



ENERGY-WATER NEXUS FOR GREEN GROWTH:

Towards a better basis for policy and investment decisions

**AN EXPLORATION AND INITIAL ASSESSMENT OF
KEY GAPS IN KNOWLEDGE AND METHODS**

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Executive summary

The next few decades will see an intensification of multiple challenges at the nexus of energy and water. Expanding energy production will place new demands on water (including for hydropower, cooling thermal power plants, and growing energy crops). Demands for water also will increase with population growth, economic development, and rising incomes. At the same time, water and energy systems in many countries will be put under increased pressure by increasingly complex interactions, the exhaustion of low cost supply options, and the impacts of climate change.

These trends and complex interactions mean that the future will be different from the past, and that established practices may longer provide a reliable guide for future energy and water policies and investments. Despite growing concern over energy and water trends, decision makers often remain ill-informed about these trends and their implications, and countries do not have access to the models and data required for robust analysis and decisions.

To address this need, the World Bank has commissioned this report, in partnership with CSIRO, to assess the state of knowledge and recommend practical options for addressing key gaps in tools and methods, in the context of practical country decision making about energy and water policies, investment projects, and related sector strategies. The review focuses on the capacity of models to assess the impact of water constraints on the economic returns of different investments in energy and water supply, and on the economy-wide performance of nations and regions. The water constraints considered include future water supply, economic cost, security, and the cross sector impacts and externalities associated with consumptive and non-consumptive use of water in energy production.

From a user perspective, the report assesses the capacity of existing and potential modelling tools to help answer the following questions:

What are the merits of different energy investments given potential future water constraints and interacting social, economic and environmental trends?

How much should we invest in enhancing the supply or security of water required for energy production? What are the merits of alternative investments?

What are the wider social, economic and environmental impacts and implications of potential water and energy policies and investments intended to address water constraints?

How can we assess multi-dimensional synergies, trade-offs and risks?

The report finds that 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 supplies. Encouragingly, however, the report also finds that several modelling frameworks already capture important aspects of the nexus (although only a small number of models and projects have been actually implemented in most cases).

Addressing these shortcomings is not simply a matter of integrating physical water use into energy models.

The report recommends two primary approaches to developing more the integrated modelling capacity required to address this shortcoming¹. The first involves a hybrid ‘model coordination’ approach that draws on and extends existing models. This involves four main activities:

- (1) Extending bottom up energy sector models to account for relevant water constraints (including price, availability and security) at appropriate spatial and temporal resolution;

¹ More details are provided in Section 4.4.3, supported by Sections 3 and 4.2.

- (2) Extending economy-wide computable general equilibrium (CGE) models to account for water as both a factor of production and a consumption good, including relevant water supply options;
- (3) Ensuring hydrological and water system models are calibrated to provide data and projections at spatial and temporal resolution compatible with relevant energy sector models; and
- (4) Developing protocols for coordinating or integrating model runs to achieve coherent results across these different modelling platforms, including aggregation of bottom up energy and water model output to CGE sectors and regions.

These steps are relatively straightforward conceptually, but require appropriate skills and significant interaction across disciplines and domains, supported by good will and shared commitment. Importantly, there are examples of bottom-up and economy wide CGE models that already incorporate water along the lines recommended in (1) and (2) above, and can be used to guide the development of integrated models for other countries and regions. There are also established examples and frameworks for delivering what is required for activities (3) and (4), although there will be data and capacity challenges to be overcome in some countries and regions.

The second model development approach would invest in delivery of a new more flexible modelling framework that combines the strengths of the bottom up and top down models. This would recognise the distinctive dynamics of water and energy systems and interactions, and overcome a number of limitations to using CGE framework to explore the nexus. These limitations are likely to become increasingly problematic for policy making (and associated analysis) as interactions and pressures increase. For this reason, this second approach has a longer term focus than the first, allowing for a more experimental approach for a period.

The report also finds that providing effective decision support depends on the relationships between analysts (including modellers) and decision makers, and on how models are used, as well as on the technical capabilities of the models.

For this reason, the report recommends that model development should give careful consideration to the best way of designing and implementing modelling and decision support processes, in light of the circumstances and challenges of different countries and decision contexts. Specific issues and risks arising from the energy-water nexus include (i) water security (primarily in terms of water volume), with linkages to food security, (ii) energy supply and affordability in the context of climate mitigation policies, and (iii) feedbacks through the nexus from water constraints to the energy system, and from energy choices to water and food.

This implies that modelling capacity needs to be able to support two complementary modes of exploring the nexus.²

In implementing improved modelling capacity, many countries would be likely to begin with some form of scenario process to identify the range of potential national futures that should be considered in policy, planning and investment decisions. This analysis would draw on a wide range of skills and expertise, supported by multi-sector or economy wide modelling, and would provide an initial sketch of the context of water and energy policy and investments, including in relation to food security, livelihoods, and ecosystem services. This mode of analysis needs to be complemented by deeper, more comprehensive modelling and analysis of energy and water issues, and the implications of potential water and energy constraints and feedbacks. Together, these two modes would allow exploration and assessment of physical and economic constraints (represented within models through prices, factor constraints, and market processes) and of more general cross-sector impacts, opportunity costs and externalities arising from water use and energy options (explored through analysis of different user-defined scenarios).

² More details are provided in Section 4.4.1, supported by Sections 2, 4.1 and 4.3.

1 Introduction

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1.1 FOCUS AND INTENDED AUDIENCE FOR THIS REPORT

This report focuses on understanding and improving the information base that underpins energy policy and investment in developing countries, in the context of the increasing challenges of the energy-water nexus.

The next few decades will see an intensification of multiple challenges at the nexus of energy and water. Expanding energy production will increase accompanying demands on water (including for cooling coal-fired and nuclear power generation, hydroelectricity, and growing feedstocks for biofuels). Demands for water also will increase with population growth, economic development, and rising incomes. At the same time, water and energy systems in many countries will be put under increased pressure by increasingly complex interactions, the exhaustion of low cost supply options, and the impacts of climate change. In many but not all countries, opportunities to cost effectively increase supplies are limited. The good news is that in many developing countries there is significant scope to increase the efficiency of water use, and thus much of the projected growth in demand can be accommodated by improving the way water is used. Adoption of policies and management practices that rapidly improve water use efficiency is rarely easy, however.

Despite growing concern over energy and water trends, decision makers often remain ill-informed about them. Energy models typically examine changes in energy supply options without taking stock of accompanying water requirements and challenges. While simple projections of water demand based on economic and population growth are made, currently only a limited body of tools and analysis is available to inform decision makers about the economic consequences of water constraints and pressures arising from population growth, economic trends, climate change and other environmental feedbacks, both in the aggregate and across sectors. Moreover, existing tools for quantitatively assessing water policies, investment projects, and sector strategies remain constrained by the fact that relevant data typically are collected according to economic or geopolitical boundaries, not by basin or other specification of a hydrologically integrated area.

At heart, this report is focused on existing and potential tools to help answer the following questions:

What are the merits of different energy investments given potential future water constraints and interacting social, economic and environmental trends?

How much should we invest in enhancing the supply or security of water required for energy production? What are the merits of alternative investments?

What are the wider social, economic and environmental impacts and implications of potential water and energy policies and investments intended to address water constraints?

How can we assess multi-dimensional synergies, trade-offs and risks?

The primary goal of this report is to assess the current state of knowledge, tools and methods for analyzing the impacts of future water constraints (availability, cost, and security of supply) on the merits of different energy-supply options and potential water investments intended to service energy supply needs, including

- (i) impacts of these constraints on the economic returns of different investments in energy and water supply; and
- (ii) impacts on the performance and structure of the economy as a whole, including patterns of energy and water use over time.

In some cases these tools and methods may also be used to explore the potential effects of policies aimed at enhancing the efficiency of energy and water use (such as through changes to market structure, pricing and entitlements), or improving energy and water security for specific groups. This is particularly relevant where water supply constraints can be alleviated more cost effectively through policy changes that induce improvements in water use efficiency rather than by increased investment in supply side solutions.

The second goal of this report is to identify options for improving analytical support for energy and water policy and investment decisions in developing countries, given the multiple pressures associated with the energy-water nexus, and practical limitations on data and projections of water demand and supply.

The report is thus interested in the impacts of water constraints on the merits of different energy options, including constraints arising from population growth, economic development, and adverse climate change, and options for addressing these constraints. The report does not, however, seek to provide a comprehensive overview or assessment of the tools and methods available for understanding how climate change may impact on water supply and demand.

The report seeks to serve the needs of practical decision makers, and those who are responsible for supporting them through providing tools and information. The emphasis is on practical applied approaches that build on established and well understood energy and water investment and management models.

Addressing these questions involves analysis and models that better account for how changes in water availability, security, and cost arising from adverse climate change and growing demand may impact on the cost or relative merit of some energy options, and follow through possible cross sectoral and national economy impacts. As set out below, we approach these issues from two perspectives – ‘meso scale’ analysis of the energy sector and ‘macro scale’ national economy-wide analysis – each providing valuable insights for energy and water policy and investment decisions seeking the best possible welfare outcomes for the national economy and society as a whole. We also argue that this will involve the development of models and tools that enhance understanding and decision information not only of water constraints on energy investment, but also of the key food and water production consequences of energy investments.

1.2 WHY THE ENERGY WATER NEXUS AND POTENTIAL WATER CONSTRAINTS ARE IMPORTANT

The physical laws of mass balance mean that, on a global basis, supply of fresh surface water resources tend to remain nearly constant, though in total, increasing temperature under climate change should actually slightly increase the rate of global fresh water cycling (Hinrichsen, Robey, & Upadhyay, 1998). Predictions for supply under climate change for many of the world’s arid and semi-arid regions models are less optimistic: less precipitation and higher rates of evaporation are likely to reduce freshwater supplies in such setting (Barnett, Adam, & Lettenmaier, 2005; Bates, Kundzewicz, Wu, & Palutikof, 2008; Kundzewicz et al., 2008; Milly, Dunne, & Vecchia, 2005; Seager et al., 2007; Shindell et al., 2006). Global down scaling studies such as Döll *et al.* suggest that significant parts of the developing world’s arid and semiarid regions will be impacted including (but not limited to) the northern China plains, the northern Indian subcontinent, Central Asia, and parts of Southern Africa. Wetter regions won’t likely be immune from impacts either as changes in snow melt patterns and increased monsoonal rains may lead to redistributions of water seasonally, including possibilities of exacerbated dry season constraints in many cases (Doll *et al.*, 2003). On the whole the aggregate future effect of climate change on world food supplies and security is expected to be negative (G. C. Nelson et al., 2010).

Considering that water is a crucial input into both food and energy production, and that global population is expected to grow to nine billion in 2050, there are substantial concerns that water could become a critical constraint to economic growth and wellbeing (Cohen, 2010; Godfray et al., 2010; Harvey & Pilgrim, 2011;

Khan & Hanjra, 2009; van Vuuren & Bouwman, 2005). Bates et al. (2008) emphasise that impacts of climate change on hydrological systems can already be observed (Bates et al., 2008; Rosenzweig et al., 2007; K. Strzepek & McCluskey, 2007), and that this is already introducing water constraints in an increasing number of energy and food related contexts. These shortages will play out with large local differences due to spatial variation in changes in temporal rainfall patterns, temperature and evaporation (Moss et al., 2010; Post et al., 2012), and interactions with existing and proposed dams, such as on the Mekong River.

This report focuses on the relevance of increased water shortage and changed water availability timing for the energy sector. Energy is crucial input to development strategies in much of the developing world. It will be crucial to understand the extent to which changing water supplies may constrain power generation opportunities or drive up cost as a result in particular of persistently growing demand for electricity in developing regions with growing populations and rising affluence. Many studies highlight the relevance of increased water shortage for energy sectors (Förster & Lilliestam, 2011; Hightower & Pierce, 2008; Lettenmaier, Wood, Palmer, Wood, & Stakhiv, 1999; Muñoz & Sailor, 1998; Shiklomanov, 2000; Smakhtin, Revenga, & Döll, 2004).

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 has potential to increase market prices for water and energy and lead to redistributions of these increasingly scarce resources between sectors. In the case of water for example, increasing scarcity in one area is likely to result in the increased purchase of food products from another area. When this occurs, significant structural adjustment can occur and needs to be managed with sensitivity in order to ensure that overall economic activity and employment is not reduced in the short term. Actual outcomes will depend on the capacity of a community to adjust, rates of technological progress in development of 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 will often 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 – with the associated risk that some agricultural groups may seek to use their political power redress this difference in economic power, such as by portraying the energy sector as damaging agricultural interests and threatening food security.

1.3 REPORT STRUCTURE

The remainder of this report is structured in three main sections:

- Chapter Two outlines the nature of the energy water nexus, and the two way linkages between energy and water systems, with a particular focus on how water constraints may impact on the merits of different energy supply options;
- Chapter Three provides a detailed discussion of the major approaches available to model different aspects of the energy water nexus, and identifies options for how existing approaches might be usefully extended. The scope includes direct and indirect constraints, such as water availability for cooling thermal generation plants (direct) and social concerns about the impacts of energy-related water use on food security (indirect). The section includes a detailed description of the development of an Australian economy wide model incorporating water supply and demand, and also discusses issues in representing externalities and non-market impacts in modelling frameworks.

- Chapter Four shifts focus from modelling to decision support, discussing potential priorities for improving models, and exploring issues in how models can add value to social decision processes.
 - Section 4.4.3 recommends developing a scenario approach to energy modelling that specifically accounts for changes in the perceived opportunity costs of water use (which provide the long term social and political context of water allocation).
 - Section 4.4.4 then outlines a more detailed strategy for development of integrated modelling capacity, built around deepening existing models (to integrate water use and constraints), linking different types of models (to address different aspects of the nexus), and developing an innovative hybrid modelling framework to explore the implications of the energy-water nexus in the context of interacting population, development and climate trends.

The final chapter provides a summary of the main messages and conclusions of the report.

2 The Energy-Water- Nexus

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2.1 CONCEPTUALISING THE NEXUS

The word ‘nexus’ is commonly defined as a ‘means of connection’, tie or link. The *energy-water nexus* refers to energy and water interactions, ties and linkages in processes of water and energy production and use. It is useful to consider this nexus in terms of ‘water for energy’ and ‘energy for water’ (Rothausen & Conway, 2011), recognising that energy systems use water and water systems use energy (PMSEIC, 2010). Energy and water are key factors of production and consumption within the economic, social and environmental systems of all communities. They also intersect with each other in many areas of the economic, social and environmental systems. Given the interactions between energy and water, any effort to address problems in one area without consideration for its consequence elsewhere can have unintended repercussions with potentially undesirable outcomes. The interactions between energy and water are further complicated by the challenge of maintaining green house gas emissions below dangerous levels (PMSEIC, 2010).

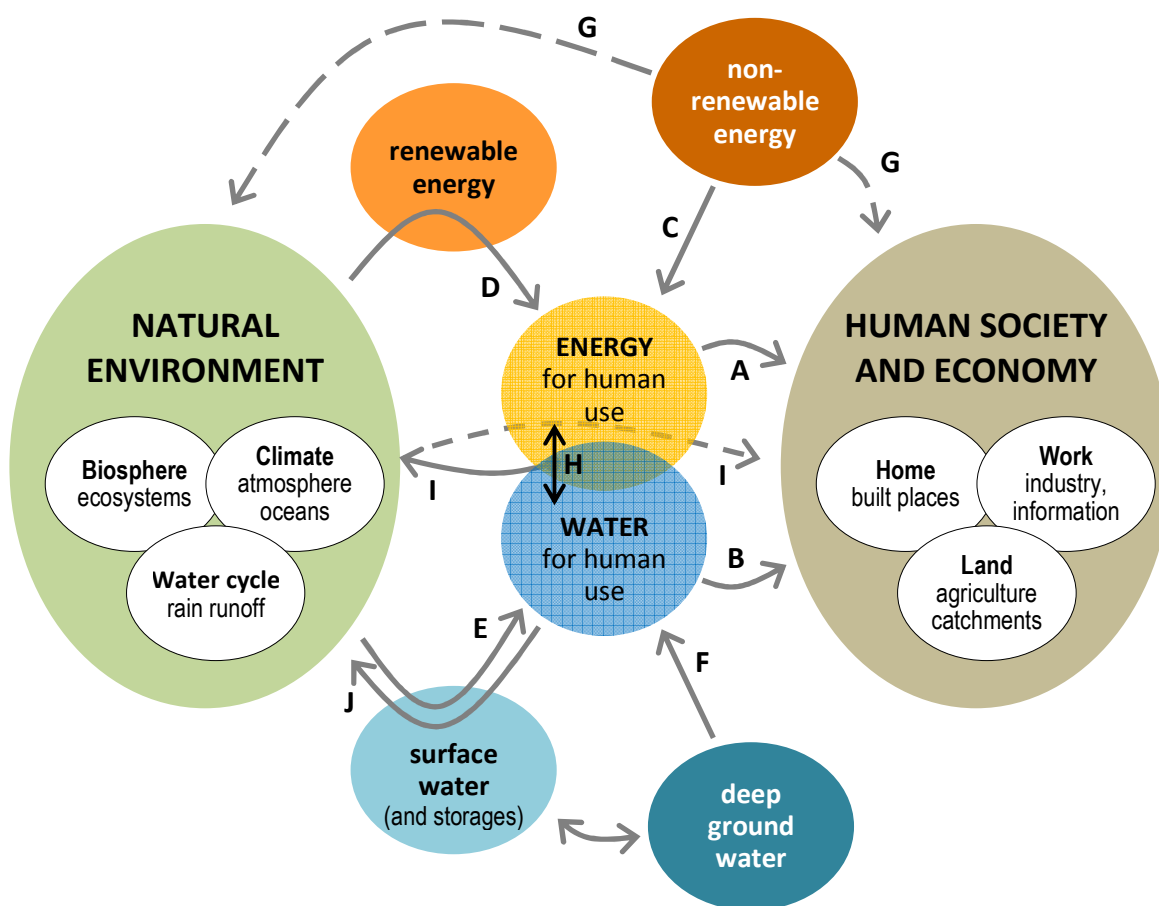


Figure 1: interactions between energy and water in the context of climate change

Source: Adapted by the authors from PMSEIC (2010)

Figure 1 above illustrates key interactions between energy and water in the context of climate change.(adapted from PMSEIC (2010).

Energy, carbon and water are central to the interaction between the natural environment (left) and human society and economy (right). Energy and water are both vital for all human activities (A, B). Energy for human use is derived primarily from fossil fuels and other non-renewable sources including nuclear energy (C) and from renewable sources (D). Water for human use is dependent on the natural water cycle, conditioned by the construction of dams and weirs as a means to reduce supply variability (E), and on the use of ground water (F). Energy production results in various forms of pollution impacting on human health and natural systems (G), including indoor air pollution from burning biomass. Fossil fuel energy generation is a primary contributor to the build-up of carbon dioxide and other greenhouse gases in the atmosphere, which is changing the earth's climate. These processes influence water availability (E, B), ecosystem function and agricultural productivity. There are also interactions between water supply and energy supply because energy systems use water and water systems use energy (H). This can impact on natural and human systems (I). For example, the use of water for hydro-electricity can alter river flow, reduce wild fish populations, and impact on access to water for irrigation – all with consequences for people and livelihoods. Water extracted for human use remains part of the water cycle, including through evaporation and short term return flows to rivers and shallow ground water (J), and flows into ground water aquifers. Many more connections could be shown in this figure.”

There are several significant facets of the energy water nexus. Water and energy are significantly interconnected within the social, economic and environmental systems both on the supply side and the demand side.

Water is a critical input into a range of economic activities in households, agriculture, manufacturing, mining, services and infrastructure related sectors. Water also plays a crucial role in supporting the functioning of the natural ecosystems that in turn support services of great value. The supply of the quantity and quality of water (both ground water and surface water) is influenced by a range of factors. Perhaps most significant, in the energy-water nexus context, is climate variability and change which results from carbon intensive energy use. Careful consideration also needs to be given to the degree of investment in dams and other forms of infrastructure.

Energy is also an essential input in almost all socio-economic activities, and water is an essential input into energy production (especially for cooling, hydroelectric power, some fossil fuel extraction, and increasingly in biofuel production). Furthermore, energy is used in a range of processes for supplying, treating and using water: as clean fresh water becomes scarcer, energy use per unit produced often grows as capital and energy (for example desalination) is substituted for services previously mainly provided by natural capital (e.g. natural filtration capacity of wetlands). Figure 2 below shows some of the main processes where energy is an input in clean fresh water production (Rothausen and Conway 2011).

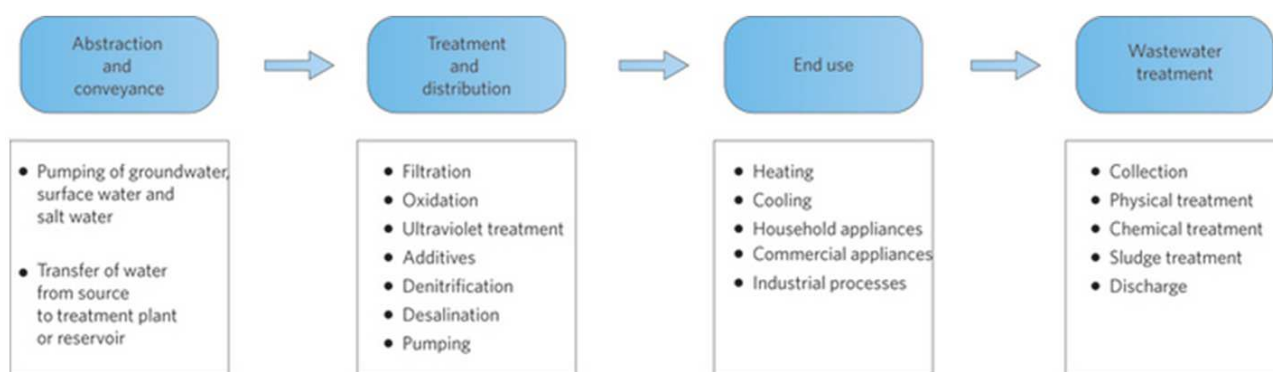


Figure 2: Conceptual model of water-sector processes involving energy use

Source: Rothausen & Conway (2011), Figure 1, p 211.

The current and future energy water nexus and the associated challenges need to be viewed within the context of global changes. These changes include climate variability and change, resource over use and the ongoing need to maintain socio economic activities as well as critical ecosystem services. In this context, economic growth and development, along with expanding population, place growing pressure on capacity to satisfy aspirations for access to energy and water. This pressure tends to worsen as ecosystems degrade and their natural capacity to supply things like clean water is eroded. Volatility in commodity markets can be another manifestation: for example, recent reductions in rainfall disrupted world grain supplies to such an extent that they contributed to the spike in world grain prices, to which a number of countries responded by banning grain exports (Headey & Fan, 2008).

Box 1. Groundwater: Too often overlooked

Global groundwater withdrawals are estimated to be from 600 – 1100 km³ per year, most of which is for irrigation (Siebert et al., 2010). Siebert et al. (2010) estimate global consumption of groundwater for irrigation to be 545 km³ per year (43 % of the total irrigation water consumption), whereas Shah et al. (2007) estimate groundwater use to be 900 km³ per year. India, the United States, China, Pakistan, Iran and Bangladesh account for about 80 % of the use of groundwater.

Groundwater use and energy use and policy are intimately connected. Energy use in groundwater pumping is significant. In India, the world's largest consumer of groundwater for irrigation, there are an estimated 20 million shallow tubewells owned by one quarter of the 80 million farming families; groundwater pumping is estimated to account for 15-20% of the total power consumption in the country (Shah, Scott, Berkoff, Kishore, & Sharma, 2007). In contrast, countries such as Mexico, the United States and Iran have fewer, deeper wells irrigating larger areas (Shah, Scott, Kishore, & Sharma, 2007). Mexico was estimated to be have about 95,000 wells in 2001, consuming about 6% of the total national energy demand (Scott & Shah, 2004).

While pumping groundwater has brought benefits of increased food production and, particularly in south Asia, increased access of poor farmers to irrigation water (Shah, 2009) has also led to problems. Aquifers in many countries are being depleted at rates that exceed recharge, including the central and western United States, Mexico, northern China, northwest India, Iran and the Yemen (Wada et al., 2010). In India, many areas are supplied with free or subsidised electricity, which has exacerbated the groundwater depletion problem and also created financial difficulties for electricity suppliers (Shah, Scott, Kishore, et al., 2007). In contrast to other parts of India, in the lower Ganges basin of eastern India farmers have less access to cheap electricity and pumps are usually diesel. High diesel prices in recent years have led to declining use of groundwater and lower production and farm incomes (Mukherji, 2007).

Resolving the problems is often seen as a matter of removing subsidies or introducing regulatory measures to halt overuse. This is politically difficult. In India, for example, attempts to introduce charging have been difficult to implement and sustain (Shah, Scott, Kishore, et al., 2007). In the state of Gujarat, however, some success has been had with a form of rationing electricity supply to farms coupled with investments that improve supply to villages (Shah, Bhatt, Shah, & Talati, 2008). In Mexico, attempts to limit groundwater depletion through regulatory measures, such as bans on new wells, have faced similar problems (Scott & Shah, 2004), although Dinar (2012) finds that reducing water supply entitlements can be both more equitable (and politically viable) and effective in promoting improved irrigation efficiency than price increases.

This raises a range of questions and challenges in applied investment analyses for energy and water projects and in evaluation of energy and water policy in relation to the energy water nexus. Key trends including:

- Increasing demand for consumptive use of water and energy at local, national, regional and global levels, along with accelerating trends in groundwater water depletion, reductions or increased variation in natural river flows, and pollution or contamination of both surface and groundwater;
 - Dinar (2012) argues that water scarcity calls for substantive attention to water allocation and associated policy issues, in addition to consideration of supply enhancements. Dinar finds water allocation and policy can have significant impacts on economic efficiency, growth, and wider issues of household vulnerability and societal conflict.
- Increasing dependency on food supply from other countries, implying greater global connectivity (and associated gains in economic efficiency, but also risks around transmission of food price shocks);
 - According to (Hoekstra & Mekonnen, 2012) about one-fifth of the global water footprint during 1996-2005 was allocated to export production rather than domestic use;
- Expanding interest in the use of dams to reduce the variability of water supply and to meet increasing water demands (both as a catalyst and consequence of economic growth).

- Brown and Lall (2006) have found that drought frequency, which can be reduced through investment in storage and flood risk, has a highly significant negative influence on GDP growth (see also Grey and Sadoff (2005); Barrios, Bertinelli and Strobl (2003));
- Increases in the scale of international flows of virtual energy (and hence greenhouse gases), and the associated external energy dependencies;
- Emerging trends in the potential to use alternatives for non-renewable water (including recycled and desalinated water) and energy (including renewable energy such as solar and wind power), both associated with the role of increasing prices to trigger backstop energy and water related technologies;

These interacting trends give rise to substantive challenges around:

- managing and supplying water and energy to growing populations in ways that are economically and environmentally sustainable;
- adapting water and energy use, policy settings and regulatory standards to meet expanding demands, changing quality requirements (such as water quality and energy security), and shifts in the relative importance of different sectors and needs; and
- identifying and implementing effective strategies for managing climate risks and variability

From a water sector perspective, one of the unique characteristics of the energy sector is its capacity to bring about a sudden change in water needs. While a plant is being developed, little water is needed; but as soon as the plant comes into operation, a significant shift in local water demand suddenly occurs. In contrast, changes in the agricultural sector, for example, tend to be slow and often go un-noticed.

Box 2. Potential Impacts of Climate Change on Energy and Water Sectors

Climate change will have a range of impacts in different parts of the world, including impacts on the supply and demand for energy and water within human societies.

Impacts on water supply will vary, and are likely to include:

- increases or decreases in average precipitation, surface runoff, and stream flow (with drier average conditions in the central areas of many continents)
- increases in evaporation from soil
- changes in the seasonal distribution of rainfall (such as potential shifts in monsoon patterns)
- increases or decreases in rainfall variability
- increases in the probability of extreme events, such as intense storms and floods, or droughts
- reduction in snowpack over time, implying higher average annual meltwater flows for a period and then likely lower flows.

In some cases these changes may have impacts on demand for water extractions, such as increased demand for irrigation water to offset the effects of higher temperatures and reductions in rainfall (green water). In some areas the combined effects of population growth, trend changes in climate, and increasing variability will result in increased reliance on relatively energy-intensive water supply options, such as water transport or desalinisation 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 then to meet increased energy demands for the cooling of houses, offices and factories.

Climate change will also impact on 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. Population growth, economic development and rising incomes will drive trend changes in energy demand that will interact with climate change to result in shifts in seasonal energy demand, such as lower growth in heating demand in areas with cold winters, and higher cooling demand in the tropics and areas with hot summers. A warmer world means that more water will be needed for adaptation. Stressing water supplies to their limits, this increased demand will be greatest when it is driest and hence water most scarce.

The often ad hoc development of climate change mitigation programs can be expected to have similar effects. Mandatory requirements for the inclusion of ethanol in fuel, for example, can be expected to increase demand for irrigation water in many cases. Similarly, pressures for the 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.

The increasing cost of energy can also be expected to have adverse effects on water security as non-conventional sources of energy are developed. Many of these non-conventional sources have significant impacts on water supplies. The extraction of hydrocarbons from oil sands and the development of coal seam gas extraction are two particular examples that can have massive local impacts on opportunities to use water. Increased demand for plant-based energy sources, or carbon sequestration, could also have very significant impacts for water run-off and supply.

In addition to the above impacts, it needs to be appreciated that in comparison with the water sector the energy sector is highly organised and highly regulated. Moreover, they are more likely to be accustomed to discussions about the need for the development of emissions trading schemes, carbon taxes and so forth. The sector is aware of the need to consider and plan both for the adverse effects of climate change and anticipate the most appropriate way to mitigate the extent of anticipated impacts. As a general observation, major players on the demand and supply side of the water sector are generally less organised and less accustomed to engaging in discussions about the extent of change necessary to both adapt to and mitigate climate change risks.

2.2 WATER CONSTRAINTS IN POWER GENERATION AND BIOFUELS PRODUCTION

As described above, there are a wide range of interactions between demand for and supply of water and energy. In the past, it has been uncommon for empirical analysts to carefully consider how changes in demand or supply of one these factors influences demand for and supply of the others.

This sub-section focuses on one part of the energy-water nexus: the significance in energy investment analysis of increasing water scarcity and increasing demand and competition for water in multiple uses. We describe: the most significant ways that water is used in energy production, technological possibilities to reduce water use in energy production, the mechanisms through which increasing water scarcity and changed flow timing expected with climate change and increasing demand may constrain energy production and raise energy costs, and the ways that increasing use of water in energy production may impose cost on other sectors of the economy.

2.2.1 Water in power generation and technical opportunities to reduce water use in electricity generation

Water is used extensively in energy production. This is especially true for hydro-electric and thermal (coal, and natural gas) power production. Neither of these power production processes consumes a significant share of available water, however. Rather, water is used as an essential non-consumptive throughput in hydro-electric and thermal power production: in hydropower it is run through turbines, in thermal power production it is run through cooling towers to regulate thermal plant temperature. In both cases, however, this non-consumptive use can have important impacts. The development and operation of hydropower, for example, can involve significant impacts on water availability and the timing of water flows. While few statistics are available providing a worldwide perspective, indications can be inferred from the United States, a very energy intensive economy. There, withdrawals from surface and groundwater for thermal power plant cooling represent 39% of all withdrawals and are roughly similar in magnitude to withdrawals for irrigation (Hutson et al., 2004). Significant amounts of this cooling water, having served its purpose, are then returned back to river systems.

As noted, for both of these power sources water is primarily needed as a throughput. None-the-less, both power production processes involve some evaporative water losses. In the case of hydro-electric power, evaporative losses rates are very dependent on both dam design characteristics (dam surface area relative to depth) and climate (with evaporation obviously greater in hot dry climates). Both water throughput levels and evaporative loss rates in thermal cooling depend critically on cooling technology.

The predominant pre 1980's technology, which is still a large share of existing plants, is open loop cooling: while these systems involve large throughput volumes, losses to evaporation are small: only approximately 1% of throughput. Newer systems are predominantly closed loop, and these systems use only about 5% of the water throughput that open loop systems do. However, evaporative loss per KWH is typically 50% to 100% greater than with closed loop systems (EPRI, 2003).

There are also dry cooling systems that do not rely on water, though this tends to come at some loss of efficiency and hence higher cost, especially in dry and hot as opposed to cool and humid climates. Natural gas thermal plants operate at lower temperatures than coal burning plants and thus use about half as much water per KWH. Burning biofuels for energy production tends to be the most water intensive form of energy production when the embedded water in feedstock production is taken into account. Of course, there are energy technologies that use very little water such as wind and solar power (U.S. Department of Energy, 2006). Concentrated solar power – which typically most attractive in hot dry regions – can involve significant water use, however.

A new impact of hydropower generation is the use of dams as a battery. In many countries, highly sensitive markets for the generation of wholesale power have emerged and, in such environments, hydropower plants can take advantage of short-term price peaks faster than any other source. In some cases, the revenue advantage is such that a hydropower company can afford to drop large amounts of water through

its turbines when prices are high and then pump the water back up to the dam from which the water came when prices are low. In regions where this occurs and, if minimum flow requirements are not well specified, the impact of this practice of using dams as a battery primarily to meet peak electricity demands can be substantial.

Whilst unlikely to be a major near-term issue in developing countries, it is interesting to observe that 44 of France's 59 nuclear reactors are cooled by river water and, in the recent 2011 drought, the need to maintain sufficient river flow for these plants significantly affected allocations to other sectors and the environment.

2.2.2 Water scarcity as a cost and constraint in electricity generation

As outlined above, hydro and thermal power generation both involve substantial water throughput and significant water consumption (through evaporation). The most immediately obvious constraint that increasing water scarcity is likely to impose on energy production is loss of hydro-electric power generation potential. Climate change predictions of increasing drought in arid and semi-arid regions are of particular concern in this regard. Changes in seasonality of flow may also be a concern, as hydro-power is often used to provide peak electricity supply as it can be brought on and off line nearly immediately. This is in contrast to thermal plants that require time to start up and bring to full power. Water scarcity can also constrain or raise costs of thermal power generation, although in most cases the cost of accessing water is very small in comparison with the revenue generated.

With open loop cooled thermal power systems, low flows can lead to increased water temperatures at the cooling system inlet. In order to function within operating permit requirements for temperature at discharge, it is not uncommon to have to reduce power generation at times when ongoing generation would be lucrative. In cases where closed loop cooling water rights are relatively junior or variable, reductions in available supply can also limit ability to generate in drought.

In general, increasing water scarcity is increasing incentives to switch from more water intensive open loop to less water intensive closed loop technology. Dry-cooled systems are an option to overcome such constraints, but can cost 2% to 16% more than closed loop cooled systems (CEC, 2002; Maulbetsch & DiFilippo, 2006). Such systems are best suited to wet cool climates where they can operate at nearly the same efficiency as water cooled systems. In hotter and drier climates they tend to operate at considerably lower efficiency than water cooled systems.

2.2.3 Water scarcity and the opportunity costs of alternative energy crops

Development of plant based alternative energy sources has long been seen as an attractive mitigation option for reducing greenhouse gas emissions. However, biofuels and biodiesel require water and land, introducing complexity to the implications of this strategy. For instance, tropical regions allow for rain-fed plantations, minimising irrigation needs. But implementation of this mitigation strategy has seen substantial areas being transformed into plantations, in particular in Brazil and Indonesia. This has had two important effects where these plantations have replaced primary or secondary forest. First, the resulting carbon balance had frequently been negative, resulting in net emissions to the atmosphere (directly contrary to the policy intent). Second, hydrological impacts often exacerbated peaks, leaving longer periods of low flow, with implications for thermal power plants.

Where biofuel and biodiesel plantations have not replaced forests, they have often displaced or diverted food crops (Harvey & Pilgrim, 2011), impacting negatively on food security in many countries, particularly sub-Saharan Africa (Rosegrant et al. 2008).

The impact of biofuels on water use varies greatly, increasing water use in some cases but decreasing in other cases (where the biofuel crop replaces a crop, such as rice, with higher water demand). Chiu et al. (2009) estimate that in the USA bioethanol water requirements vary from 5 to 2138 L of water per litre of ethanol produced, depending on regional irrigation practices. They estimate that the total water consumption for bioethanol production in the USA increased from 1.9 trillion litres (1.9 km³) in 2005 to 6.1

trillion litres (6.1 km³) in 2008, with bioethanol production increasing from 15 to 34 billion litres over the same period. This water consumption may have contributed significantly to the withdrawals from the vulnerable Ogallala aquifer, the largest groundwater reserve in the USA. De Fraiture et al. (2008) estimate that the impact of increased water use requirements of expanded biofuels make it unlikely that China and India will pursue biofuel options at scale, given existing and projected water stress in these countries. Yang et al. (2009) note that China in 2007 developed a target of 12 million tonnes for biofuel production by 2020, which would require between 32 and 72 km³ of water, including impacts on rain-fed agriculture and irrigation diversions – approximately equivalent to the annual discharge of the Yellow River. On a global level, however, Rosegrant et al. (2008) and de Fraiture et al. (2008) agree that, overall, biofuel expansion is not likely to alter regional- or national-aggregate patterns of water use. De Fraiture et al. (2008) and van Lienden et al. (2010) estimate that by 2030 biofuel production will consume about 6 % of the water used globally for irrigation.

In addition to these impacts on water availability and direct food production, biofuels can have adverse impacts on land, soil quality, air and water pollution, and biodiversity loss (Solomon, 2010).

While recent years have seen mounting evidence for negative impacts and trade-offs of these alternative energy sources – resulting in reduced policy support and incentives in some cases – market mechanisms have continued to encourage biofuel and biodiesel production in many countries, such as oil-palm in Indonesia, sugarcane and maize in Brazil, and recently Cassava in Thailand (Holmes, 2000; S. S. Scriciu, 2007). These investments have also increase social and economic vulnerability to climate change, as future changes in temporal and spatial rainfall patterns are likely to impact on the productivity of these plantations and, therefore on the availability of alternative energies.

2.2.4 Cross sectoral costs and impacts of water use in energy production

Cross sectoral costs of water use in energy production have the potential to be even greater than the direct costs of reduced generation capacity and the higher capital and operating costs in production outlined above. This is because regulated water systems are managed for multiple objectives. For example, the water system in a location might be required to supply to household, municipal, industrial and irrigation water needs, while also delivering sufficient water to maintain river navigation, fishery, recreational and amenity opportunities, and also providing adequate flows for hydro-power and thermal power cooling. The ideal dam release patterns and river flow regimes for each of these competing uses will tend to differ, and releasing water in the pattern best suited to one use will thus tend to involve some forgone opportunity to generate other types of benefits. Conflicts and opportunity costs tend to rise with increasing water scarcity.

Use of water for throughput in hydropower and thermal power cooling can also influence quality aspects of the water that flows downstream. In the case of thermal power cooling, it is water temperature effects that are of greatest concern. Elevated temperature in rivers can adversely impact fish and wildlife, and raise probabilities of water quality issues such as algal bloom, that can make water unfit for consumption or raise costs of treatment required to meet consumptive use standards. A key concern in the case of hydropower is the capture of silt behind dams that would otherwise lead to renewal of farmland fertility further downstream.

Investment in increased storage and inter-regional transfer schemes

As regional demands for water grows, one of the options available is to consider the case for transferring water from one catchment to another. In most developed countries, remaining opportunities to do this are few. Opportunities, however, do remain in a number of developing countries. Arguably, the best known example of such a scheme is the Three Gorges Dam Development in China which is shifting large amounts of water from more water abundant regions in southern China to northern China where water is already very scarce. As well as diverting water from the south to the north, this scheme will produce large amounts of hydro-electricity and reduce flood risk in southern China. Schemes like this, however, tend to be highly controversial as they impact on the opportunities and livelihoods of large numbers of people. When schemes of this nature are under consideration, detailed modelling of the economic, environmental and social consequences of the proposed scheme is justified. Sub-Saharan Africa, and also some parts of South

and South East Asia, are often cited as a regions where opportunities for much more investment in large dams is justified (Molden, 2007; Sirte, 2008).

Trans-border impacts and the potential for mutual benefits through better coordination

Cross sectoral trade-offs and opportunity cost issues can be exacerbated in basins that spread over national borders, and even where basins cross over multiple state borders within a country. An example is the Syr Darya River Basin which overlaps national borders of Kyrgyzstan, Uzbekistan and Kazakhstan. A significant set of reservoirs was built in the basin in the Soviet era for hydro-power and irrigation water supply purposes. With the breakup of the Soviet Union, the upstream Kyrgyz Republic abandoned the previous agreement on water sharing and changed release arrangements to better meet their power needs – but at considerable cost to opportunities to irrigate in Uzbekistan and south Kazakhstan. As this new arrangement resulted in an overall economic efficiency loss, subsequent negotiations resulted in downstream-to-upstream compensation payments which have improved the overall efficiency of water use in the Basin (World Bank, 2004). Section 3.1.2 below discusses technical issues in modelling trans-boundary systems issues, and Section 4.3 and 4.3.2 explore the role of modelling and stakeholder interactions in trans-boundary situations.

3 Modelling the Energy-Water Nexus

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3.1 MODELLING SCALE AND SCOPE

There are a large number of energy and water sector models with extensive energy and water system and economics representations. Integrating water constraints in energy investments is relevant for three scales: *micro*, the power plant scale, *meso*, the national or regional sector scale, and *macro*, which is generally the national economy scale. Additional scales like continental and global scales are often required for the sectoral or national analysis if, for instance the trade of fossil fuels is a critical dimension. Models may represent supply and demand at different scales, along with different scope across sectors and sectoral interactions.

Table 1: Scales and scope of analysis

Scope:	Energy only	Water only	Multi-sector
Micro	Generation facility or specific section of a distribution network	Water storage (dam), processing facility, channel or pipeline	Facility level energy and water model, e.g. for hydropower analysis
Meso	Major interconnected grid National energy system	Major catchment, river basin or aquifer National water system	National economic model incorporating detailed physical energy or water sector
Macro	Global energy system model	(Not applicable)	National multi-sector economic model Global multi-sector economic model
Trans-boundary	Interconnected grid across political jurisdictions	Major catchment, river basin or aquifer across political jurisdictions	Regional (or global) multi-country multi-sector model

Source: Developed by the authors.

Trans-boundary issues can occur at a variety of scales, particularly due to mismatches between the physical scale of water systems (largely determined by topology, geography and regional climate) and political boundaries within or between nations.

3.1.1 Meso and macro scale modelling frameworks

This section provides an overview of the diversity and range of relevant models from two lines of the applied economics literature, focusing on the meso and macro scales as they are the most relevant for exploring the energy-water nexus. These approaches are:

- Energy sector planning models that include economics;
- Whole of economy models with consideration of energy or water – typically computable general equilibrium (CGE) models that take into account how changes in energy and/or water scarcity or production costs ripple through other sectors of the economy.

The *meso scale* representing the national energy sector is often the entry-point for national energy planning or investment planning of a power generation company. Consider first the application of a national energy planning model to evaluation of an individual power plant investment from the perspective of the investor. This involves first modelling to forecast future demand for electricity (and fossil fuels) and a projection of supply capacity. Demand projections are largely based on regression models, which will be discussed in Section 3.2.2. Projection of supply capacities is typically done in simulation models, which is distinguished from other modelling approaches in Section 3.2.1.

Once capacity gaps are quantified, options are specified, engineering-type approaches to identify things like potential timing of supply and how it corresponds with demand or transmission grid constraints are combined with cost-benefit analysis to identify feasible and lucrative investment options. This process requires the *micro scale* evaluation of individual plants. At this scale water constraints are typically considered and hydro-engineers take tightening constraints into account to determine feasibility and cost of a particular project. There are no severe methodological problems at this level of analysis to integration of information on relevant physical and direct economic water constraints (such as water volumes, quality, or unit costs).

Typically, the main challenge is uncertain data and lack of data. Non-trivial issues include the need to understand the likely impact of increased demand on river flow, and the ranges of costs associated with accessing increasingly scarce water. These issues and assumptions are particularly challenging when water resources are already over-allocated and major water policy reforms are under consideration. Choice of the modelling technique chosen to deal with emerging deficits in sectors where there is a supply deficit is important. Some modelling approaches seek to close these deficits automatically. Others leave choice of the best way to do this to the analyst or decision maker.

A second scope issue is the need to address indirect social and economic constraints, such as changes in cross-sector opportunity costs or the negative externalities of water use within the energy sector. In principle these issues can also be integrated within modelling frameworks, such as through shadow prices or setting boundary conditions on acceptable outcomes – once these values and conditions are agreed and quantified. In practice current water policy and planning rarely accounts for these evolving systemic constraints, and so in most developing countries there will not be an established body of information to draw on as a basis for understanding the implications of these wider water constraints for the energy sector.

At the *macro scale*, energy-related modelling typically analyses the impact of changes in energy sectors on macro-economic indicators, such as GDP, trade, inflation and unemployment. Focus is typically on consequences for fossil fuel prices, carbon prices and new power generation technology. It is rarely on implications for politically sensitive sub-sectors like the irrigation component of the agricultural sector.

3.1.2 Trans-boundary issues – Mismatches in physical, economic and political scales

Trans-boundary issues occur wherever physical system boundaries do not align with economic or political boundaries. This can occur within a single country, where a number of states in a federation may share a major river or catchment, and across nations in a region who share a common river basin or aquifer. Similar issues can arise in energy modelling, such as gas pipelines or import and export of hydropower.

Analysis and decision support for trans-boundary issues offers particular institutional challenges, such as data sharing, as well as distinctive opportunities, such as the role of modelling in identifying potential net gains from more cooperative water and energy management. There are also a range of technical issues, such as ensuring data is consistent and sufficiently comprehensive, and that relevant instructions and policy settings are appropriately represented across different countries or jurisdictions. While this may involve some additional modelling skills and country-specific knowledge, trans-boundary analysis of this kind does not involve any fundamental additional modelling challenges.

3.2 ENERGY SECTOR MODELS

There are a large number of energy investment models which are oriented towards engineering issues and perspectives. The most comprehensive overview of these energy models is provided by Connolly et al. (2010), in the context of integrating renewable technologies into the energy system. Other valuable overviews have a similar focus on renewable resources and also on developing countries but are less comprehensive (Jebaraj & Iniyar, 2006; Segurado, Pereira, Pipio, & Alves, 2009; Urban, Benders, & Moll, 2007; Van Beeck, 1999; van Ruijven et al., 2008).

Before going further we note that in essence there are two basic types of models: those that simulate, and those that optimise. Simulation models project what will happen when a pre-specified set of conditions occur. Optimisation models attempt to find the best outcome given the opportunity to change most factors. Optimisation models are particularly useful when a proposed decision will change many conditions. Simulation models are particularly useful when one wants to understand the consequences of one or more scenarios and assume that most other things remain constant. It is possible to build models that combine simulation and optimisation methodologies but it is more common to pass the resultant data sets from one modelling system to another.

To understand the scope and diversity of what has been done in this space, we found it useful to broadly classify these models in terms of three attributes:

- Modelling method – simulation or optimisation;
- Bottom up or top down, which includes the resolution of supply and demand
- Spatial or non-spatial representation

3.2.1 Modelling method – simulation or optimisation

In the domain of national energy planning the dominating methodologies are optimisation methods, such as linear or non-linear programming or mixed integer programming. These optimisation methods often include multiple objectives. Recent approaches utilise evolutionary techniques, such as genetic algorithms to make solution of high spatial and temporal dimensionality feasible. The aim of most optimisation methods is to find the cost minimising way to mix known energy technologies. Feasibility is largely determined by input constraints. Such constraints include typically the availability of fossil and renewable energy sources and the requirement that the mix of installed power plant is flexible enough to meet peak demand loads. Technically, these constraints could consider water availability as an input constraint, which will be discussed further below.

A number of energy sector models use simulation, as opposed to optimisation methodologies. In the context of energy sector modelling simulation models allow evaluations of how additional supply options perform under specified price, demand or other assumptions (i.e. ProTRAX simulation model). Such simulation models require a disaggregated specification of the relevant energy supply system and response

functions to simulate how individual system elements such as energy using industries and households respond to changed conditions such as prices. Simulation models neither involve equilibrium conditions nor an optimisation objective function, such as profit or a multiple objective function that predicts the likely aggregate behaviour of individual system entities.

Simulation models are most relevant if a study aims to analyse the likely changes as the result of actions such as introducing a new technology into the supply mix. The main advantage of simulation models lies in their capacity to allow detailed exploration of technical, biophysical and economic relationships. This is possible because they do not attempt to exhaustively search all possible combinations and thus tend to be much less computationally intensive than large optimisation models.

Simulation models answer a different set of questions to optimisation models. Optimisation model search for the best option for achieving a particular objective and, hence, are most useful when assessing the relative merits of changing strategy or policy. They often use exhaustive least cost search techniques and compare all possible combinations in the time and space. In contrast, simulation models are particularly useful when one wants to understand *how* things are likely to change under different climatic, demand, market and policy conditions.

The 'normative selection' implicit in optimisation once an objective is chosen is an exogenous step in simulation: it is left to the model user to compare outcomes of alternative options under differing conditions before drawing a conclusion about what they believe to be the most desirable approach. However, the boundary between the two approaches can look blurred in some cases because simulation approaches can be used for a systematic search of solution space in some cases. Some energy sector models simulate multiple sets of assumptions and then rank all saved results: the *Homer* model is an example. Strictly speaking, solution space searching with simulation models is not an optimisation technique, as each simulation does not involve full enumeration of possible outcomes and selection of the optimum. The feasibility of selecting near optimal solutions with simulation generally becomes more limited the greater the scope of temporal and spatial and technology options becomes. As a result, we perceive that the proportion of money invested in simulation model development has been greater in the water sector than in the energy sector.

Optimisation modelling is particularly well suited to the estimation of 'shadow prices. This is because these models can be used to quantify how much more of an outcome can be produced if the constraint was eased by one unit. This is the shadow price. It is useful to know, for example, how much more electricity or more income would be produced if one more unit of water was made available to the electricity sector. Adding water as an additional constraint for each energy option within this approach thus quantifies the shadow price of water for each energy option. The approach assumes economically optimal allocation of water among options and calculates the optimal expansion trajectory for generation capacity (typically based on cost-optimisation, but the objective function can be specified in a variety of ways). Simulation models typically do not provide this information, but instead provide information on total value (such as net profit) rather than the marginal or incremental value of relaxing water or other constraints.

Some tool-boxes combine simulation and optimisation models. For example, some electricity sector models use a simple linear programming optimisation to determine which group of power plants in an electricity system will supply power for a given time of day (usually hourly increments) based on the state of the power plants in the previous time step and their assumed bidding strategy in the relevant spot power market. This type of model has become necessary as various countries have moved to implement competitive bid-based electricity markets where power plants compete to supply electricity at prices that change every few minutes.

Initially, these electricity market models applied optimisation only to determine the winning bids for each time step. Assumptions about which new plants were to be built in the future were explored using simulation techniques (e.g. user defined or Monte Carlo simulations). However, more recently some models of this type also include some degree of optimisation to determine future electricity plant investments (e.g. *PLEXOS*). For example, a combined model might be used to identify each hourly bid price for a year and then determine the least cost set of plant investments to commit to. It would then assume

that these investments were made, find the bid price for the next year, and again revise the future plant construction plan.

3.2.2 Bottom-up, top-down or hybrid?

Bottom-up models focus on the supply side with less detailed consideration of demand: they specify in detail a number of relevant technical and economic characteristics of existing and available technological options for new power plants. Such bottom-up energy models are often used to optimise either management or return-on-investment. They are often also the basis for simulating various energy sector scenarios such as how the technical mix would have to change in order to stay within a carbon emission targets or how introduction of a specific technology would influence production costs or supply reliability. They are liked and trusted by engineers as they have their roots derived from that profession’s interest in the way things are built. As such, bottom up power planning models typically set energy demand exogenously, although some bottom up policy analysis models calculate demand endogenously.

Top-down models are more demand side focussed with less detail on the supply side. Top-down models tend to be preferred by policy advisors and those responsible for the provision of strategic advice. Often the supply capacity of several plants will be represented by a single function. Much more detailed consideration is given to the search for understanding more about the ways that energy demand is likely to evolve in response to demographic trends and changes in economic conditions. Typically, these models represent relationships region by region with entire economic sectors represented as an aggregate.

A third group of models is often labelled as hybrid because their aim is to combine disaggregated energy supply options that endogenously adjust to changing energy demands. The most successful example for hybrid energy models is the MARKAL model family, which implement a partial equilibrium approach as a top-down approach and a highly disaggregated optimisation for the power sector in a bottom-up approach (Loulou, Goldstein, & Noble, 2004; Manne & Wene, 1992)

Table 2: Modelling approaches and research questions

Modelling approach		Typical question of analysis	
Bottom-up	Optimisation	Cost-minimising	Which investment provides a target capacity at minimum cost?
		Operation	Which investment optimises technical and management indicators such as water flow in the context of hydro-power?
	Simulation		Can supply capacity meet peak demand when water supplies are limited?
	Combined	Profit maximisation	Which operating strategy maximises profit from a given power station in a competitive market, and how will future power plant builds affect the market balance?
Top-down			How will interventions (i.e. taxes, policy changes) impact on the energy sector supply mix and power cost? Which sectors and regions will lose out as water use by power stations increases?
Hybrid			Which plant should be build next considering potential changes in population, income and inputs such as coal, gas, water and labour?

3.2.3 Spatial resolution in different energy modelling frameworks

Spatial relationships are important determinants of the cost of producing energy. Often there is a disconnect or distance between supply and demand that necessitates construction and maintenance of costly transmission infrastructure and significant efficiency losses as power is moved around a grid. A key challenge when seeking to understand the energy-water nexus is the need to understand spatial water flow considerations and build these into planning models. As noted earlier, the recent drought in France has forced this country to carefully rethink its capacity to cool nuclear power plants.

Knowledge about the ways that changes in water availability and flow seasonality changes can and are likely to impact hydro and thermal power option costs is critical both for the power sector and for those who must manage and are expected to deliver supplies to competing water uses. The costs of environmental externalities also have to be taken into consideration as hydro and thermal power stations aspire to modify flow patterns. Known costs include changes in silt transport and follow on impacts on agriculture, fisheries and, also, municipal and industrial water supplies.

Electricity market simulation models often include considerable spatial detail which is comparable with that commonly found in the water sector. If, for example, the aim is to represent a country's competitive electricity market bidding system, typically that requires including every plant. This type of model will also represent the layout of the high voltage electricity transmission system, transmission between plants and consumption by end-users in each region. One of the advantages of a simulation model is that they have lower computation requirements and, as a result, can usually accommodate considerably higher spatial information and temporal disaggregation than an optimisation model without significantly impacting on the time it takes for the model to run. This implies considerable potential to link these models to spatially detailed water information (such as supply, seasonal availability, cost, quality and other constraints).

Optimisation models, on the other hand, are often broader than the electricity sector and typically include all of the energy and transport sectors. As a consequence, they typically contain much less spatial detail. In particular, the number of data regions tends to be limited to those collected by national agencies. An exception to this is that nearly all models used to explore hydropower generation options include a conceptual representation of distance and water flow.

However, changes in water availability will also have effects beyond the energy sector, making a partial (or physically focused) perspective potentially misleading. Examples of potential complex dynamic feedback effects include:

- Households strategies for reducing water use will often involve increased energy use;
- Water pricing is likely to reduce water availability disproportionately due to differences in behavioural and technological potential to reduce water use and differences in willingness to pay for water, putting potentially a higher pressure on energy sectors than climate models suggest;
- Cross-sectoral impacts of water scarcity can have substantial implications; and
- Considering food production and relationships to the energy-water nexus is of particular cross-sectoral relevance (discussed in Section 4.2).

Capturing such systemic water availability constraints and underlying cross-sectoral impacts requires an economy-wide perspective, which is discussed in the next Section.

3.3 WATER SECTOR MODELS

In many ways, the issues and approaches used in water sector modelling and when modelling the nexus between water and energy are the same as discussed in the previous section on energy modelling. The main challenge unique to the water sector modelling is the need to find ways to represent hydrological relationships. The complex temporal and spatial relationships in water stocks and flows at basin scales make optimisation challenging, resulting in much greater use of simulation models. A specific issue is the need to account for what are known as return flows. A significant proportion of irrigation water, after

being applied to a field, returns back to a river through surface flows or shallow groundwater flows through the root zone. Typically a very large amount of sewage water is returned to a river after various degrees of treatment. Nearly all of the water used in hydro-power generation returns to a river and becomes available for downstream purposes. Much of the water used in cooling power plants that are close to a river also returns to a river. The timing of these flows varies widely, as do losses from evaporation and other processes. Moreover, river and aquifer modelling involves much more uncertainty. There are many unmeasured losses to groundwater, to the environment, and to unmeasured users. The nature of overland flows into a river following rainfall also needs to be accounted for, along with the impacts of changes in land use. To account for this, models are typically developed and “fitted” to specific catchments and regions to replicate what is observed to be happening at points where flow can be measured. All these factors mean that the use of simulation rather than optimisation models is high.

Optimisation models have their place in the water modelling arena and are becoming more common as the need to manage scarcity increases. By 2030, the OECD (2009) predicts that over half the world’s population will be receiving its water supply from systems where water supplies are limited – scarce. Modelling the nexus between water and energy is a relatively new activity where optimisation comes into its own. Here the management of storages and release control strategies is particularly important. An issue that is still emerging is the question of how best to define the power sector’s rights to take water when it is best suited to their purposes without unduly or unintentionally compromising needs of other sectors.

3.4 MULTI-SECTOR AND ECONOMY WIDE MODELLING

In this section we explore the integration of energy and water into economy wide frameworks. This discussion focuses primarily on Computable General Equilibrium Modelling (CGE). We then move to integrated assessment models which take economy wide frameworks one step further to include bio-physical feedbacks. We round out this section by putting forward what we see as the basic modules required to fully explore the energy-water nexus and bio-physical, social and demographic feedbacks that need to be taken into account.

3.4.1 Economy Wide Analysis and Computable General Equilibrium (CGE) Models

In the domain of economy wide analysis the main objective is to predict the impact of policy changes and external shocks on sectors and macro-economic indicators, such as GDP, real consumption, trade or wages. To build a CGE model one needs a set of Input-Output tables that quantifies the value of inputs and outputs for each sector. These models show for example how much fertiliser, water and energy is needed (in monetary units) to produce a (monetary) unit of wheat that as an agricultural output becomes an input into that part of the manufacturing sector that produces food that is consumed by people who work in the agricultural sector and elsewhere. Applied economists identified the need to consider cross-sectoral relationships like these many years ago. Arrow and Debreu (Arrow & Debreu, 1954; Debreu, 1959) then developed the mathematical basics for such an economy wide analysis of such relationships by building a modelling structure that assumes that markets will find a way to move to a state known as general equilibrium. Computable General Equilibrium (CGE) models improve upon input-output models by introducing an endogenous demand and price system, input substitution possibilities, optimal production and consumption, factor scarcity and a detailed representation of institutions and the macroeconomic environment.

The evolving availability of software accelerated the uptake of CGE methodology. Key packages include GAMS (Brooke, Kendrick, & Meeraus, 1998; Ferris & Munson, 2000; Rutherford, 1995), specialized CGE modelling software such as GEMPack (Harrison & Pearson, 1996), and relevant data such as social accounting matrices (Robinson, Cattaneo, & El-Said, 2001).

CGE models recognize that there are many markets and that these markets interact with each other in complex ways, largely driven by relative prices given the structure of the relationships embodied within the model. Demand for any single good depends on the prices of other goods, preferences, income, and policy settings. Income, in turn, depends on wages, profits, and rents. These in turn depend on technology, factor

supplies and production. Production or supply is a function of price and availability of inputs. Put simply, prices are determined by the interactions between supply and demand for all final products, intermediate inputs and primary factors of production. To keep them relatively simple, the functions in most CGE models assume constant elasticities or ratios of elasticities. That is, the proportional effect of an increase in one product on the production of another is not a function of the amount produced. This allows a CGE model to estimate the change in prices, output and welfare resulting from a change in a policy or a specified external shock (such as change in world oil prices) given assumptions about technology, trade policies, factor endowments, producer behaviour, and consumer preferences. In most cases, dynamic CGE models are used to analyse the medium to long term impact of shocks or changes, rather than short-run adjustment pathways.

One of the key strengths of CGE models is that each sector is modelled in a consistent manner. For example, these models track how exports from one country are imported by other countries. They also require that the sum of all sectors' employment does not exceed the labour force. Those that include water, for example, require that the total amount of water consumed is not greater than the amount available. This consistency feature generates empirical insights that might otherwise be overlooked in complex policy analysis, and also highlights compensating effects across the economy. Investors in a major project, for example, may seek tax concessions or other support based on claims about increases in employment or regional output, without accounting for decreases in employment or output in other sectors or regions of the economy. CGE analysis helps provide a coherent whole of economy perspective on such issues.

The value of a 'system wide' perspective can also be illustrated by a water policy example. In Australia, the Government is in the process of buying water for the environment and investing in expensive projects that produce water savings. Use of a CGE model has indicated that the result is an increase, not a decrease, in regional income because the money paid for the water is reinvested in sectors that make a greater contribution per dollar invested to regional prosperity (Dixon, Rimmer, & Wittwer, 2011). Information of this kind helps prevent sectional interests distorting public debate through partial analysis, and can help give policy makers the information and the confidence required to continue with a policy reform when a vocal few are trying to stop its implementation.

3.4.2 Including Energy and Water in Computable General Equilibrium (CGE) Models

Capacity to investigate energy related issues in CGE modelling experienced a substantial boost in the late 1990s, because of the need for assessments of the likely global impacts of global warming and policies necessary to reduce its extent. This has required the development of CGE models that pay close attention to the energy sector. One of the strengths of the CGE modelling system is that it is relatively simple to take a sector such as the energy sector or the water sector and break it up into several sub-sectors and then constrain each subsector in ways that represent market structure and other factors relevant to each sector. While first models were mainly focused on trade-related and tax-related issues, hundreds of models have since been developed for the global warming context (Unfccc, 1998), in particular for estimating carbon prices under alternative emission trading schemes (Bernstein, Montgomery, & Rutherford, 1999; Nordhaus, 1993; Smajgl, 2002, 2003). The combined modelling effort during this period generated the need for consistent datasets that account for physical quantities for different fossil fuels and other energy inputs into the energy sector and for physical units of Greenhouse Gas outputs. Assembly of these data has been greatly assisted by pre-existing data on the production and consumption of electricity, gas and vehicle fuels, which largely occur through markets. The extension of the existing trade-focused GTAP datasets to include energy and emissions (in GTAP-E) is one of the most significant responses to this need, as outlined in Box 3.

In general, economy wide models have been very successful in incorporating physical energy supply and demand at national and global scales. Climate change mitigation policies, for example, can be attached to

the cost of fossil fuel combustion or by constraining the quantity of allowable emissions.³ The consequences of doing this can then be tracked region by region and sector by sector. These processes have been effectively represented in most cases by integrating an adequate resolution of energy sectors in CGE models, but a range of approaches are possible.

Dinar (2012) reviews recent model-based analysis of water policy in several countries, including analysis of the impacts of water constraints, rural urban transfers, farm level water management, and trade policy. This analysis features micro-macro linkages through the application of disaggregated bottom up irrigation sector models to assess water constraints linked to CGE models. Country policies analysed include Mexico, Morocco, South Africa and Turkey.

Like all economic models of this kind, the resulting economy-wide models do not generate reliable predictions of the future. Rather they allow comparison of policy scenarios to a reference case. One of the main weaknesses of this approach is that it is difficult to judge how well endogenous innovation and technological change processes are represented in a CGE model. Assumptions on energy efficiency improvements are critical for resulting carbon prices. In principle, CGE models can include technological change by determining exogenously energy efficiency improvements or implementing how innovation occurs endogenously due to increased use of particular energy technologies. However determined, the more energy efficiency improves, the lower estimated carbon prices (Edenhofer, Lessmann, & Bauer, 2006; Huntington & Weyant, 2002; Löschel, 2002). Assessments of ex ante evaluations of economic impacts of environmental policies have consistently shown that economic modelling tend to overstate the actual cost of achieving environmental goals because the constant elasticity assumptions used tends to estimate potential for innovation and substitution (Goodstein, 2005; Harrington, Morgenstern, & Nelson, 2000, 2010).

³ Over time, these policies drive new investment towards known energy technologies involving lower greenhouse emissions, along with slower growth in energy demand (due to higher energy prices than would otherwise be the case). Policy assessment has also involved considerable model development to allow representation of increasingly sophisticated policy scenarios and implementation mechanisms at national, regional and global scales. At national scale the carbon price to emerge from quantity based policies can be materially affected by details of electricity market structure and generation mix (which influences bid order and thus the technology that sets the carbon price at the margin).

Box 3. The development of economy-wide models accounting for energy and emissions

Malcolm and Truong (1999) proposed an extension to the standard GTAP model called GTAP-E. GTAP-E incorporates carbon emissions from the combustion of fossil fuels. The resulting model provides a substrate through which carbon trading and taxes can be explored. Burniaux and Truong (2002), also provide an extensive review of the main approaches to integrating energy into CGE models including the fusion of top-down economic models with bottom-up energy sector process models; and the energy technology bundle approach of MEGABEAR and GTEM models. The GTAP initiative extended their previously trade-focused goal and provided the global emissions dataset to support GTAP-E (Complainville & van der Mensbrugghe, 1998; Hertel, 1997; Malcolm & Truong, 1999) and other emissions and climate change modelling exercises.

The Fondazione Eni Enrico Mattei (FEEM) developed an expanded version of GTAP-E model called GTAP-EF (M. Berrittella, 2006). Like GTAP-E, GTAP-EF is a comparative static model, and the model has been used to study the impact of climate change on tourism (M. Berrittella, 2006), coastal inundation (Bosello, Roson, & Tol, 2007), human health (Bosello, 2006) and the impact of extreme weather on the economy.

The calibration of GTAP-EF involves generating snapshots of the global economy for points in time far enough into the future to be of interest in the context of climate change. These snapshots are calibrated using a two-step process. First, the baseline scenario is generated by using standard database projection techniques. Climate change is assumed to have no impact in these scenarios. Second, the baseline scenarios are shocked with climate change impacts taken from a range of models including FUND (R.S.J. Tol, 1999; Richard S. J. Tol, 2002), IMAGE (Bosello et al., 2007) and G-Cubed (McKibbin & Wilcoxon, 1999). The impacts of climate change are then shown as deviations from the baseline. As the model is comparative static model which compares state A with state B, there are no time paths, limiting the usefulness of these results for assessing the adjustment paths and the costs and benefits of climate change.

The Dynamic Applied Regional Trade (DART) model (Deke, Hooss, Kasten, Klepper, & Springer, 2001) was developed at the Kiel Institute for World Economics for the purpose of assessing the impacts of climate change and climate policy. DART has been used to assess prevailing issues in the debate of the Kyoto Protocol such as different regimes for international emissions trading and to investigate the implications of different degrees of capital mobility. DART was one of the first models to integrate economic impacts of climate change into a CGE model by using data directly provided by a simplified ocean-atmosphere model. Essentially, DART translates emissions into climate change, through the use of an impulse response function. DART was able to explore issues such as the relationship between economic activity, emissions and the impact of sea-level rise.

The ENVIRONMENTAL Impact and Sustainability Applied General Equilibrium Model (ENVISAGE) (Bussolo, de Hoyos, Medvedev, & van der Mensbrugghe, 2008) is a global dynamic recursive CGE model, derived from the World Bank's LINKAGE model (Van der Mensbrugghe, 2008). ENVISAGE consists of a series of modules that describe emissions generation, the translation of emissions into atmospheric greenhouse gas concentrations, and the impacts of greenhouse gasses on global temperature. A Damage function transforms projected global temperature change into shocks for agricultural productivity.

The Global Trade and Environment Model (GTEM) (Pant, 2007) is a global dynamic recursive CGE that was developed by the Australian Bureau of Agricultural and Resource Economics (ABARE). GTEM is a variant of the GTAP model, and the successor to ABARE's MEGABARE model. GTEM has an advanced energy technology bundle, and an innovation technology advancement sub-system. GTEM is capable of creating time paths of economic, climate and environmental variables. GTEM has the facility to track greenhouse-gas emissions including ozone depleting substances, and other gasses. One of GTEM's strengths is its capacity to track emissions at a detailed sector and region-specific basis. Refinements to the GTEM database are allowing users to take more flexible regional and sectoral approaches (Sealey, Newth, Gunasekera, & Finnigan, forthcoming). Sealey et al. (forthcoming) have placed GTEM in a probabilistic Monte-Carlo framework to explore uncertainties in the climate-economy interactions.

Dinar (2012) provides an example of innovative micro-macro linkage, coupling bottom up irrigation sector models with CGE models to investigate a variety of water and agricultural issues, including a comprehensive review of the use of CGE modelling of water issues.

Like energy, water resources are recognised as scarce and ‘valuable’ (WMO, 2007). Increasing stresses on water resources as a result of population growth, rising per capita incomes which increase consumption of all goods including water, and the emergence of long dry periods has resulted in significant international interest in the importance of water in policy assessments.

However, far less progress has been made in the inclusion of water in economy-wide models, and there is relatively little modelling internationally that integrates water and water constraints into models that also provide detailed representation of energy issues. The GTAP-W model (see Berrittella et al. (2007), Calzadilla et al. (2011) and recent Australia work described in Box 5 below are exceptions. Reasons for this slower progress include the fact that policy and research interest in water and its wider economic significance has emerged only more recently, and it is less widespread than the attention to energy and greenhouse gas mitigation. Attempts to incorporate water into existing economic models has also been complicated by data and accounting conventions, as water is not usually identified as a factor of production or separate intermediate input in the national accounts, and is typically not disaggregated in the social accounting matrix (Smajgl & Liagre, 2010). Water availability is also generally far more granular and locally specific than energy supply and emissions factors – water is expensive to transport relative to its economic value (contrasting with fossil fuels), and historically has frequently been supplied naturally or through engineering works at little or no cost in many locations (Byatt, Ballance, & Reid, 2006; Zhou & Tol, 2005).

The progress that has been made on integrating water into economy-wide models focuses largely on water as an input to agricultural production, exploring issues such as the economic impacts of groundwater constraints, the significance of embodied water in agricultural trade flows, and the national impacts of water variability (such as droughts). Two primary approaches have been taken to assessing the socio-economics of changes in water supply and demand to handle these data limitations. Where functioning water markets and water accounts exist, water use in agricultural and industrial processes may be disaggregated from capital in the national accounts data. In the absence of functioning water markets and in cases of unregulated use, water supply and demand shocks may be implemented indirectly. A reduction in agricultural water supply, for example, could be implemented as a reduction in crop yield.

Some of the most interesting recent advances in incorporating water into national economy wide models have occurred in Australia, where significant over-allocation of water entitlements coupled with highly variable rainfall created a demand for models that predict the sectoral and economy-wide impacts of water constraints. Hanslow (2010) describes the development of national CGE model based on the Monash Multi-Regional Forecast Green (MMRF-GREEN) model used to analyse proposals for a national emission trading system (Centre of Policy Studies, 2008). An extended version of MMRF (MMRF-H2O) was designed as the economic engine of a national Integrated Assessment Model (described in Boxes 4 and 5 below) for analysing the impacts of climate change, domestic policy settings and global economic and technology trends.

The resulting CGE model includes a set of water accounts for each sector, and a water supply industry, and has been modified to include irrigation sectors and to establish “regions” that follow catchment boundaries. Implementing the model involves adding a matrix of the quantity of water used by industry and region; assigning prices to water and including the cost of water in production; enabling substitution between water and a composite of non-water inputs; and specifying the model so that water could be traded between agents as well as diverted for environmental and non-consumptive uses (G. Wittwer, 2003). The water supply industry is disaggregated into three sub-sectors: (1) Surface & Groundwater (which encompasses the most climate-sensitive supply option based on rainfall and dam levels), (2) recycling and (3) desalination. This means that water can be traded, recycled or generated by desalination where there would otherwise be a shortage of available water in a region. Since the cost of irrigation water is not detailed in available national input-output tables, actual costs are assumed to be embedded in statistical survey data as a capital cost. Importantly in the context of the energy-water nexus, the energy requirements for each water industry are included, so the model accounts for water demands by the energy sector, and the energy demand for the water sector. Building on the advances of TERM-Water, Dixon et al. (2011) have created a dynamic version of the model, TERM-H2O, to evaluate the effect of a government buyback of irrigation water.

Box 4. Representing water constraints in economy-wide models

Although water-sector modelling with CGE is considered a relatively new approach to water resources policy and management issues (Roy Brouwer, Hofkes, & Linderhof, 2008), experience with integrating water into economy-wide modelling is growing. One of the earlier examples is that of (Berck, Robinson, & Goldman, 1990) who evaluated water supply constraints in the San Joaquin Valley in the United States. In this regional model, water is disaggregated as a factor of production and land is combined with water in fixed proportions to form irrigated land. Water is fixed in supply and mobile between sectors, while water use coefficients are fixed in the agricultural sector (Berck et al., 1990).

Berrittella et al. (2007) evaluate groundwater scarcity in a context of international trade with the GTAP-W model. This model is the first global, multi-regional model of its kind where economic sectors use water as a factor of production. With an assumed reduction in water supply, it is expected that the relative price of water-intensive goods will increase, resulting in a shift in the competitiveness of some industries, and in the terms of trade. Regional water use is determined by coefficients representing the amount of water required to produce a specific output (Maria Berrittella et al., 2007). In another application, Berrittella et al. (2006) investigate the economics of water pricing.

Calzadilla et al. (2011) use GTAP-W to evaluate improvements in irrigation efficiency. Advances over the GTAP-W model developed in Berrittella et al (2007) are two-fold: the model production structure differentiates between rain fed and irrigated agriculture, and there are substitution possibilities between irrigation and primary factors. In this model, water is combined with irrigable land, forming an irrigated land composite which is then combined with other primary factors through a CES function to thereby create value added (2011). The modelling framework does not, however, consider domestic, industrial or environmental water uses.

The Centre of Policy Studies (CoPS) in Australia has investigated various issues related to water scarcity, allocation and pricing. Horridge et al. (2005) developed TERM, a bottom-up national CGE model, where each region in the model is treated as a separate economy. Horridge et al. (2005) compare the impact of one of Australia's most severe droughts (2002). The direct impact of the drought was simulated as agricultural productivity losses; these were calculated for each agricultural industry by region based on rainfall deficit figures (2005). These direct output shocks were used as inputs into TERM to evaluate drought impacts. Wittwer (G. Wittwer, 2003; Glyn Wittwer & Griffith, 2011) has also modified TERM to include irrigation sectors and build "regions" that follow catchment boundaries (as explained in more detail in the main text). As the cost of irrigation water is not detailed in Australian input-output tables, actual costs are assumed to be embedded in statistical survey data as a capital cost.

Another major innovation common to TERM H2O and to GTAP-W is the capacity to differentiate between rainfall (green water) and irrigation (blue water) used in production.

Kraybill et al. (2002) developed a comparative static CGE to assess economy-wide impacts of reduced irrigation subsidies and an elimination of a rice tariff in the Dominican Republic. This model has a sector which combines surface water with intermediate inputs to form distributed water. This water is then either used as an intermediate input or is consumed by households. Diukanova and Lennox (2011) model the impacts of water supply constraints on irrigation considering both growing demand and a reduction in rainfall. Both agricultural land and water resources are distinguished by region and land is mobile between agricultural uses. Rainfall is associated with land in fixed proportions for each sub-region. Irrigation water and rainfall are treated as imperfect substitutes. Unit costs of irrigation are assumed to increase as increasingly marginal land is brought into irrigated production. The value of rainfall is assumed to contribute to land rent: it is assumed that 25% of land rent is attributable to rainfall (Diukanova & Lennox, 2011).

3.4.3 Representing externalities and non-market impacts in multi-sector models

Related analysis has explored externalities associated with water use, particularly in agriculture. These efforts typically find that the external impacts of water use are significant, as are the benefits of reducing water use in stressed river ecosystems, and need to be accounted for in decision making (CSIRO, 2012). The costs and benefits of different impacts are often difficult or expensive to quantify in monetary terms to a standard appropriate for policy makers, but can provide valuable input to decision making in a wide range of contexts, such as the implementation of ‘full cost’ pricing of water use (Arrow et al., 1993; R. Brouwer et al., 2009; National Research Council, 2004). In practice, however, it can be challenging and sometimes counterproductive to seek to express all major impacts in monetary terms, because the assumptions and uncertainties involved in transforming physical impacts into monetised values may reduce the utility and reliability of this information for decision makers (Frank, 2000; Hatfield-Dodds, 2005).

There are additional challenges in including externalities in economic models. A first hurdle, for simulation models, is that these estimates represent shadow prices or values that are explicitly not accounted for in market decisions, and so should not be included in how models represent decision making, but – ideally – should be included in the representation of consequences. For example, if thermal discharge from power plants is not regulated and adversely impacts on fish populations, a simulation model should represent expected actual behaviour of operators, and also the decline of fish stock or the associated impacts on local diet and health. These impacts could be reported in physical units or in loss of equivalent income or consumption. (An agent based model might explore a range of potential behaviours by operators, including local norms, knowledge diffusion, and social networks; along with a variety of downstream livelihood strategies and impact pathways).

There have been a variety of efforts to incorporate the impacts of ‘downstream’ externalities in agent based models and hybrid modelling frameworks, including exploration of land use, soil erosion, river sediment and water quality (Matthews, Gilbert, Roach, Polhill, & Gotts, 2007; Parker, Manson, Janssen, Hoffmann, & Deadman, 2003; Smajgl, 2006; Smajgl, Morris, & Heckbert, 2009), and also the interplay between local natural resource use, incentives for community enforcement of management regimes, and income from cash crops in developing countries (Becu, Perez, Walker, Barreteau, & Page, 2003; Castella & Verburg, 2007; Smajgl & Bohensky, 2011).

We are not aware, however, of any attempts to systematically account for externalities of this kind in economy-wide CGE models. (Accounting for the impact of greenhouse emissions in integrated assessment models is a special case, discussed below.)

An alternative to seeking to develop ‘fully coupled’ representations of economic activity and associated non-market impacts would be to use a variety of modelling approaches to address different types of issue, as discussed in Section 4.4.1. This approach may also help to build understanding and confidence among decision makers and key stakeholders, should be decided that a more flexible or dynamic coupled modelling approach is necessary for robust analysis and decision making.

3.4.4 Coupling model types

In cases of integrated assessment in which critical aspects cannot be readily captured by the highly aggregated framework of general equilibrium modelling, other modelling techniques can be used in combination (S. Serban Scriciu, 2007). Water quality, for instance, is difficult to be considered in CGE models, in particular because impacts vary significantly across locations. Local and regional economies, however, can be largely affected by decreasing water quality. Measures for improving water quality are often impacting on agricultural activities, defining complex economic trade-offs for regions like the Great Barrier Reef in Australia. Using CGE model in combination with agent-based models allows linking of these micro and macro dynamics (Smajgl et al., 2009). Similarly, Smajgl and Bohensky (2011) combine CGE modelling and agent-based modelling to analyse for the Indonesian Government the impacts of fuel subsidy changes on poverty. This is relevant because poverty is determined by many local circumstances, such as the availability of and access to natural resources. Many of these factors cannot be considered effectively within a CGE model. However, macro-economic impacts such as sectoral employment and

inflation are difficult to simulate in an agent-based model. Combining macro and micro analysis can thus often be an effective strategy for considering dynamics that operate at different system scales (Dinar, 2012; S. Serban Scriciu, 2007). Agent-based modelling has been identified as one of the most promising methods for issues on energy and water (Boulanger & Bréchet, 2005) and has been tested in a variety of applied policy contexts (Bousquet & Le Page, 2004; Matthews et al., 2007).

3.5 GLOBAL AND NATIONAL INTEGRATED ASSESSMENT MODELS

Another potential window into examining the energy-water interaction is through the use of integrated assessment models (IAMs). IAMs attempt to integrate knowledge from two or more domains into a single framework to help decision makers understand complex social, economic and environmental problems. Most integrated assessment models and projects have been developed in the context of climate change: addressing interactions and feedbacks between economic activity, greenhouse emissions (particularly from energy production) and climate change, and exploring the potential technological, social, political and economic shifts involved in achieving different potential global climate trajectories. Box 5 briefly outlines several integrated assessment models (IAMs).

In general, these models can be considered as being similar to the economy-wide CGE models reviewed above, particularly in relation to the degree to which the water cycle is integrated into the representation of economic activities and human water use. One advantage over standard economy-focused CGE models, however, is that many IAMs already incorporate the capacity to provide climate projections that can – in principle – be applied to help produce coherent and internally consistent projections of the climate-linked precipitation and runoff, at relevant scales, as an input to water supply outlooks under climate change. One practical issue is that projections of precipitation need to be treated as probability distributions; given greater uncertainty about potential impacts on regional precipitation, implying a need for more scenario-based analysis to deal with these uncertainties. A second issue is that the relationship between precipitation and water availability (in rivers and storages) is complex, and strongly influenced by land use and land use change, and thus may require the development of specific climate linked water projections if these are not already available.

Box 5. An overview of global and national Integrated Assessment Models (IAMs)

The Integrated Model to Assess the Global Environment (IMAGE) (Bouwman, Kram, & Klein Goldewijk, 2006) is a complex modelling framework that connects several stand-alone models including TIMER (energy supply and demand model), the FAIR model (policy model and the IMAGE land-atmosphere model). The core application of IMAGE is the development and analysis of scenarios of global environmental change. The model provides a framework for representing an energy system and its interconnections. MESSAGE was used to create IPCC Representative Concentration Pathway scenario 8.5.

The Asia-Pacific Integrated Model (AIM) (Fujino, Nair, Kainuma, Masui, & Matsuoka, 2006), developed by National Institute for Environmental Studies in Japan, combines three models: (1) The Greenhouse gas emission model (AIM/emission); (2) The Global climate change model (AIM/climate); and (3) The climate change impact model (AIM/impact).

The AIM/emission model estimates greenhouse gas emissions and assesses policy options to reduce them. The AIM/climate model forecasts concentrations of greenhouse gases in the atmosphere and estimates the global mean temperature increase that will occur as a result of those emissions. This model also estimates climate change impacts on the natural environment and the socio-economy of the Asian-Pacific region. AIM has made major contributions to policy debate in this arena at the national, regional and global scale. The AIM model has been used to provide global and regional emission scenarios, and was used to create the IPCC Representative Concentration Pathway scenario 6.

The Global Change Assessment Model (GCAM), previously known as MiniCAM (Brenkert, Smith, Kim, & Pitcher, 2003), is a global integrated assessment model, developed by North West Pacific Laboratories. GCAM has a heavy focus on the representation of human earth systems including interactions between the global economic, energy, agricultural, land use and technology systems. GCAM is disaggregated into 14 geopolitical regions explicitly linked through international trade in energy commodities, agricultural and forest products, and other goods such as emissions permits. Its economic core is a dynamic-recursive general equilibrium model. GCAM was used to create the IPCC Representative Concentration Pathway scenario 4.5.

The Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) was developed by IIASA, and is a systems engineering optimization model designed to be used for medium- to long-term energy system planning, energy policy analysis, and scenario development (Messner & Strubegger, 1995). The model provides a framework for representing an energy system and its interconnections. MESSAGE was used to create IPCC Representative Concentration Pathway scenario 3PD.

The Global Integrated Assessment Model (GIAM) and the National Integrated Assessment Model (NIAM), and integrated assessment models developed by collaboration between CSIRO and Monash University are collection of stand-alone models that can be flexibly coupled together to answer social, economic and policy questions around global change issues. GIAM (Newth, Gunasekera, Handslow, & Finnigan, 2011) contains three main modules: (1) The Economic Module, consisting of GTEM which models economic, policy settings, technological advancement and emissions; (2) The Climate Module, consisting of the Simple Carbon Climate Model (SCCM) (Raupach et al., 2011) used to simulate climate responses to emissions; and (3) The Climate economy interactions Module, that models the impact of climate change on the global economy. NIAM (Hanslow, 2010) provide a regionalized assessment of the impact of climate change on the Australian economy. NIAM is nested with GIAM and uses climate and economic outputs from GIAM as boundary conditions for MMRF-H2O (see above). The climate information is downscaled into regional climate and weather information, and then fed into MMRF-H2O. Climate economy interactions are also downscaled to regional impacts to allow assessments, for example, of the impact of climate change on the productivity of the Victorian dairy industry.

4 Suggestions for improving decision support for energy and water policies and investments

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4.1 OPPORTUNITIES AND PRIORITIES FOR IMPROVING ENERGY MODELS

This section brings together the implications of the review of existing modelling capacity in relation to the demands of the energy-water nexus, discusses the scope of issues to be addressed (including the case for explicitly including food in the analysis), and explores the role of modelling and implications for the interactions between models, modellers and decision makers. The section concludes with recommendations for how models are used, and for developing the modelling capacity required for a sound understanding of the energy water nexus.

4.1.1 Recommended priorities and implementation issues

Sections Two and Three above have provided an overview of the energy-water nexus, and current practice in considering water constraints in the two main domains of energy modelling.

The key finding of this report is that 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. There are a variety of conceptual frameworks and methods that provide insights into different aspects of the nexus, but no existing framework appears able to analyse the all the important issues raised by the nexus, or to provide the decision support and risk management information required. This is of particular concern for countries with strong energy demand growth, or significant declines in per capita water supplies.

Against this, we also find that several frameworks and methodologies capture important aspects of the nexus, but that in most instances only a small number of models and projects have been actually implemented.

Addressing these shortcomings is not simply a matter of integrating physical water use into energy models.

In principle, all types of energy models can consider water as a physical input and, therefore, can include the quantity of water supplied as a physical constraint. Many models in current use are able to include hydropower, and are thus capable of explicitly representing reservoir inflows throughout the year. Mathematically there should not be a problem with extend this coverage to integrate physical water inputs – consumptive or non-consumptive – for all power generation technologies. However, while this may be a

necessary component of a coherent modelling strategy, it is not itself a sufficient response to the challenges presented by the nexus. Other key issues include addressing the cross-sectoral impacts (and opportunity costs) of water use in a specific location, or interactions between energy sector water use at different times and locations, and assessing the overall impacts and benefits of potential energy and water policies and investments. This implies that appropriate decision support will require more than simply integrating physical water flows and availability.

Instead, the challenge is to provide the *combination* of the following modelling features (see

Table 3):

- Representation of the extent to which the costs and returns of different power generation options are influenced by water constraints (and underlying causal processes), including future water availability, cost, security, and potential conditions on access and use;
- Adequate spatial and temporal representation of water constraints in relation to energy supply (including probability distributions of key parameters), where there is a material risk these constraints could impact on energy supply over the life of existing and planned power generation assets;
- Representation of how competing demands for water are likely to evolve and influence the opportunity cost of water use in the energy sector;
 - Ideally this would involve the ability to explore expression of these evolving demands both through markets (through prices), within the model structure, and through political process (through policy changes), represented as alternative modelling scenarios;
- Representation of the degree to which different energy supply options impose externalities or influence other water use values, and assessing how this may change over time (explored through alternative scenarios, and potentially through hybrid simulation models that represent key externalities); and
- Representation or assessment of the macro-economic consequences of alternative water and energy policies and investments.

Table 3 summarises the capacity of different existing modelling approaches to address these and related issues.

Table 3: Capacity of optimisation, simulation and CGE models to analyse key aspects of the energy-water nexus

	Optimisation	Simulation	CGE models
Plant-scale representation	YES	YES	NO
Spatially referenced supply side	Maybe	YES	NO
Daily or weekly time steps	YES	YES	NO
Temporal and spatial hydrological processes	Maybe	YES	NO
Disaggregated representation of energy demand	Maybe	YES	NO
Disaggregated representation of water demand	Maybe	YES	NO*
Micro-economic variables (i.e. shadow price)	YES	Indirect	YES
Macro-economic variables (i.e. GDP, employment)	NO	Difficult	YES
Cross-sectoral dynamics	YES	Maybe	YES

* Box 4 and Section 3.4.2 above discuss some exceptions that indicate it is feasible to develop CGE models with disaggregated water supply and demand, aligned with catchment boundaries.

Disaggregated power generation options

Meaningful power grid representation at a national or regional level requires some disaggregated representation of different power generation technologies in a manner that recognises the extent to which each type of generation technology uses water and the degree to which the supply of water is constrained. In addition to these supply realities, other factors like the range of allowable discharge temperatures has to be represented. For example, constraints such as the quantity of available water or allowable discharge temperatures will have different effects on the generation efficiency of different thermal generation technologies. Potential changes in the value of competing water uses also need to be understood and mapped back to impacts or constraints on consumptive and non-consumptive water use.

Detailed assessment of the water management implications of different energy technologies needs to be underpinned by an understanding of how competitive advantage of these technologies may change with increasingly binding water constraints, and changing alternative water use values. For some issues, relatively aggregate technology representation may still be reasonable, as long as technologies with similar coefficients for water input per kWh are grouped together for the main technology options. In general, bottom-up models will have an advantage for this purpose, as these models typically include detailed disaggregation of energy technologies.

Spatial and temporal resolution

In terms of temporal resolution, top-down energy sector models tend to be annual time step, whilst bottom-up models tend to operate at higher temporal resolution. For representation of hydrologic constraints and impacts less than annual resolution is necessary: monthly or weekly time steps would suffice in many cases. If the purpose of the model is strategic (rather than operational), a weekly or monthly time step should also suffice for power plant planning; if an understanding of an energy spot market were needed, daily or hourly time steps would be necessary (but water data may not be required with the same temporal resolution unless supply or other parameters could vary within these time frames).

Another consideration in spatial scale is the level of spatial disaggregation for water and hydrological processes. Like energy grids, river basins can be represented at varying levels of aggregation. Conceptually one could consider flows at exactly the point where each water dependent power plant is or could be located and projections of how this might change from downscaling models. Typically, however, resolution of flow and more so downscaling models is at a coarser resolution: catchment or sub-catchment is often

the resolution of hydrology models as this is the level at which flow monitoring points are typically disaggregated. There are nearly always significant flow differences at this spatial resolution. The need for further disaggregation of water data will depend, in part, on extent of likely future water scarcity and the balance between highly water dependent versus less water dependent energy options in the relevant country or region.

In many instances an ideal power planning model would explicitly represent each current and potential future power plant spatially. The spatial reference would link to hydrological processes and water availability temporal patterns and spatial interactions. The incorporation of hydrological processes is feasible and has been exercised for simulation models (Carlin et al., 2007; Manson & Evans, 2007; Reaney, 2008; Smajgl & Bohensky, 2011; Smajgl et al., 2009) Whilst this is also technically feasible for optimisation models full system optimisation over large temporal and spatial domains can lead to such large problems that reasonable solution time becomes an issue – mixed approaches with some optimisation components within a simulation model may be desirable. Such architecture has for example been applied successfully in the system dynamics literature.

Competing demands

Projections of impacts of water shortages on energy sectors need to consider competing water demands from other sectors (including because of the potential for changes in water and energy policy settings in response to these evolving pressures and opportunities). Existing water access rights upstream of power generation units can increase water supply constraints, beyond potential climate driven changes. Vice versa, demands in other sectors, such as agriculture, can suffer disproportionately more from declining freshwater availability if, for instance, water pricing is introduced and sectors with lower price elasticity maintain their water demand. CGE models have a clear advantage in this regards although their efficacy decreases with increasing sectoral aggregation. Bottom-up models, such as optimisation and simulation models, theoretically have the ability to capture cross sectoral dynamic but in practice most tend to assume away relationships with other sectors.

The explicit modelling of competing water demands outside of energy sectors has an additional advantage.

Policy responses to managing water scarcity and other impacts of climate change include both supply-side and demand side options. Supply focused options include the investment in additional water infrastructure, including the adoption of new technologies. The most cost effective supply side measures might be much more expensive than some demand side options, however, such as water pricing and non-pecuniary incentives for behavioural change. It would be an advantage to assess the scope for such demand directed strategies to contribute to the alleviation of water constraint on the energy sector. Top down models have a clear disadvantage in assessing demand side options, as most demand directed strategies cannot be assessed. Simulation models have a clear advantage when behavioural aspects are important and where the explicit representation of the uptake of new technologies makes a real difference to understanding policy and investment options.

Externalities

Another dimension of cross-sectoral implications is the assessment of the impact of externalities, such as downstream water quality or ecosystem services. Changes in the energy water nexus, and investments in response to such changes, are likely to have implications for food security, urban water values, the environment and other sectors. Quantifying such externalities is essential for managing trade-offs and fine-tuning policy instruments and investments. Depending on the externalities at stake and what indicators are required to inform the assessment some methods are stronger than others.

Macro-economic outcomes

Assessing macro-economic outcomes requires the representation of national economies, which is the stronghold of CGE and Input-Output modelling. Methodologically simulation models could be extended to cover a national economy, but this is rarely done. The excessive data demands of such simulation models could be managed by different levels of aggregation of economic activities.

In summary, there is not one methodology that provides a comprehensive perspective, allows exploration of all issues and features (Hodgea, Huang, Siirola, Peknya, & Reklaitis, 2011; Smajgl et al., 2009). Optimisation models are strong in economic terms while simulation models have strengths in representing social and physical processes. Table 3 lists the critical features for an ideal national energy planning model in the context of climate change adaptation.

Before identifying a way forward on modelling the energy-water nexus more effectively we note two dimensions that are highly relevant to assessing water and energy related investments. First, the relevance of the food sector for energy water interactions. Second, the relevance of the *process* in which the modelling activities are embedded when operating across multiple sectors.

4.2 THE CASE FOR INCLUDING FOOD

Most analysis and modelling of energy and water interactions identify food as a crucial dimension or consideration, but fail to include it explicitly within the analysis.

We argue that in many cases that impacts on food security and food production will be increasingly material – if not central – to decisions about energy and water policy and investments. Explicit attention to food issues would thus be likely to result in more robust and transparent support for these decisions. Examples of additional issues and linkages brought into scope by explicit attention to food include:

- Decisions about water pricing, allocation and entitlements (including tradable water rights), and supply priorities and related investments will impact on the level of food production, on the mix of crops and shares delivered to domestic and international markets, and on domestic food access, nutrition outcomes, and food security (Dinar, 2012) – in addition to the indirect effects of water policies and investments on energy demand;
- Decisions about energy supply options will impact on food and water availability through water use and increased competition for arable land due to the production of energy crops (including biofuels from food crops, bioproducts and waste) and carbon plantings (biosequestration), through the indirect impacts on fish stocks from hydro infrastructure and thermal pollution (from power generation), and through tradeoffs between irrigation and hydropower generation benefits in the timing of delivery of water releases; and
- Decisions about food production will impact on water and energy demand (including water quality requirements, and seasonal water availability), such as for use in the production and use of fertilisers and agricultural chemicals, and in food production, processing and distribution.

This is consistent with recent arguments in the literature that attention be given to integrating analysis and understanding of cross domain linkages between energy-water and food – sometimes also extended to explicitly include carbon (Berndes, 2002; Kenneth Strzepek & Boehlert, 2010). These issues have implications for research as well as policy.

The Bonn2011 conference on the Water, Energy and Food Security Nexus, for example, argued that improved understanding of the dynamics and linkages between these sectors is crucial to understanding potential opportunities, trade-offs and synergies, and thus for avoid mal-adaption and ineffective investments. This implies, they state, that “Understanding the nexus is needed to develop policies, strategies and investments to exploit synergies and mitigate tradeoffs among these three development goals with active participation of and among government agencies, the private sector and civil society. In this way, unintended consequences can be avoided.” (Bonn2011, 2011) This statement emphasises the importance of this Plexus for the development context. Figure 3 shows key processes in Plexus dynamics.

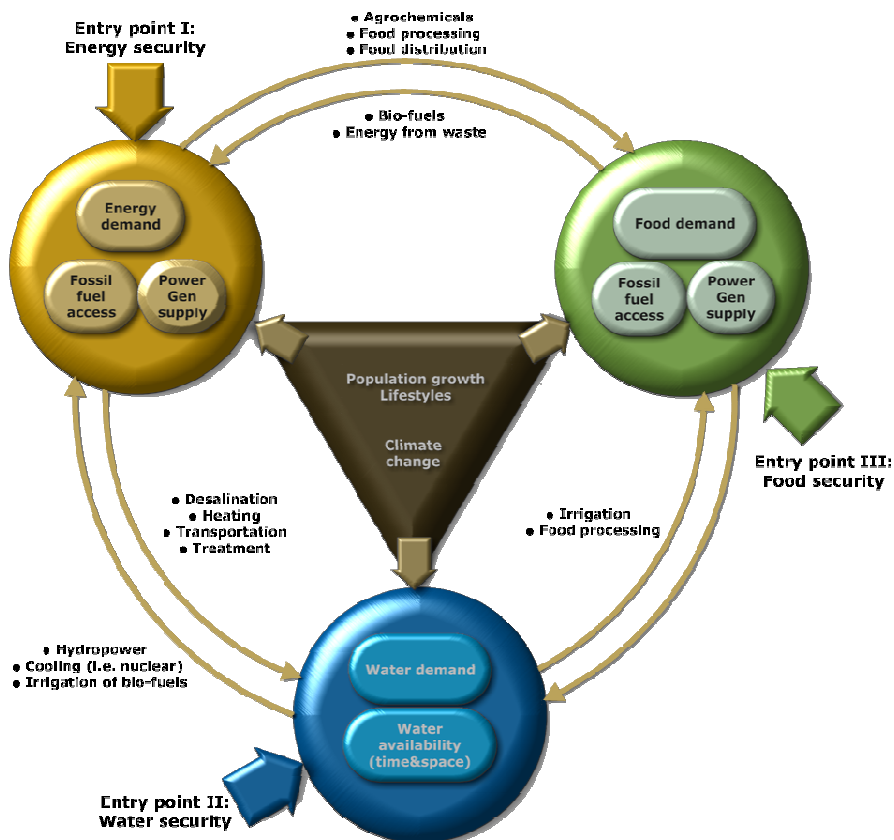


Figure 3: The energy-water-food plexus

Source: Smajgl & Ward (forthcoming)

Acknowledging these potential trade-offs and synergies makes some of the risks explicit when addressing sectoral goals in isolation. Investments that pursue energy goals could create substantial trade-offs or synergies. Trade-offs might offset expected impacts of investments in the food security space or vice versa. Coordinating investments and developing consistent policies that allow for sustainable development would ideally involve:

- (a) the understanding of these relevant connections;
- (b) specifying potential trade-offs and synergies for the particular context;
- (c) the design of effective measures that help mitigating trade-offs and exploiting synergies; and
- (d) monitoring and assessing impacts of investments on Plexus dynamics.

It is crucial to understand the Plexus as a dynamic system; investments in this Plexus are likely to change or even transform the nature of some or all links, which emphasises the importance of monitoring and assessing impacts.

However, methodologies are limited, as discussed above for the energy-water nexus. The development of analytical tools, methodologies and empirical processes are even more challenging for the water-food-energy Plexus (Smajgl, Foran, Dore, Ward, & Larson, forthcoming). Currently, CSIRO is implementing a new approach for analysing the water-food-energy Plexus for the wider Mekong region.

The Mekong Futures project creates cross-sectoral (and trans-boundary) bridges by implementing the ChaRL framework (Smajgl et al., forthcoming).

Methodologically, this study combines the workshop process and visioning approach with agent-based models and a series of disciplinary tools focusing on hydrology, crop growth and livelihoods. The agent-based simulation provides the necessary platform to combine hydrological, economic, social, and agricultural process, to assess impacts of development investments (i.e. irrigation, hydropower) and climate change.

Such a combination of complex systems understanding, advanced methodology and engagement design allows for effective evidence-based support of decision making processes. Depending on the particular indicators of interest a different blend of methods could be employed, for instance agent-based simulation and CGE modelling that was trialled in Australia and Indonesia (Smajgl, 2010; Smajgl et al., 2009), as described in Section 3.4.4 above.

4.3 THE CONTRIBUTIONS OF MODELLING TO SOCIAL CHOICES ABOUT ENERGY AND WATER

There are numerous challenges to be addressed in supporting sound social choices about energy and water policies and investment. Social, economic and environmental systems are complex, and deeply uncertain. Future national needs, circumstances and relative priorities are all contested, as are the variety of drivers shaping our shared future, and the causal mechanisms and interactions that underlie these. No one discipline can marshal the insights required to chart the way forward. This makes it difficult to develop the consensus required for long term policy and investment decisions.

4.3.1 Multiple social roles of model-based decision support and scenario analysis

The quantitative modelling tools outlined in this report have a central role in helping to explore and understand these complex interactions and uncertainties, and to help identify the keys issues that should be taken into account in making energy and water decisions with long term implications.

Modelling can contribute to supporting these social choices and processes in a variety of ways. These include:

- (1) Resolving technical issues within a shared framework of ideas and objectives, such as where there is consensus about the costs and environmental impacts of different generation technologies, and the task to identify the lowest cost sequence of investments to meet a specified demand schedule within agreed environmental standards; and
- (2) Helping to build a shared understanding or working consensus on potential future outlooks and pathways (such as for a nation, or a major river basin), and the key factors likely to shape future resource flows, security, livelihoods, and living standards;
 - (i) One aspect of this is to explore the range of potential drivers that should be considered accounted for. These form the context of energy and water decisions, such as the potential combined effects of population growth and climate change on water security, or judging whether water extraction trends risk undermining ecosystem services that are important to local livelihoods;
 - (ii) A second aspect is to explore the range of impact pathways; assessing the consequences of potential water and energy strategies in the context of wider interacting trends. This can help establish a shared language for discussing the nature and magnitude of potential impacts on different groups.

These different potential roles are shown visually in Figure 3 as contributions within quadrant A (Mode 1 'computation'), or helping to move from 'deadlock' and disagreement in quadrant D (through Modes 2a 'settling' and 2b 'planning' respectively). An open discussion about system processes and social goals can also help deal with stable but maladaptive policy deadlock, particularly where incomplete understanding or poor problem framing is preventing the identification and implementation of options that would provide win-win outcomes by addressing long term risks (Hatfield-Dodds, 2006).

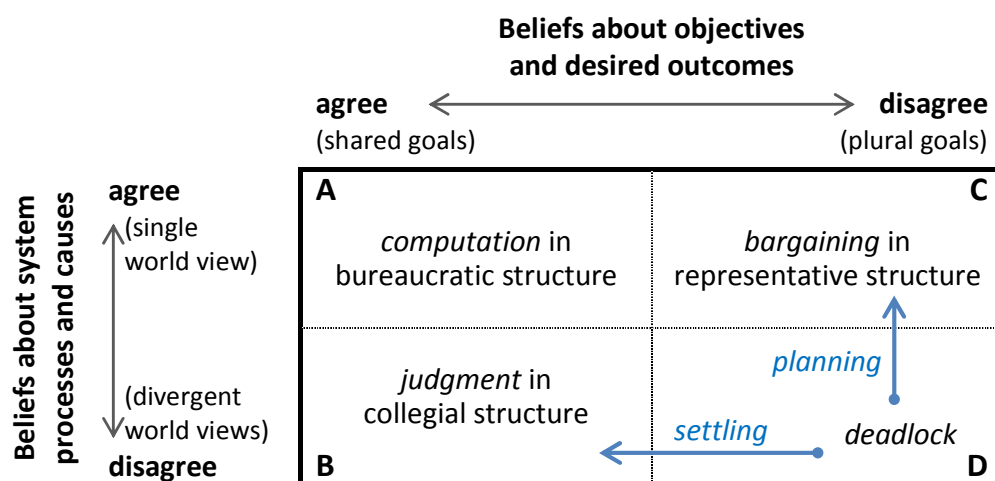


Figure 4: Modes of social learning and social choice under uncertainty

Source: Adapted from Lee (1993) in Ast et al (2008), see Hoppe (2005).

The last three decades have seen the development of a variety of structured ways of assisting the interactions between models, modellers, and different types of stakeholders (see (Barreteau, Bots, & Daniell, 2010; Smajgl, 2010)), and related social processes involved in group decision making. Examples relevant to water and energy management and planning include scenario planning, adaptive leaning and modelling strategies (Pearson, Coggan, Proctor, & Smith, 2010), ‘discussion support’ software (R. A. Nelson, Holzworth, Hammer, & Hayman, 2002), participatory modelling and multi-criteria assessment (Antunes, Santos, & Videira, 2006; Barreteau et al., 2010; Pahl-Wostl, 2002; Smajgl, 2010), and deliberative multi-criteria support (Proctor & Drechsler, 2006).

These efforts reflect a number of motivations: a recognition that local stakeholders are the primary managers of many natural resources and ecosystems (and so rules need to be ‘owned’ by stakeholders in order to be effective, see (Ostrom, 2005), a desire to harness local knowledge of both ecosystem processes and self-governance arrangements (Lebel et al., 2006), and – perhaps most importantly in this context – a view that these social processes are crucial to achieving the best possible outcomes from investment in modelling effort and related scientific knowledge and technical expertise, while not imagining that they can resolve all decision support challenges (Borowski & Hare, 2007; Poteete, Janssen, & Ostrom, 2010). These insights also apply to the value of recognising multiple perspectives and values across different disciplines and professions.

This highlights the importance of ‘negotiating knowledge’ and recognising differences in worldviews (as well as in values) in order to craft durable policy frameworks, and to achieve stakeholder cooperation and support for relevant rules and institutions (Syme & Hatfield-Dodds, 2007). In contrast to ‘simple managerialism’ approaches, real world adaptive governance highlights the risks of ‘single perspective’ decision and governance processes, and argues that contested or negotiated governance can add value by requiring a deeper engagement with uncertainty and a more imaginative approach to seeking solutions that meet the needs of plural constituencies (Brunner & Steelman, 2005; Hatfield-Dodds, Nelson, & Cook, 2007; Hoppe, 1999).

4.3.2 Using models to challenge ideas and build consensus in the Mekong

These issues are particularly important and challenging in trans-boundary modelling and decision support, which expands the set of issues and cross sector trade-offs to be considered, and adds new complexities of spatially mismatching institutional boundaries, missing or inconsistent data, differences in policies and institutions, and the need for bi-lateral and international coordination. The effectiveness of such cross-sectoral and trans-boundary coordination relies on the willingness of stakeholders to think beyond silos.

Thus, process-related elements of design applied research become equally important as questions on analytical methods.

The Challenging and Reconstruct Learning (ChaRL) framework used by CSIRO in the Mekong Basin provides a practical example of a model-linked social learning process (Smajgl et al., forthcoming). The framework connects research methods in four principle steps of a participatory process. First, a list of pending investments is selected. Then decision makers from different sectors, mostly representing water, food and energy, develop a shared vision. This *visioning* or *scenario development* is guided by a formal process that (a) identifies drivers, their magnitude of impact and their uncertainty, and (b) translates envisioned changes into storylines. This creative process deliberately spans sectoral perspectives and silos, and facilitates a more plural understanding of priorities, options, constraints and dependencies (Foran, Ward, Kemp-Benedict, & Smajgl, in Review). The trans-boundary context requires sharing these visions and the discussion of possible cross-border implications, which leads to revised visions. In a third step, research results are presented regarding the potential impacts of pending decisions, including results from water sector modelling and macro-economic analysis. During these workshops, stakeholder statements and evidence are recorded, and belief statements identified. Such belief statements specify causal relationships (i.e. “If we build these dams we will lose all the fish!”). In a fourth and final step, existing beliefs are explicitly compared with scientific evidence (=alternative beliefs) with a view to determining whether or not stakeholders think that their shared vision can be achieved by the pending decisions and investments.

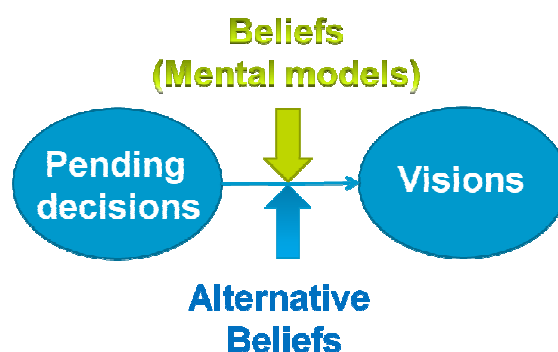


Figure 5: Challenging and Reconstruct Learning (ChaRL) framework

Source: Smajgl & Ward (in review)

Some professions and disciplinary groups, including many quantitative modellers, tend to dismiss the relevance of such ‘soft’ aspects of research, and expect that the pathway to impact will be guided by rational understanding of decision makers (Hoppe, 1999, 2005). There is little evidence, however, that scientific evidence alone is sufficient to achieve worthwhile policy change (Haas & Stevens, 2011), as illustrated by the gaps between climate science and international mitigation efforts. Clearly, addressing the mode of conveying research insights explicitly is less relevant if the analysis is focused on one sector only. However, in a cross-sectoral approach such as the energy-water nexus, competing goals can lead to sub-optimal investments.

4.4 RECOMMENDED APPROACH AND POTENTIAL WORK PROGRAM

This report has identified a range of challenges in providing the insights and information required for the development of sound policies and investments in the context of the energy-water nexus, including the need to consider a range of sector interactions, the case for explicit attention to food, and technical and data issues in providing robust cross-sectoral decision support.

4.4.1 Recommended approach to using models to explore the nexus

We begin by reviewing the context of decision support, and the nature of the issues arising from the energy-water nexus, and the implications of these for how models can support the best possible national policy and investment outcomes in this area.

We recommend investments in improved decision support for energy sector policy and investment should recognise three central issues:

- First, model-based decision support is part of the social process policy development and implementation.
 - Modelling and other professional and scientific inputs to decisions thus should be firmly grounded in the needs of decision makers, and the people they serve. This has implications for deciding the scope modelling outputs; desired confidence around methods and data; and the capacity to undertake sensitivity and risk analysis. Decisions on these issues need to centre on user needs, informed by modelling expertises about options and feasibility. The investment of financial resources and scarce (trusted) in-house expertise should be commensurate with the value of the insights and benefits gained, including the identification and management of potential risks.
 - Careful consideration should also be given to the best way of designing and implementing modelling and decision support processes, paying attention to the technical content of the decisions, the preferences of the decision makers, and the explicit and implicit requirements of the decision context and long run implementation.
- Second, the multiple dimensions of the energy-water nexus raise different types of issues for modelling and decision making, which at least in the short term will be best addressed through different types of models and modelling processes.
 - The imperative to understand and respond to the energy-water nexus is that there are deep uncertainties about the potential impacts of interacting social, economic and environmental trends. Specific issues and risks include (i) water security (primarily in terms of water volume), with linkages to food security, (ii) energy supply and affordability in the context of climate mitigation policies, and (iii) feedbacks from within the nexus from water constraints to the energy system, and from energy choices to water and food.
 - This implies a need to identify the set of potential national futures that should be considered in policy, planning and investment decisions. This implies a scenario process, drawing on a wide range of skills and expertise, and supported by multi-sector or economy wide modelling. Other inputs could include projections of demographic changes, climate, environment and ecosystem services, renewable and non-renewable resources, and internal and external economic risks and opportunities.
 - Such a scenario process can thus provide the foundation required for other deeper, more comprehensive modelling and analysis of energy and water issues, including the implications of potential water constraints for the energy system. For example, multi-disciplinary analysis could be used to establish a set of potential planning or investment benchmarks that reflect cross-sector opportunity costs and different levels of external impacts. These benchmarks could then be used to inform analysis using both energy sector and CGE models – such as by analysing water use ‘as if’ the operator had to pay a minimum cost per unit of water used (based on the shadow price, or more general analysis of food security requirements), or undertaking and reporting policy and investment analysis against a standard range of climate and development scenarios. This deeper more sector focused analysis would require the development of energy models that take better account of integrating multiple water constraints, discussed in more detail in Section 4.4.4 below.
 - Together, this would provide two complementary ways of exploring and assessing evolving water constraints. Physical and economic water constraints can be explored within models,

through endogenous representation of prices and market processes. Wider cross-sector opportunity costs and water constraints that might arise through wider economic and social mechanisms (such as political or policy responses to concerns about food security, or environmental issues) can be represented exogenously through modelling a range of different scenarios. In practice, these modes are implemented together to represent relevant uncertainties and capture interactions.

- Third, effective management of the national risks presented by the energy-water nexus is going to involve staged precautionary action, and significant investments over time. This will require the development of a cohort of trusted technical experts and policy makers who appreciate the complexities of interconnected systems of energy, water, food and livelihoods, and their multiple connections through to economic development, human security, and social resilience. This implies a need for an evolutionary and somewhat iterative approach to the development of models and decision support capacity, to ensure appropriate trust and responsiveness.

We thus consider it important to give explicit consideration to the best ways of engaging different decision makers and other stakeholders, as the best approach will vary with context, circumstances, and the specific challenges that motivate the modelling. In general, the use of multiple approaches has advantages in providing greater transparency, enabling the use of models and processes that best serve different needs, and building a shared understanding of the key issues to be addressed and accounted for in the analysis.

4.4.2 Potential approaches to developing models of the energy-water nexus

The development of improved modelling capacity could occur in three main directions. First, effort could be focused on improving top-down methods such the development of as CGE models that properly account for water supply (such as through aligning sub-regional boundaries with catchments, providing appropriate temporal resolution, and accounting for the economic and energy costs of reallocation of water between industries and physical regions). . Second, effort could be invested in improving bottom-up methods to include cross-sectoral dynamics and associated impact on macro-economic processes and performance. Third, we consider it is possible to develop a meaningful and effective hybrid of bottom-up and top-down approaches.

As summarised earlier in this report, a small number of macro-economic models have been successful in accounting for and integrating water as well as energy constraints, in particular in CGE modelling and Input-output modelling (Briand, 2004; Smajgl, 2006). Some of this modelling disaggregated specific sectors to allow for an effective distinction between water and energy users (Horridge et al., 2005; G. Wittwer, 2003; Glyn Wittwer & Griffith, 2011). The spatial and temporal disaggregation, however, is a substantial obstacle as data is not provided for weekly or daily time steps and also not at the catchment scale. This may be a significant problem in contexts where seasonal variability or water security may be the limiting constraint. Recent attempts to test the applicability of CGE models at a catchment scale have shown that data preparation requires substantial investment and may not be feasible where data is scarce (Smajgl, Greiner, & Mayocchi, 2006; Smajgl & Liagre, 2010).

Bottom-up models provide an adequate framework for the level of spatial and temporal disaggregation the energy water nexus requires. Developing a bottom-up model for a national economy is challenging. While there are many attempts to utilise simulation models in the economic domain, the analysis typically remains partial, and does not capture the economy-wide perspective of CGE models. Theoretically, such an extension seems possible and has been conceptualised (Gintis, 2007). Another advantage of a bottom-up approach is the ability to effectively model the demand side and, therefore reflect water and energy consumption, and the underlying diffusion and dynamics of consumer behaviour. The data requirements for developing a bottom-up approach for a national economy with particular focus on the energy-water-food nexus are substantial, but may not be as demanding as disaggregating national data in some cases. Nevertheless, some simulation exercises have demonstrated that existing datasets on consumer behaviour could be combined with economic data to overcome this challenge. How effective such strategies are in developing countries remains to be tested, but we consider it is better to seek to quantify the role of water than to assume that water is not scarce (and thus does not constrain or shape economic activity). Here we

agree with Wittwer's (2012) view that this process is best seen as a journey, that is likely to lead to rich insights and results..

The combination of bottom-up and top-down methods seems the most promising as an immediately available strategy. It implies the development of separate models, one from the bottom up and one from the top down in order to combine the strengths of each perspective. The MARKAL model is a successful example for such an approach. The success of the MARKAL model family (i.e. MARKAL-MACRO, TIMES, MARKAL/SAGE) is evidence for the promise and potential of an effective hybrid model (Loulou et al., 2004; Loulou, Remne, Kanudia, Lehtila, & Goldstein, 2005). The MARKAL models would require modification to provide a more explicit representation of water, however, before they would be suitable for analysing the energy water nexus issues addressed in this paper. Such integration is methodologically possible and feasible from a data perspective, particularly through drawing on GTAP-W model and data (see Box 3). However, the top down MARKAL model represents the economy only as one single sector, and so does not provide the cross-sectoral insights that are central to understanding water allocation and opportunity costs. The bottom-up model implements an optimisation approach, which comes with its own methodological problems, as explained above. This limitation also prohibits the analysis of side-effects of investments in the energy- water nexus, which is in particular relevant for the food security domain. Moving from a partial equilibrium approach (MARKAL) to a CGE approach would allow for the analysis of sector specific outcomes if water was explicitly integrated, as exercised by Newth et al. (Newth et al., 2011) and (Sealey et al., forthcoming). This strategy is seemingly the most promising for the immediate needs. However, such a water-extended hybrid approach requires a meaningful linkage between bottom-up and top-down models, which is not without problems: Theoretical underpinnings are often inconsistent, the link between both perspectives remains a challenge, and data requirements may be prohibitively high in some countries. Nevertheless, this strategy is likely to be the best readily available technique.

It is important to emphasise that for each of these strategies parallel arrangements are needed to quantify contextual water constraints. First, climate projections need to be downscaled for a particular country or region. In some regions additional sea-level rise projections are required. Second, hydrological models need to specify hydrographs for each relevant location of existing and potential power generation unit based on the new precipitation and temperature forecasts. These hydrographs depict the water availability throughout the year, mostly in daily time steps. Depending on which of the three strategies above is adopted the hydrological data needs to be processed, i.e. aggregated, to suit the modelling requirements. In addition to this biophysical information, information on likely population increase and water consumption by sector is needed.

4.4.3 Recommended approach to the development of integrated modelling capacity

In light of the above discussion, we recommend two primary approaches to developing more integrated modelling capacity to deal with the energy-water nexus.

First, nations with well developed energy and water sector models and established CGE models could pursue a hybrid modelling or 'model coordination' approach that extends existing models and runs them in a tightly or loosely coupled way. This would involve four main activities:

- (1) Extending bottom up energy sector models to account for relevant water constraints (including price, availability and security) at appropriate spatial and temporal resolution;
- (2) Extending CGE models to account for water as both a factor of production and a consumption good, including potential water supply from rainfall (via land surface flows, river routing and storages), water recovery or re-use, and desalinisation; and
- (3) Ensuring hydrological and water system models are calibrated to provide data at spatial and temporal resolution compatible with relevant energy sector models, including projections of water supply volumes and prices to energy generation and other sectors (as well as projections of water-sector energy demand, if possible);

- (4) Developing protocols for coordinating or integrating model runs to achieve coherent results across these different modelling platforms, including aggregation of bottom up energy and water model output to CGE sectors and regions.

These steps are relatively straightforward conceptually, but require appropriate skills and significant interaction across disciplines and domains, supported by good will and shared commitment.

This hybrid approach is unlikely to satisfy the long needs of nations facing more complex interactions or more severe water constraints, however, including nations managing strong growth in energy demand or significant declines in per capita water availability.

To address the needs of these nations, the second approach would invest in the development of a new more flexible modelling approach that combines the strengths of the bottom up and top down approaches, while recognising the distinctive dynamics of water and energy systems and interactions. This approach would seek to overcome a number of material limitations to the suitability of using a CGE framework to explore these issues, particularly inherently poor spatial resolution (linked to jurisdictions and political boundaries, limited representation of physical system characteristics, smooth linear dynamics (arising from a focus on price-based adjustments across relatively unconstrained market sectors, rather than potential input constraints), and a focus on flow variables rather than stock vintages and legacy effects. Bottom up models, in contrast, tend to take a partial approach which assumes that the water sector can be viewed in isolation from the rest of an economy. Few pay attention to demand issues and likely changes to behavioural responses. They tend, also, to be better at describing interactions between water scarcity and water quality issues.

Implementing this approach would involve development of mutually supporting teams, and the design of a bottom-up and top-down synthesis that progressively strengthens the bottom-up method. Such strengthening would be focused on the ability to cover macro-economic aspects in the assessment tool. This would need to include cross-sectoral dynamics, similar to a CGE model. However, we believe that there is an opportunity to represent market dynamics without some of the assumptions and practices of general equilibrium theory (Ackermann, 2002), particularly in relation to smooth adjustment pathways and associated difficulties in representing threshold effects. Such an innovative bottom-up design could draw on evolutionary and behavioural economics.

Considering the long-term relevance of the energy-water nexus we suggest combining both strategies, providing an operational tool kit in the short term (through harnessing existing models and capacity) and building a more robust and flexible method over the longer term, based on an increasing rich bottom-up platform. The short term approach would be based on a combination of agent based and CGE modelling. The agent-based model would allow for linking

- climate change scenarios,
- hydrological dynamics,
- water availability at the spatially referenced power stations,
- water and electricity pricing, and
- water and electricity demands.

Additionally, the agent-based simulation would allow for including land use and, thereby, agricultural production and food security. Implementing the water food energy plexus in *one* model (or dynamically coupled suite of models) will allow for quantifying trade-offs for supply- and demand-focused policy options. To allow for demand-sided scenarios the model development would need to include power and water demands across all sectors. Such an approach would also provide the platform to integrate and assess impacts of interventions on environmental and ecological variables. Such a development covers most aspects that top-down models cannot address. The modelling of energy sectors would require some innovative implementation with energy companies minimising costs. In principle, agent-based modelling platforms allow for such optimisation for individual agents.

The CGE model would allow for the assessment of cross-sectoral and macro-economic effects, covering the remaining dimensions relevant for effective decision support in the energy water nexus. The link between bottom-up and top-down modelling can be created by using CGE results for informing the agent-based model about

- prices, and
- market transactions on other sectors than energy, water and food.

The agent-based model would inform the CGE model about

- elasticities and how elasticities change over time,
- power and water demand trajectories, and
- shifting supply constraints due to lack of water availability.

Such linking could be realised by model users transferring iteratively results from one model to the other. Alternatively, but much more challenging, is the design of a meta model that runs both models automatically in iterations.

Over the longer term, it may be possible to strengthen and expand the bottom up processes to the point where CGE modelling is rarely required for exploring water issues or the energy-water nexus.

In general, investment in the first hybrid modelling approach would be able to deliver useable results earlier, and is likely to have significant benefits for later implementation of the second 'new modelling framework' approach.

The limitations of CGE modelling (and the first approach are likely to become increasing problematic for policy analysis and decision support as nexus interactions and pressures increase. For this reason, this second approach has a longer term focus than the first, allowing for a more experimental approach for a period. It is likely, however, that some countries would find it faster and more cost effective to leapfrog to the second strategy if they do not have a full set of well developed existing models, or future water constraints are likely to be severe and require a more exploratory approach to assessing future options and strategies.

5 Conclusion

The energy water nexus is gaining the attention of national and international leaders and policy advisors. It is clear that the next few decades will see an intensification of multiple challenges at the nexus of energy and water. Despite growing – and well based – concerns about energy and water trends, decision makers often remain ill-informed about these trends and their implications, and countries do not have access to the models and data required for robust analysis and decisions.

The key finding of this report is that 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. No existing framework appears able to analyse the issue raised by the nexus, or to provide the decision support and risk management information required. This is of particular concern for countries with strong energy demand growth, or significant declines in per capita water supplies.

Addressing these shortcomings is not simply a matter of integrating physical water use into energy models.

The report recommends two primary approaches to developing more the integrated modelling capacity required to address this shortcoming. The first is a hybrid, or ‘model coordination’, approach involving four main activities: (1) extending bottom up energy sector models to account for relevant water constraints (including price, availability and security) at appropriate spatial and temporal resolution; (2) extending economy-wide computable general equilibrium (CGE) models to account for water as both a factor of production and a consumption good, including relevant water supply options; (3) ensuring hydrological and water system models are calibrated to provide data and projections at spatial and temporal resolution compatible with relevant energy sector models; and (4) developing protocols for coordinating or integrating model runs to achieve coherent results across these different modelling platforms.

These steps are relatively straightforward conceptually, but require appropriate skills and significant interaction across disciplines and domains, supported by good will and shared commitment. Importantly, there are examples of bottom-up and economy wide CGE models that already incorporate water along the lines recommended in (1) and (2) above, and that can be used to guide the development of integrated models for other countries and regions. There are also established examples and frameworks for delivering what is required for activities (3) and (4), although there will challenges to be overcome.

The second model development approach would invest in delivery of a new more flexible modelling approach that combines the strengths of the bottom up and top down approaches, while recognising the distinctive dynamics of water and energy systems and interactions. This approach would overcome a number of limitations to using CGE framework to explore the nexus, which are likely to become increasingly relevant to policy making as interactions and pressures increase, but will involve a more experimental approach for a period.

The report also finds that providing effective decision support depends on the relationships between analysts and decision makers, and on how models are used, as well as on technical model capabilities.

In implementing the recommended strategy, many countries would be likely to begin with some form of scenario process to identify the range of potential national futures that should be considered in policy, planning and investment decisions. This analysis would draw on a multi-sector modelling and wide range of other expertise, and would provide an initial sketch of the context of water and energy policy and investments, including in relation to food security, livelihoods, and ecosystem services. This mode of analysis needs to be complemented by deeper, more comprehensive modelling and analysis of energy and water issues, and the implications of potential water and energy constraints and feedbacks. Together, these iterative processes would enable exploration and assessment of physical and economic constraints (represented within models through prices, factor constraints, and market processes) and of more general cross-sector impacts, opportunity costs and externalities arising from water use and energy options (explored through analysis of different user-defined scenarios).

Appendix

Table A1: Model Overview

	Model name	Simulation	Optimisation	Economic Equilibrium	Top-down	Bottom-up	Hybrid
Classic bottom-up simulation	AEOLIUS (Rosen, Tietze-)	•				•	
	BCHP Screening Tool	•				•	
	EMCAS (North et al.,)	•				•	
	EMINENT (Segurado et	•				•	
	GTMax (Veselka, Poch,	•				•	
	H2RES (Fowler, Krajačić,	•				•	
	HOMER (Homer Energy	•				•	
	Invert (Vienna University	•				•	
	LEAP (Heaps, 2008)	•				•	
	Mesap PlaNet (MESAP)	•				•	
	ORCED (Hadley, 2008)	•				•	
	PowerPlan (De Vries,	•				•	
	RETScreen	•				•	
	SimREN	•				•	
	STREAM	•				•	
TRNSYS16	•				•		
Hybrid simulation	AIM (Morita, Kainuma,	•		○			•
	GCAM (Wise et al.,	•					•
	GIAM (Harman et al	•		•	○		•
	IMAGE (Bouwman et al						
	MESSAGE (Messner and	•		•			•
	MiniCAM (Edmonds,	•		•			•
	WEM	•		○			•
Classic optimisation	BALMOREL		•	•		•	
	COMPOSE		•			•	
	E4cast		•	•		•	
	EMPS		•			•	
	EnergyPLAN		•			•	
	energyPRO	○	•			•	
	HYDROGEMS		•			•	
	IKARUS		•			•	
	MESSAGE		•			•	
	PERSEUS		•			•	
	ProdRisk		•			•	
	RAMSES		•			•	
	SIVAEL		•			•	
	UniSyD3.0			•		•	
	WASP		•			•	
WILMAR Planning Tool		•			•		
Top-down Optimization	ASF		•		•		
	MARIA		•		•		
Hybrid optimization	MARKAL/TIMES		•	•			•
Macro-economics and Economy wide Models	ENPEP-BALANCE		○	•	•		
	GTAP (All)	•		•			•
	GTEM (Pant 2007)	•		•	○		•
	NEMS			•	•		
	PRIMES			•	•		
SGM			•	•			

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