabilities of all of these options must be known in order to determine the best investment decision.

Resource extraction operations such as coal mining and shale gas extraction are also affected by water constraints. Unlike new power plants, however, the locations of resource deposits cannot be changed and water availability and costs will be dependent on the location of the resource. Investments regarding the development of new mines and wells will have to take into account the consumptive water use required per unit of potential energy recovered. Should the proposed resource be located in an area with low water availability or high costs, possible solutions may involve changing extraction methods, developing alternative locations, or extracting alternative resource types with lower water requirements. Each of these options must be evaluated on the basis of cost and production impacts.

Energy crop production relies most heavily on water resources and therefore may be most affected by water constraints. Irrigation of energy crops requires access to a steady supply of freshwater. Constraints on water availability may have an impact on crop selection and location, and may require investments to improve irrigation efficiency. Water constraints will play a role in shaping investment decisions in the various processing operations required for biofuels and fossil fuels after the extraction stage. If water availability is low, there may not be enough supply to perform the processing operations required. The location of the processing operations may be moved to areas with higher accessibility to water. However, this may cause increases in the costs to transport the fuel to the processing site. Choosing less water-intensive processing methods may also be an option, but will affect costs as well. The costs and impacts to production output must be viewed together to determine the best investment decision.

Dealing with Regulatory and Management Issues

In many areas of the world, laws and regulations governing water use are complex and difficult to navigate. In other areas, laws are vague and unreliable due to a lack of adjudication. The process of determining the possible regulatory obstacles in obtaining new water withdrawals may be expensive and time consuming. Dealing with the various regulatory and management issues will require a thorough knowledge of the laws and the locations to which they apply. Water rights laws in a region may apply to the entire region, but there may be basin-specific laws as well. Certain groups may also hold special privileges for water use, giving them "first rights" to water withdrawals. Where water basins are fully appropriated, the only way to provide water for new projects will be through the transfer of existing water rights. Restrictions to water transfers and the costs associated with it vary by region, and the process of acquiring the transfer may become lengthy and expensive with no guaranteed result. Where there is uncertainty over the validity of water rights laws, the risk of potential changes to the law should also be taken into consideration. Knowing the local regulations, costs, and time constraints that will be encountered for acquiring new water withdrawals will be vital to selecting the optimal location for a new project.

Accounting for Externalities

Energy system models regularly report a variety of pollutants, including CO_2, SO_2, NOx, particulates, and VOCs. Some models provide output to dispersion models to determine atmospheric concentrations, which are then used as inputs to health and environmental impact models. Modeling water quality in an energy system framework will allow several levels of water quality to be modeled. These levels will need to be defined with specific quality characteristics, and with each water process withdrawing water of one quality and discharging water of a different quality. Treatment plants would be defined as required to clean water from one quality level to another. These water qualities could be high organic return flows from municipal uses, waste water from industry, agricultural return flows, and wastewater from hydro-fracking processes. Water temperature changes could also be modeled as a quality change if treatment were required to cool the water, but an energy system model would not be able to determine the environmental impacts of heated water. The BNL-NYC study modeled water from freshwater and groundwater sources, wastewater (impaired water) from processing (treatment) plants, and three water service demands: agricultural, drinking water and process water, which includes water flows for power production. The level of water quality data tracked in the integrated model will need to be driven by the model and study objectives.

Dealing with Uncertainty and Risk

Resource costs and availability are typically defined by supply-cost curves, which are inputs to the model. Uncertainty in the cost or availability of specific resources is traditionally handled through scenario or sensitivity analyses that can determine how much the model results change when these parameters are changed. Examples of when it is important to investigate uncertainty in this area include situations where the energy system is dependent on a significant amount of imported fuels, or where environmental or technological concerns may significantly alter the cost or availability of extracting or processing

certain resources, and where weather/climate unpredictability may have extreme impacts on water for power generation. Uncertainty in demand projections is typically only investigated through scenario analyses, where specific changes in future energy demands are postulated based on specific changes in underlying assumptions behind the original demand projection, such as a change in GDP or population growth rates.

Technology characteristics are the area of uncertainty in energy models that typically gets the most attention, with the greatest uncertainties perceived to exist in the future investment cost and efficiency for the various conversion devices (power plants, refineries, etc.) and end-use devices (furnaces, air conditioners, process heat boilers, automobiles, etc.). Sensitivity analyses are a common tool used to examine the robustness of the model results when different assumptions are made regarding the future development of what are often new technologies. However, given the large number of these devices and their complicated interaction within the model, this approach provides limited (although useful) insights. To deal with technology uncertainty in a more comprehensive matter, it is necessary to use Monte Carlo techniques to determine the distribution of likely results given the likely distributions in the cost and performance of each technology in the model. Managing the amount of information in a single energy system model runs is already challenging, but when considering hundreds or thousands of model runs, the challenge becomes interpreting and gaining insights from the multiple overlapping time series results. New techniques are emerging for organizing and displaying information from these large data sets.

New areas of uncertainty are introduced with the introduction of water into energy models. The biggest of these is the variable nature of the underlying weather data projection and its correlation to the energy service demand projection. Energy system models do not normally deal with this kind of variability. Water models are often used to determine the resilience of the water system to extremes of weather. Energy system models are more often used to identify economically optimal investments out of a large variety of possible options.

Integrating water systems into energy optimization models will require careful design of the input data sets to avoid or minimize inconsistencies. Precipitation levels and temperature data are primary drivers of water availability, and they also directly drive the levels of energy services required for space heating, space cooling and many other energy services. Integrated models will require development of a coherent set of weather and energy demand projections. Multistage stochastic is a modeling feature available in MARKAL/TIMES models that presents a more dynamic way of dealing with uncertainty. A point in the future is defining at which time there is a resolution of uncertainty in a critical parameter (e.g., emission reduction target, price of oil or water, availability of a technology, etc.). The probability that this critical parameter will take a particular value is also specified, and the model will then identify a hedging strategy for the period up to the point the uncertainty is resolved.

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