The water-energy nexus: Review of current studies and recommendations for future development of integrated assessments

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***Abstract*—** The aim of this paper is to review existing studies and models which address the interdependencies of water and energy resources. Freshwater is becoming a limited resource in some parts of the world as a result of an increasing demands (due to population growth and urbanization) and decreasing water resources (due to climate change and pollution). There is increasing competition for this limited resource between the agriculture, residential, industrial and energy sectors. Inefficient water use in shortage situations has led to power cuts, crop failures and unaffordable residential water. Water and energy are increasingly becoming limiting factors in each other's day to day operations and thus new, as well as changes to existing, tools and techniques are being proposed to address these issues. The inspiration of these efforts as well as that of this paper is the creation of better integrated water and energy assessment methodologies and models. The paper reviews the existing literature to identify the benefits of integrated assessments as well as the drawbacks of a lack of such collaboration. Existing models and studies are analyzed for common themes and recommendations which are then compiled as a guide line for future projects.

***Index Terms*— Environment, energy, linear programming, nexus, optimization, sustainability, water**

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1. Introduction

This section lays out the context of the paper by giving a background to the problem being addressed and stating the objectives of the paper.

1.1 Background

Rising world population along with economic development is increasing the global energy, water and food demand. The amount of global water is roughly constant (about 1.4 billion km^3) [1]. Of the total about 97.5% is saline water in oceans and only 2.5% is freshwater suitable for human agriculture and domestic needs. Of the 2.5% about 70% is trapped in glaciers and ice caps. The freshwater available per capita is decreasing due to the increase in population, economic development and lifestyle changes. Already, around 1.2 billion or one fifth of the global population live in regions of physical water scarcity which is defined as less than 1000 cubic meters of annual water supply per person [2]. One of the highest users of water, the United States, withdraws about 1600 cubic meters per person per year of water for industry, agriculture and residential uses [3]. In addition to physical water scarcity, another problem is human access to existing water resources as a result of the regional distribution, local infrastructure and water policies [4]. Accessible freshwater resources are further decreasing due to pollution, groundwater depletion and climate change (resulting in receding glaciers, reduced stream and river flows, and shrinking lakes). In locations where water stress is increasing, competition between the agriculture, urban, industrial and energy sectors for water is also increasing. The International Energy Agency in the World Energy Outlook 2012 [5] estimates the world energy production in 2010 to be responsible for 15% of total withdrawals, predicted to increase by 20% by 2035. Water consumption is expected to increase by 85% as a result of higher efficiency plants with advanced cooling as well as biofuel expansion. If current trends continue Hoff (2011) [6] estimates an increase of 70% in world agriculture production by 2050 and a 50% increase in primary energy production by 2035.

Water in particular; being a limited resource is the key factor in nexus systems. Water use has increased by 800% compared to a population increase of 400% from the 1900s [7]. This increase in demands coupled with climate change is altering the hydrological cycle with serious consequences in the availability of both renewable and non-renewable (on a human time-scale) freshwater resources. Some regions are reaching 'peak water' where renewable resources are being withdrawn at the same rate of renewal, while non-renewable resources are being tapped faster than the recharge [1]. Some examples include large rivers like the Colorado and the Indus drying up [8], lakes like the Aral lake and lake Chad shrinking [9] and drastic drops in groundwater levels in the US [10], China and South Asia [7]. Woods [11] in their documentary 'A World Without Water' point out the increasing value of water and how water privatization can undermine water access to local communities in Bolivia and Dar-es-Salaam. The Pacific institute gives a long list of the increasing water conflicts from ancient times to the present [12]. Water prices are strongly related to water access resulting in higher prices in regions poor regions lacking infrastructure [4]. The regional impacts of future water shortages on energy, health and trade will be imperative in determining development and progress.

The predicted changes in demands and resources will vary greatly from region to region. The total population and energy demands in developed countries are not expected to increase much. About 93% of energy consumption growth by 2030 is estimated to be in developing nations [13]. Population is also expected to grow by 58% in developing nations compared to 2% in developed nations by 2050 [14]. However, this does not preclude developed nations from future resource scarcity problems. Internal migration will result in regional demand changes even in developed nations. For example the European Commission estimates a greater than 15% increase in population in south and eastern Spain by 2030 [15]. These parts of Spain are already the most water stressed and the migration will deteriorate the situation further. Climate change in some developed countries will also exacerbate scarcity situations. Glassman (2011) [16] stresses the point that despite becoming a critical business, security and environmental issue the water-energy nexus is not receiving its due importance. 2.8 billion people currently live in water-stressed areas and this will increase to 3.9 billion by 2030 if current trends continue. Issues related to the dependence of energy on water resources are becoming more common in every day news. Some example headlines from 2014 are: “Water Scarcity forces shutdown of 4 RTPS units” (India) [17], “Impending water shortage threatens energy development” (Indonesia) [18], “Water shortages slow energy production worldwide” (Global) [19], “California’s drought could mean power shortages this summer” (US) [20].

Thus, the demand for energy, water and food is expected to increase in some regions of the world as a result of life style changes, population increase and migration to urban centers. At the same time our finite sources of water are expected to decrease in some regions as a result of climate change and pollution. The regions where these two situations overlap will need to plan and manage their resources in order to meet the demand while managing the corresponding tradeoffs in the economic, agricultural, industrial, environmental and residential sectors. These regions include large parts of middle and western United States, south eastern Spain, Bolivia, Australia, Central Asia, India, China and many countries in Africa. The situation is further complicated by the interdependencies of the sectors, and calls for an integrated management approach.

1.2 Problem Statements

As identified in the background the general problems within the scope of the water-energy nexus to be addressed are as follows:

i. Energy needs are increasing and need to be met.
ii. Water needs are increasing and need to be met.
iii. Emissions from both water and energy processing need to be controlled and reduced.
iv. Climate change effects need to be considered since they affect the availability of resources as well as the demands.
v. Water scarcity can limit energy production
vi. Energy production methods and mixes can substantially effect water resources

The specific problem is that energy and water have been traditionally managed and planned independently. With the growing dependencies between the two sectors the general problems listed above cannot be addressed in isolation. The specific problem is thus a lack of *integrated* water and energy resource planning and management.

1.3 Objectives

The objectives of this paper are:

i. To identify the benefits of integrated analyses & decision making in the context of the water-energy nexus
ii. Review the existing literature on water-energy nexus studies
iii. Review existing water-energy nexus models
iv. Identify common themes and elements desired for integrated water-energy assessments and models
v. Give a summary of recommendations for future models and methodologies

2. Methodology & Layout

This paper reviews various sources which address issues related to the water energy nexus including scientific journals, periodicals, books, documentaries, company reports, conference proceedings, software guides and personal correspondence. The data and information was categorized into various themes from the more general such as hydrology, water, energy, economics, climate change, optimization to more specific themes such as water used for energy, hydro-electric optimization, energy modeling, energy used by water, water-energy interdependencies and finally water-energy nexus models. The more general data was used to gain an understanding of the overall problem and is described in Section 1: Introduction. The more detailed themes were used to address the specific objectives of this paper and are discussed in Section 3: Literature Review. These are; identifying the benefits and need for integrated management; analyzing existing water and energy nexus studies; and analyzing existing and ongoing nexus integrated models and developments. The common themes and recommendations from the various studies are then compared and analyzed in Section 4: Discussion and finally the overall lessons learnt from the paper are compiled into final recommendations in Section 5: Conclusions and Recommendations.

3. Literature Review

3.1 Benefits and need for integrated management

The correlation or dependence of water on energy and energy on water is not an abstract one. Current energy generation technologies require water for cooling, extraction and generation, while energy is needed for water extraction, purification and transport. If one of these resources run's short the other resource suffers.

'Traditionally, from the lowest level of governance to that of federal regulation and oversight, water and energy resources have been managed separately, with very little overlap between the two domains [21].'This attitude of isolated management is generally true for most countries as pointed out by Marsh (2008) [22] for Australia and for various developing nations by Bazilian (2011) [23]. Bazilian [23] further points out that isolated single sector policies only result in temporary short term benefits. One of the key challenges to tackling the nexus issue is co-operation between different sector ministries and regulatory bodies, in order to come together for an integrated planning approach. FIG1 shows some of the interdependencies amongst the water, energy and food nexus. The following cases are some examples of the implications of non-integrated policies.

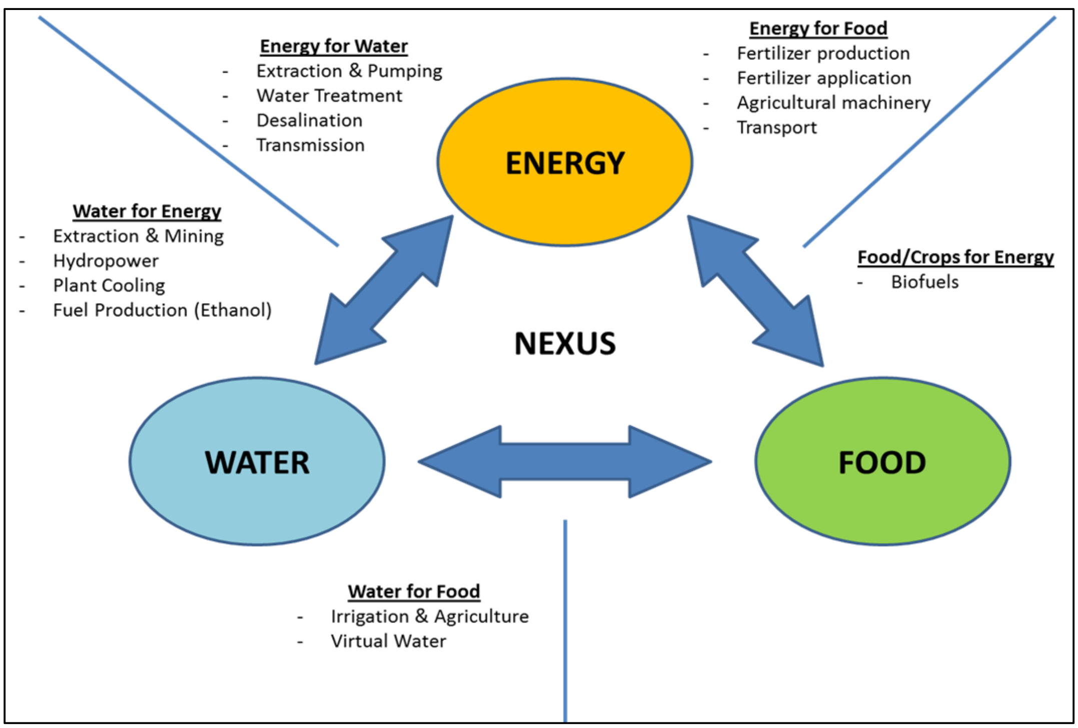

Fig 1. Interdependencies in the water- energy-food nexus

3.1.1 Nexus Tradeoffs

Wahlquist [24] as cited in Marsh [22] gives an example of the tradeoffs between the hydropower, environmental and agricultural sectors. The operations of Snowy Hydro Power Plant along the New South Wales and Victoria border severely limited water availability in the lower reaches of the river leading to a government investigation and recommendations to increase environmental releases by 15% in 1998. Several downstream irrigators claimed the hydro plant had placed their access to irrigation water in jeopardy, in order to conserve water until peak summer demand, when electricity prices are highest in the Australian National Electricity Market (NEM). Another example of energy and environmental tradeoffs is from

2001 in Oregon when the Bonneville Power administration had to declare a state of emergency and divert water reserved for preserving salmon populations in the Columbia River for energy production use. The administration said it was necessary to avoid rolling blackouts in the state. Downstream local tribes with treaty rights to the salmon protested the decision which led to the highest number of salmon deaths ever recorded [25] [26]. Malik [27] and Mukherji [28] discuss some of the tradeoffs between water, energy and irrigation. Lack of resources and regulation coupled with over-subsidized electricity prices in India encourage overexploitation of the non-renewable groundwater resources. This has led to lowering of the groundwater table and a corresponding increase in salinity and arsenic levels contaminating the local community water. Another 'nexus' tradeoff is seen in the growing of biofuels. The immediate benefits come as reduced emissions and an alternative fuel however there can be serious consequences, such as increase food crop prices, when scarce water and land resources are diverted from other sectors such as agriculture in regions like the Central and Western United States [29].

Stokes [30] analyzes the different options for California to meet its water demands in the future. They conclude that if energy intensive technologies like desalinization are used, the water sector could consume 52% in 2030 (was 19% in 2009) of the state's entire energy budget. Imported water would consume 22%. Bazilian [23] discusses the energy-environment tradeoffs in countries dependent on biofuels like Uganda, where deforestation is becoming a serious environmental issue. Integrated planning is critical when it comes to international shared politics. Water treaties between nations (like the Indus Water Treaty between Pakistan and India) are critical strategic and security risks that need to be addressed in the countries future resource management and investment decisions. Another international example is the tension between water release schedules in Central Asia, where Southern Kazakhstan and Uzbekistan need to reserve water for summer irrigation, while northern Kyrgystan needs the water in the winter for electricity generation [23].

The examples cited above are only a few of the increasing number of tradeoffs occurring as a result of the interdependencies between different sectors. It is clear that the shared resources between energy, agriculture, residential, environmental and industrial users need to be managed and regulated holistically. Current practices are clearly unsustainable and as G. Klein [31] points out, the single largest supply of new water resources will be efficiency. Because of the interdependencies of the different sectors, this efficiency can only be maximized by analyzing the interdependent sectors as one integrated system.

3.1.2 Integrated Planning Recommendations

Many authors stress the importance of the need for integrated analysis as conclusions to their papers. The Utah Division of Water Resources, in their 2012 paper [21] on the nexus in Utah, recommend that to face the challenges of increasing population in the water scarce region there is a need for integration of resource planning and management, increased funding for basic water/energy science data and models as well as incorporating water efficiency into energy planning and energy efficiency into water planning. Scott 2010 [32] comments on the complexities of integrating the two sectors given the number of stakeholders involved in and influencing infrastructure developments. The need for collaborative policymaking between public decision makers, private initiative and others is stressed to counter special interest groups´ influence over development projects, given that part of the industry is driven by the very concept of scarcity. The United States Department of Energy (USDOE) XXX, point out that for the US, most of the freshwater resources have been tapped through infrastructure like dams with freshwater withdrawals recently leveling off or ´peaking´. Given the projection for increases in population by up to 70 million by 2030 and a corresponding growth of 50% in electricity demand there is concern for non-renewable sources like groundwater being exploited beyond sustainable limits. Changing traditional practices can be challenging however, as Pate 2007 [29] observes, the business as usual scenario projections for the United States will lead to more than double the water consumption by power plants in 2030 (equaling the entire countries domestic consumption from 1995). Following the current trends of managing water and energy separately, it may not be possible to meet the future energy and water demands. Along the same lines of arguments, Maas 2010 [33] recommends conservation of water and energy instead of new infrastructure projects as well as increasing efficiency through integrated monitoring, reporting and management. Sovacool 2009 [34] points out that improved energy efficiency may not be enough to compete with growing energy needs. Research projects need to be advanced to address integrated nexus issues such as advanced thermoelectric cooling cycles, power plant permitting procedures and planned integration of water-efficient energy mixes.

3.2 Review of Quantitative Water-Energy Nexus studies

There have been several quantitative analyses on the use of water for energy services as well as energy for water services. These serve as useful inputs to models and to get a sense of how the two sectors are inter-connected. TABLE XX summarizes the various quantitative studies on the water and energy nexus. FIG XX summarizes some of the water use by different energy technologies. The data vary considerably from study to study because water and energy needs depend on a number of factors including local weather and climate, specific technology used, age of plants, water temperatures and fuel efficiency. Key issues and recommendations are discussed below.

TABLE XX

NEXUS SECTOR	MODEL/STUDY	Case Study Location
Both Water needs for Energy & Energy needs for Water	Utah(2012) [21]	Utah
	Scott (2010) [32]	SW US
	Stillwell (2010) [35]	Texas
	Siddiqi (2011) [36]	MENA
	Gleick(1994) [37]	General
	D. Perrone (2011) [38]	Arizona

NEXUS SECTOR	MODEL/STUDY	Case Study Location
Energy demand Only	Jacobson(2010) [39]	World
Energy needs for Water Technologies	Maas(2010) [33]	Ontario
	Hoover(2009) [40]	Arizona
	Kenway (2013) [41]	General (US, Australia)
	Stokes (2009) [30]	California
	Klein (2005) [31]	California
Water needs for Energy Technologies	Glassman (2011) [16]	US
	World Energy Council [42]	Global
	Grubert (2012) [43]	Texas
	Sovacool (2009) [34] [44]	US
	Pate (2007) [29]	New Mexico
	Averyt (2013) [45]	US
	Herath 2011 [46]	New Zealand
	Hardy Garrido (2010) [47]	Spain
	Hardy Garrido Juana (2012) [48]	Spain
	Hardy Garrido (2012) [49]	Spain
	Carrillo (2009) [50]	Spain
	Elena (2010) [51]	Spain
	Martin Delgado (2012) [52]	General/US
	USDOE (2006) [53]	US
	Mielke (2010) [54]	US
	Macknick (2011) [55]	US
	Poole (2009) [56]	US
	Martin Delgado(2014) [57]	General
	EPRI (2002) [58]	California

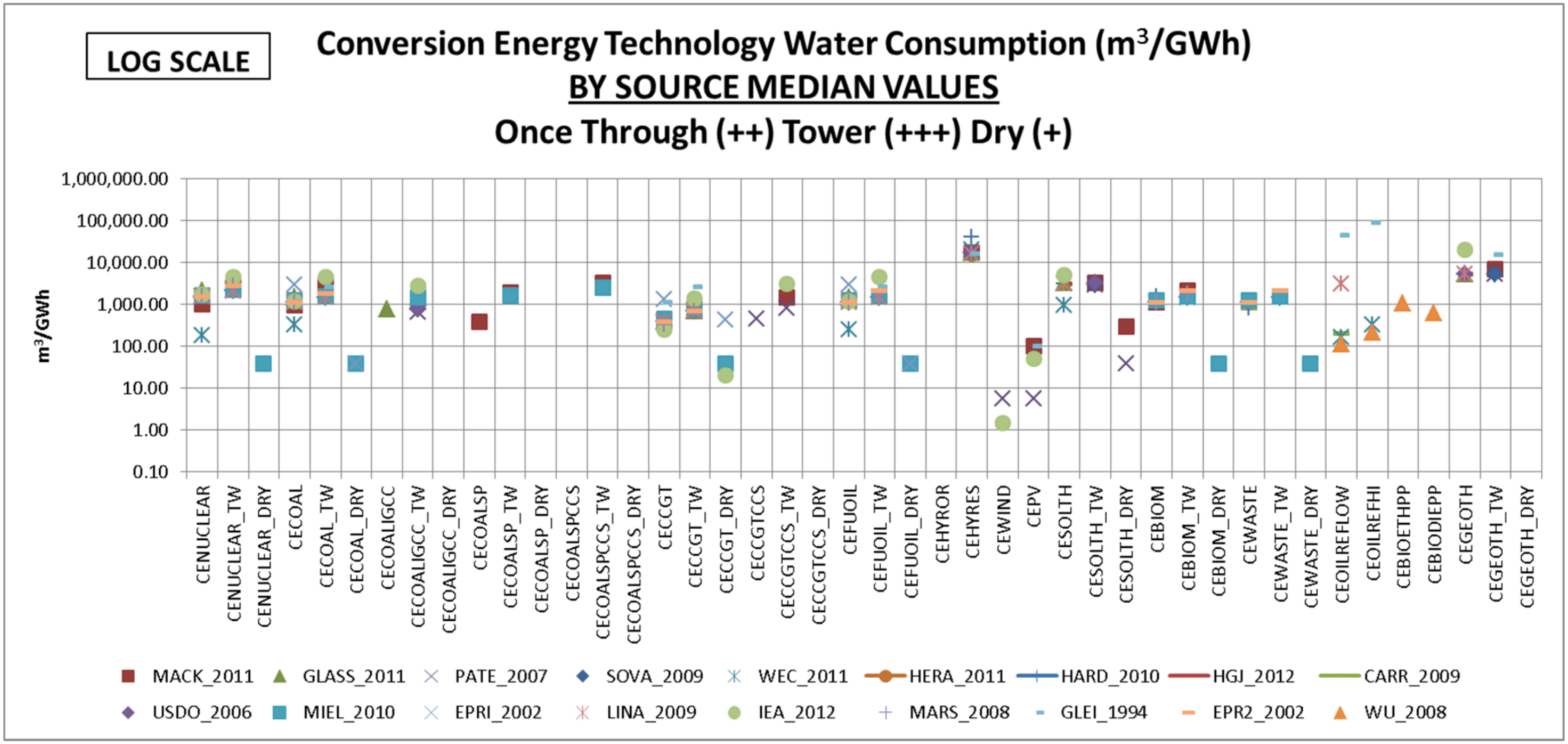
LOG SCALE
Conversion Energy Technology Water Consumption (m3/GWh)
BY SOURCE MEDIAN VALUES
Once Through (++) Tower (+++) Dry (+)
m3/GWh
1,000,000.00
100,000.00
10,000.00
1,000.00
100.00
10.00
1.00
0.10
CENUCLEAR
CENUCLEAR_TW
CENUCLEAR_DRY
CECOAL
CECOAL_TW
CECOAL_DRY
CECOALIGCC
CECOALIGCC_TW
CECOALIGCC_DRY
CECOALSP
CECOALSP_TW
CECOALSP_DRY
CECOALSPCCS
CECOALSPCCS_TW
CECOALSPCCS_DRY
CECCGT
CECCGT_TW
CECCGT_DRY
CECCGTCCS
CECCGTCCS_TW
CECCGTCCS_DRY
CEFUOIL
CEFUOIL_TW
CEFUOIL_DRY
CEHYROR
CEHYRES
CEWIND
CEPV
CESOLTH
CESOLTH_TW
CESOLTH_DRY
CEBIOM
CEBIOM_TW
CEBIOM_DRY
CEWASTE
CEWASTE_TW
CEWASTE_DRY
CEOILREFLOW
CEOILREFHI
CEBIOETHPP
CEBIODIEPP
CEGEOTH
CEGEOTH_TW
CEGEOTH_DRY
MACK_2011
GLASS_2011
PATE_2007
SOVA_2009
WEC_2011
HERA_2011
HARD_2010
HGJ_2012
CARR_2009
USDO_2006
MIEL_2010
EPRI_2002
LINA_2009
IEA_2012
MARS_2008
GLEI_1994
EPR2_2002
WU_2008

FIGURE XX

3.2.1 Data Quality

In many regions basic data collection and quality is a serious problem. In the United States, one of the better documented countries, Averyt 2013 [45] notes that the Energy Information Agency (EIA) is the only body collecting water use by power plants data and points to the need for more specific information on the types of cooling technologies and locations of plants. Stilwell 2010 [35] reiterates the need for more site-specific data. She points out that future water use for electricity generation will depend on several factors, including the fuel mix, the type of power plant and cooling system technology that is deployed as well as where the plants are located. Similarly energy use for water will depend on the water source and treatment technology chosen. Glassman 2011 [16] explains the need for detailed site specific plant data when considering locations of new plants in light of local water requirements, cooling technology tradeoffs (water, energy efficiency and emissions) as well as impacts of energy choices on water availability for forests, agriculture and other users.

3.2.2 Water and Energy Interdependencies and coupling

Water and energy interdependencies on each other vary from region to region and thus have correspondingly different implications on the management methods and strategies used to plan and site investments. Siddiqui 2011 [36] showed a skewed coupling for the Middle East and North African regions where energy systems had a relatively weak dependence on freshwater (0.5% consumption of freshwater resources for electricity production) while energy dependence of water abstraction and production was heavily reliant on energy. This is mainly due to the lack of freshwater resources and a larger dependence on seawater desalination. 5 to 12% of total electricity consumption was attributed to desalination in the Arabian Gulf. In other countries like the United States the nexus is critical on both sides with about 40% of all national water withdrawals being for power plant cooling [53] while at the same time water becoming the highest consumer of electricity in some states such Arizona (Due to the long distance conveyance in the Central Arizona Project) [40] and California (19%) [31]. According to Maas 2010 [33] in Ontario, Canada, water services consumed 12% of electricity and 40% of natural gas. In Spain, Hardy 2010 [47] estimates 7% of total energy is used for water systems while 25% of all water withdrawals are for energy production (Not including hydro plants).

3.2.3 Technology Considerations

Many authors have stressed the importance of careful considerations of the technologies chosen for both water and energy mixes. For example Hoover 2009 [40] points out how the energy intensity of transferring water via the long distance ‘Central Arizona Project’ in Arizona is twice that of reclaiming local water. Stokes 2009 [30] concludes, in the case of California, that meeting the average annual per capita water needs using desalination would have an energy and emission footprint from 1.5 up till 2.4 times larger than using imported water. Klein 2005 [31] ranks desalination as the most energy intensive source of future water, while efficiency as the least intensive. The World Energy Council 2010 [42] stresses the importance of careful consideration of the nexus dependencies for governments when considering unconventional technologies like oil sand, oil shale and deep gas which can be several times as water consumptive as traditional technologies. Grubert 2012 [43] elaborates on these choices of unconventional technologies for the case of Texas, where she concludes that even though freshwater consumption for natural gas extraction in Texas will likely continue to increase with unconventional resource exploitation, lignite or coal extraction is over three times as water intensive as the most water-intensive shale gas expected in Texas, primarily because of the need to dewater mines. Hardy & Garrido 2012 [49] show interesting results where modernization of irrigated areas to improve water usage in Spain since 2002 are shown to be performing worse, from an energy perspective, than desalinization or water treatment would. Another interesting conclusion is that, given the overcapacity in the Spanish system, from a water consumption point of view turning off nuclear power saves more water than increasing renewable capacity in the system.

Another key discussion has been on the introduction of biofuels in the energy mix and the consequences for water. Carillo 2009 [50] showed, in the case of Spain, an increase of 25% in water consumption in 2030 energy mix (Energy mix estimated by the Spanish Electrical industry Association (UNESA)) compared to 2005 mainly due to an increase in biofuels from 3% to 6% in the energy mix. Elena 2010 [51] stresses further how the 6% biofuel plan in Spain can have serious impacts, especially in water scarce areas like southern Spain.

Apart from the energy mixes, water cooling technologies also need to be considered carefully, given the corresponding tradeoffs for energy efficiency. Mackinick 2011 [55] quantifies these tradeoffs showing a decrease of 2 to 5 % in energy outputs when utilizing dry cooling.

3.2.4 Hydroelectric Potential and water resource modeling

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3.3 Review of Existing Models

Several sector specific models which address only energy (LEAP, MARKAL, MESSAGE) or only water (WEAP, BASINS) already exist and have been well documented. New models which try and integrate the capabilities of both types are currently in various stages of development.

Antipova 2002 [59] presents an optimization model developed in GAMS (General Algebraic Modeling System) [60] to manage the use of energy and water resources in the Aral Sea basin between the Central Asian Republics of Kazakhstan, Kyrgystan, Tajikistan, Turkmenistan and Uzbekistan. It is a small model with five reservoirs, three water sources, two water users and a downstream release. A single internal energy demand is considered along with regional transfers, from and to the Central Asian Energy Pool (CAEP). The cost of electricity production and non-served energy is to be minimized and a monthly time step is used. The model gives the lowest cost energy to be produced per month from each hydro and thermal unit as well as imported and exported energy given three different policy constraint scenarios. The scenarios concern policies related to export caps, irrigation water constraints and water release volume control. The results show how the policy changes considered can lead to serious consequences such as depletion of reservoir resources or excessive releases leading to ecological problems. Even though the model addresses some large scale regional issues related to particular policies it is not detailed enough to be used to address the nexus issues that have been described in Section 1.2. In particular the model does not capture the water consumption by thermal power plants and neither the energy consumption for water treatment, abstraction or delivery. The model therefore cannot address energy planning issues such as ideal energy investment mixes nor energy operation schedules in water scarcity situations.

The Stockholm Environment Institute (SEI) has a series of projects related to water, energy, land use and food modeling 2014 [61] [62]. Some of the packages have recently been put together for integrated studies and projects. WEAP (Water Evaluation And Planning System) and LEAP (Long range Energy Alternatives Planning System) from the Stockholm Environment Institute have been bundled together with other software packages like AEZ and OSeMOSYS (The Open Source Energy Modeling System) to provide tools like CLEWS and WEAP/LEAP/OSeMOSYS nexus packages. These are good efforts to model the nexus since each individual tool has been developed for its particular specialty. Some issues are integrating the boundaries of WEAP's watershed basins with LEAPs administrative boundaries and accounting for water use by individual power plants. Furthermore LEAP and WEAP are accounting/simulation software. When integrated, the package runs in an iterative manner with a scenario being entered into WEAP followed by the results then entered into LEAP and vice versa. Optimization was added to LEAP in 2011 with OSeMOSYS. This package however runs the optimization algorithm for each LEAP energy iteration and cannot optimize both the water energy nexus in a single run. A series of applications of the CLEWS integrated approach is provided by KTH [63]. A case study was carried out for Mauritius to compare a business as usual scenario with the advantages added by CLEWS [64]. The major changes using a CLEWS approach was an increase in electricity demand due to added sea water desalination, increased water demand by urban and agricultural users, reduced hydropower generation, reduction in sugarcane exports and a corresponding loss in the economic balance. Most of these changes were results of inputs into the original model using the different packages available in the CLEWS suite. Water demands increased because additional water demands were added as inputs for urban users, sugar cane processing and desalination. Hydropower generation decreased because more water was used as a result of using the water model to represent better the monthly storage volumes and river flows. The economic balance changed as a result of converting sugar cane processing plants to produce ethanol. The CLEWS approach offers many tools to formulate scenarios and prepare the inputs for a model. However, one is faced with the dilemma of deciding how detailed to make each area of their scenario and with that gaining the corresponding knowledge and software package. Even within one discipline there can be numerous simulation scenarios, and when combined with land-use, water, and climate change the combinations can become considerable.

The MARKAL/TIMES energy models developed by the International Energy Agency (IEA) have been adjusted to incorporate water systems for case studies in New York City by the Brookhaven National Laboratory 2009 [65] [66] and for South Africa 2013 [67].

The New York City case study determines the least cost energy path based on perfect foresight and life-cycle costs of technologies. Water resources include surrounding rivers, freshwater, saline water, groundwater and precipitation. Energy and water are modeled throughout the system from primary sources, energy conversion, water treatment, resource distribution to final users and waste treatment. The model can be used to test different policy constraints as well as resource and demand scenarios. The example model for the case of NYC has a single pool of water resource (one for each type of water quality) being used by different consumers in the system. In the case of larger areas it would be important to model the geographical distribution of power generation using water from different regions. The hydroelectric relationship with power generation potential and water scheduling would also be an essential attribute for countries with a large percentage of hydropower.

The World Bank presents an example of incorporating water into the TIMES Energy model (SATIM) developed by the Energy Research Center, at the University of Cape town, for South Africa. The model is a partial equilibrium linear optimization model representing the whole energy system. The SATIM model is used in an iterative manner with the E-SAGE general equilibrium model taking into an economy wide framework. The E-SAGE model is run to establish a reference scenario for energy and provide inputs for the SATIM model. The SATIM model is first run with the reference inputs and then again with the Nexus scenarios in which energy demands are reduced as a result of increased energy prices to reflect water scarcity. The increased energy production costs are then passed back to the E-SAGE model which is then rerun to evaluate the economy wide impacts. The reference and Nexus scenarios are then compared to evaluate the impacts of water scarcity. Water is added in the SATIM energy model as a consumption parameter for power plants but without any limits. The impacts of water scarcity are incorporated as increased prices depending on representations and interpretations of water scarcity effects. Potential developments would be to include modeling the water system with limited resources and linking changes in prices due to scarcity to actual resources in the model. Other developments would be geographical representations of the water resources as well as physical links with the energy and other sectors by location.

An integrated nexus model, TIAM-FR 2012 [68] has been created at MINES ParisTech. The model is excellent integration of water and energy systems for an integrated management approach. Water withdrawal and water consumption per energy technology is considered through the energy life cycle from raw materials to final energy delivery. Furthermore the various power plants are characterized by different water cooling technologies. Water resources are also further characterized into brackish, municipal, saline and freshwater. Once through cooling systems area allowed to use the other types of water, while all other cooling systems can only use freshwater. Given the large range of water use data, some processes, such as different kinds of mining processes, are given water weights and ratios are used to model the mining methods in the system. The model also goes into the details such as allowed temperature increases around plants. Increased water use by carbon sequestration and combing cycle technologies are also reflected. The model is used to demonstrate the effects on global model water resources as a result of different energy mixes as well as optimal energy mixes minimizing water use and other constraints. Furthermore, the model shows the distribution of water use in the energy life cycle.

The model is limited by its representation of the water system and the energy used in different water abstraction, treatment and distribution processes. The authors mention further development will focus on modeling water use by other users to perform a more comprehensive analysis of both water and energy supply. For regions with a large percentage of hydropower the model will also need to related hydroelectric potential with water use, climate change and other resource usage. Finally, it appears that the model uses a global water resource available to the energy mix. Geographical distribution of water resources and corresponding power plants as well as raw material extractions are important to capture regional water limitations. Energy demand from the grid may increase globally but the distribution of types of power plants and water resources can limit the types of technology operated or invested in.

Center for Naval Analyses (CNA) 2014 published a paper [69] describing a new mixed-integer linear programming model of the power sector accounting for water used by thermal cooling. The paper discusses four cases studies applying the model to China, India, France and the US state of Texas. The model develops a baseline for each case and then runs a series of scenarios to study limits on water availability, end use efficiency, expansion of renewables and carbon caps. The model outputs include water withdrawal, water consumption, optimal power generation mix, emissions as well as total system fixed and variable costs. Conclude that cost-effective options exist to cut back water and also reduce emissions of conventional pollutants and CO2. The model considers individual power plants (therefore mixed integer) with each plant having a variable and fixed cost. Cooling technologies are modeled for each plant as well as environmental factors such as SO2, CO2 and particulate emissions. Water consumptions are limited in the “WaterLimits” scenario by including a constraint which limits total water consumption to the water consumed in the year 2010. The main limitations of the model as discussed in the paper itself are its small size and water accounting methods. The small size means the model represents a relatively small aggregated area which does not capture regional variations. The water accounting is very simple and does not represent any water resource distribution or availability. Together these two limitations prevent representing water scarcity or the effects of climate change and water competition.

The National Renewable Energy Laboratory (NREL) 2014 [70] published a paper in 2014 describing a new energy-nexus model which uses water rights as a method to analyze the nexus. The model describes the link between climate change, water and electricity systems using the NREL Regional Energy Deployment System (ReEDS) with changes in surface water projections using the Coupled Model Intercomparison Project 3 (CIMP3). ReEDS is an electric sector capacity expansion model for the contiguous US, that estimates cost-minimized construction and operation of generation and transmission assets from 2010-2050. The ReEDS system is updated include thermal power plant cooling water demands and constraints on water rights available to new generation capacity. The model linearly optimizes the problem in two year time steps satisfying an external electric demand input. The water withdrawal rates represent the water rights which must be purchased in order to satisfy the demands. Each area is specified a water rights supply curve with quantity and cost of different water rights divided into un-appropriated fresh surface water, shallow groundwater, wastewater and brackish water. In planning for future investments water rights acquisition is a one time decision and the model assumes that with purchased rights there will be no further constraints on physical water availability. Thus the model does not reflect actual physical water availability nor the water consumption or withdrawal during operation. The model also does not consider water rights for salt-water along the coast, which means the rights in these regions are underestimated. The lack of modeling physical water availability in the scenarios also excludes any temporal changes. The future developments for the model mentioned in the report include developing physical representations of the water resources. The existing model concludes that as a whole the United States has enough unappropriated or retired water rights available so that there is no significant impact on the regional or national capacity growth as a result of climate change. The highest impact is seen in the southwestern states with limited to no unappropriated water rights, in which case the model chooses wastewater as well as brackish water if need. More costly water sources are preferred by the model over investing in more expensive cooling technologies, less water intensive technologies, or building elsewhere and incurring transmission costs. The costs of using wastewater and brackish water are minimal relative to total cost of new generating capacity.

Bartos & Chester, 2014 [71] [72] present a water-energy nexus model applied to the US state of Arizona. The model is used to evaluate the water and energy co-benefits of different conservation policies for the year 2025 which meet the legislated renewables portfolio (15% of annual retail sales by renewables) and energy efficiency standards (22% of expected electricity demand with increased energy efficiency from 2009). Four different water conservation (residential water, agricultural irrigation, reclaimed, dry/hybrid power plant cooling) and three different energy conservation (residential appliances, residential HVAC, commercial HVAC) measures were evaluated for four different scenarios based on intensity of energy efficiency and renewable generation achieved. The objective function minimizes the cost of developing additional energy generation and the corresponding value of water consumed. The objective function also minimizes the cost of avoided generation due to energy and water efficiency. The input data and infrastructure modeling uses national, state, county and facility level data depending on availability. The highest resolution data used are described as follows. The energy system parameters for water consumption and withdrawal are modeled per plant type using data from Averyt, 2011 [73]. The information is augmented by other estimates for fuel extraction and processing. The water system is modeled in detail with electricity consumption data per reservoir for hydroelectric generation, per pumping station for the Central Arizona Project and per well for groundwater pumping. Electricity consumption data of water treatment and distribution is taken from provider level estimates and for wastewater treatment the data is taken per treatment facility. This representation of the system allows for detailed accounting of the water and energy consumption. Additional energy production needed is calculated in terms of energy needed in MWh. The model concludes that water conservation measures have a potential to reduce statewide electricity by 0.82 to 3.1 percent satisfying 4.1 to 16 percent of the states mandated energy efficiency reduction requirements. Energy efficiency measures and renewable generation can reduce non-agricultural water demand by 1.9-15%.

The model does not have any constraints for physical water resource quantities. The model would thus have to be developed in order to be used to study the impacts of physical water shortages in the system. Furthermore, such constraints would need to be linked to temporal time series to truly reflect not only quantities but also seasonal variations of potential water scarcity. For this the energy and water demands time series would also need to be developed. If the model is to be used for larger geographical areas with multiple watersheds, the representation of the energy capacity distribution would need to be at a resolution at least as detailed as the watersheds being considered. This would allow for studying the impacts of regional water shortages on a centralized electric system. For regions with large dependence on reservoirs the energy produced by hydroelectricity and future water and hydroelectric potential would need to modeled.

Cardenal 2014 [74] present a coupled water-power model which assesses the impacts of climate change on the power system in Spain and Portugal. The model studies the temporal and volumetric impacts of increases in temperatures and precipitation on the energy demand, irrigation water demand, hydroelectric-thermal coordination as well as energy and water demand shifts. An aggregated equivalent energy reservoir was modeled to represent the hydroelectric power of the peninsula. Various climate change scenarios were considered and the data was used in a rainfall-runoff model to evaluate future water resources for irrigation and power. The paper concludes that climate change will result in a decrease in hydropower, a corresponding increase in thermal generation and a seasonal shift in power demand from winter to summer. The model is a useful tool to estimate general trends as a result of climate changes but cannot be used for integrating water and energy management decisions. In order to capture other effects of climate change and offer more management capabilities the paper suggests some further developments. These include adding power plant water cooling needs; spatial disaggregation of power and water needs, demands and resources at the watershed level; and increasing the power system time steps to hourly intervals.

Bhattacharya & Mitra 2013, [75] present a water-energy-climate model developed as a collaborative effort of the Institute for Global Environmental Strategies (IGES) and the International Institute for applied Systems Analysis (IIASA). The model uses a modified version of IIASA's energy model MESSAGE. The modifications include additional inputs regarding sectoral water demands, water resource availability based on climate change predictions and water efficiencies of energy technologies. The model is used to evaluate the optimal mix given a water constrained future. The model is still in progress and important developments such as regional disaggregation and coupling with land use are suggested. Other useful developments would be to include a representation of the water system and its energy uses in order to model the entire nexus.

3.4 Review of Key Nexus Gaps, Objectives and Future Developments

In the review submitted to the European Commission, Pollitt, 2010 [76] identify some key gaps in existing macroeconomic sustainability models. In particular the report points out the lack of two-way integrated analyses, with a majority of models focusing on unidirectional modeling of the links between socio-economic development or energy and other themes. This bias is also seen in the list of studies shown in TABLE XX. This leads to distortion of the results as well as policy recommendations. Consumptions of non-energy resources (biomass, water, minerals) are understudied and need to be addressed by including physical capacities and stock constraints which influence model results. Resources included in existing models need to be geographically disaggregated as macro level data may not be very informative. Modeling methods tend to over-simplify treatments of technologies, uncertainty and non-linear relationships. Other areas that are overlooked are population movements and assumptions related to exogenous factors remaining unchanged.

In efforts to integrate water and energy planning the United States Department of Energy (USDOE) created the Water-Energy tech team (WETT) in 2012. Based on a detailed evaluation of the nexus the WETT put forward the following key “guiding pillars” for future water-energy developments [77]:

i. Optimize the freshwater efficiency of energy production, electricity generation, and end use systems
ii. Optimize the energy efficiency of water management, treatment, distribution, and end use systems
iii. Enhance the reliability and resilience of energy and water systems
iv. Increase safe and productive use of nontraditional water sources
v. Promote responsible energy operations with respect to water quality, ecosystem, and seismic impacts
vi. Exploit productive synergies among water and energy systems

The Water Energy Forum (WEF) [78] reiterate these same pillars recommending decision-makers and researchers to find ways to increase water efficiency in energy production, increase energy efficiency in water production, promote water-conscious energy infrastructure development and encourage best practices in water-smart energy development. A key addition to these objectives is the WEF’s emphasis on including the economic value of water in future models and analysis.

The United Nations [79] identifies key gaps in existing nexus methodologies including; necessary improvements in water and energy accounting; incorporating physical water shortages in models in addition to water values; improving details of uncertainty, dynamic choices and technology choices; improved drivers used for future demand and supply predictions; availability of raw data; and improvement of concepts related to determine the best solution.

Recent literature reviews on the water-energy nexus; Retamal (2009) [80]; Water in the West (2013) [81] ; and Wang (2014) [82], all recommend the need for modeling feedback loops from both water and energy systems within the model. Ignoring the links lead to single sector focused policies and decisions which can lead to serious problems such as biofuels as alternative energy sources increasing water stress and replacing food crops [29]. Desalinization plants as water sources can substantially increase energy consumption in some scenarios [30].

Dale (2013) [83] recommends the use of optimization algorithms to find optimal solutions for policy constraints and objectives. Rodriguez (2013) [84] compares the use of simulation and optimization modeling in water and energy systems. Simulation models are traditionally used to assess water systems given the relatively small number of allocation options and the spatial and temporal scope of water resources. Energy systems on the other hand are managed with optimization models to meet demand and cost objectives given the larger choice of technologies available. An integrated model must combine these two aspects, studying development of water systems and availability of resources using simulation scenarios, while optimizing the resources based on these scenarios.

The identification of interactions between different technologies over the life cycle of each resource is necessary in order to quantify realistic resource usage and account for indirect impacts. Both Marsh (2008) [22] and Dale (2013) [83] have conducted detailed life cycle analyses which uncover a more complete picture of the water and energy footprints in various end uses. The impacts studied include emissions, costs, land use, water use and energy use at production, construction, operation and consumption. The wide range of water consumption during the extraction and mining phase of different technologies as discussed in Water in the West (2013) [81] & Mielke [54] (from 1 gal/MMBtu for gas to 5000 gal/MMBtu for biofuels) shows the importance of considering the source of energy and not just the operation of plants.

Energy demands, growing degree days, industrial processes, heating and cooling requirements all depend on climate patterns and changes in temperatures and rainfall quantity, intensity and periodicity. Some scenarios predict up to a 4 degree Celsius temperature increase with increased extreme weather events and longer durations of droughts (IPCC [85] [86], World Bank [87]). The model must consider the uncertainty in future climate change scenarios and corresponding impacts on resources as well as demands. Ignoring climate change can lead to inaccurate estimates of future resource demands and availability as a result of not considering changes in temperatures, precipitation and aridity. Climate change impacts on nexus issues in particular, such as the increase in water cooling needs of power plants or the decrease in water cooling abilities, should be considered.

Many water-energy nexus issues are cross-watershed boundary issues and thus the single basin models will not apply. In particular the power plant location distribution has to be modeled per watershed in order to calculate the true water consumption and demand from the energy sector per basin. If this is ignored then regional water shortages will be overlooked and the water demand of the energy sector on a national level may appear satisfactory but may be of concern in certain basins (e.g. The Segura river basin in Spain has only 1% of Spain's total water resources, but accounts for 5% of its water usage [88]. On a national level Spain can be classified as a medium to low stress region, however Segura is classified as a high stress region (Alcamo Water Stress Indicator) [89]).

Some studies stress the importance of a holistic modeling approach. Marsh (2008) [22] uses a general equilibrium Input/Output analysis model to investigate in detail the backwards and forward linkages in thirty two sectors including, agriculture, mining, textiles, food, chemicals, transport and others. Rodriguez (2013) [84] also stresses the need to incorporate stakeholder and public involvement in developing the policies and objectives to be used in the model.

3.5 Review of General Nexus Related Figures and Data

Some basic data related to the water energy nexus has been compiled from various sources and shown in TABLE XX below. A range of countries has been chosen to represent different geographic, demographic and economic regions.

TABLE XX

Data	Unit	USA	MEXICO	BRAZIL	SPAIN	GERMANY	RUSSIA	AUSTRALIA
Freshwater Resources	hm3							
Reservoir Capacity	hm3							
Runoff	hm3							
Water for Energy	% hm3							
Water for Industry	% hm3							
Water for Agriculture								
Energy Capacity	GW							
Energy Mix	%							
Electricty Produced	TWh							
Energy used for Water	GWh							
Water Price	USD/m3							
Population								
GDP								
Water scarcity factor								

TABLE XX

Data	Unit	INDIA	PAKISTAN	CHINA	S.ARABIA	DUBAI	SUDAN	NIGERIA
Freshwater Resources	hm3							
Reservoir Capacity	hm3							
Runoff	hm3							

Water for Energy	% hm3							
Water for Industry	% hm3							
Water for Agriculture								
Energy Capacity	GW							
Energy Mix	%							
Electricty Produced	TWh							
Energy used for Water	GWh							
Water Price	USD/m3							
Population								
GDP								
Water scarcity factor								

4. Discussion: Integrated Water-Energy Assessment

Given the proximity of escalating nexus issues, Howells & Rogener 2014 [90] stress the need to move beyond analytical studies of nexus interlinks to creating real applicable models. Based on the literature reviewed the following key elements have been identified as key guidelines to be included in future water-energy nexus assessments and management models. TABLE XXX uses these elements to compare the models reviewed in this paper. The key elements are:

A. DATA

1. Quality: Careful interpretation of scarce data or data with large ranges
2. Uncertainty: Ranges of uncertain parameters considered carefully
3. Non-linear: Linear approximations justified and impacts on results
4. Exogenous factors: Details of fixed exogenous factors such as government actions or non-water/energy resource usage which may change.

B. ENERGY SYSTEM

1. Energy Life Cycle: Fuel extraction, transport, conversion, delivery
2. Energy Capacity Mix: Range of Energy technologies considered
3. Energy Investment decisions: Optimal energy capacity investments decisions
4. Energy Operation Decision: Operation details of meeting energy demands
5. Energy Demands Spatial: Centralized or decentralized energy demands
6. Energy Demands Temporal: sufficient details of temporal variations
7. Emissions of Energy Technologies: Emissions per energy technology
8. Emissions of Energy systems: Embedded emissions of extractions, transportation processes

C. WATER SYSTEM

1. Water Resources Spatial : Spatial representation of availability and scarcity
2. Water Resources Temporal: Temporal representation of availability and scarcity
3. Water resource Types: Distinguishing between groundwater, surface water, sea water, waste water
4. Water Life Cycle Services: Conveyance pumping, Groundwater pumping, Drinking water treatment, distribution pumping and waste water treatment
5. Water Value: Modeling or interpretation of marginal values and prices of water
6. Water system Investments: Optimal water system investment decisions
7. Water System Operation & Allocation: Optimal operation and allocation decisions
8. Water Demands Spatial: Spatial representation of water demands
9. Water Demands: Temporal representation of water demands

D. NEXUS ISSUES

1. Nexus Technologies: Desalination and biofuels modeled carefully with feedbacks in model optimization
2. Energy Lifecycle Water accounting: Water use in entire energy system life cycle
3. Water Lifecycle Energy accounting: Energy use in entire water system life cycle

4. Water use by Cooling technologies: Characterization of power plants by water cooling technologies
5. Hydroelectric Resource Relation: Reservoir water management and relationship with hydro-electric energy potential, water resource availability and hydro-thermal coordination
6. Spatial Disaggregation: Spatial representation and overlap of water and energy systems by watershed
7. Coupled Global Optimum: Coupled water and energy nexus model capable of optimizing water and energy system, resource and demand constraints.

E. CLIMATE CHANGE

1. CC Water Resources: Appropriate rainfall-runoff models used to predict changes in spatial and temporal distribution of water resources
2. CC Water demands: Analysis of changes in spatial and temporal water demands and usage patterns in agricultural, residential, industrial and energy sectors
3. CC Technology Performance: Impacts of climate change on operating performance
4. CC Cooling Needs: Impacts of water temperature on technology cooling needs

F. POLICY CONSTRAINTS

1. Emission Constraints: Evaluation of emissions constraints
2. Energy efficiency Measures: Evaluation of energy efficiency measures
3. Renewable Integration: Evaluation of renewable targets and integration requirements
4. Multi-Sector tradeoffs: Generate results to compare with other sectors such as marginal water prices, water resource left over
5. Water rights: Evaluation of water rights and allocation priorities
6. Demand Side Measures: Evaluation of demand side measures
7. Energy Export Caps: Evaluation of energy export capacities

TABLE XX summarizes and compares the following models which have reviewed in the literature review based on the key recommendations listed above:

M1 - Antipova 2002 [59]
M2 - SEI CLEWS 2014 [61] [91]
M3 - MARKAL NYC Brookhaven National Laboratory2009 [65] [66]
M4 - SATIM/E-SAGE South Africa TIMES 2014 [67]
M5 - TIAM-FR 2012 [68]
M6 - CNA2014 [69]
M7 - NREL 2014
M8 - Bartos & Chester 2014 [71] [72]
M9 - Cardenal 2014 [74]
M10 - IIASA IGES Bhattacharya & Mitra 2013 [75]

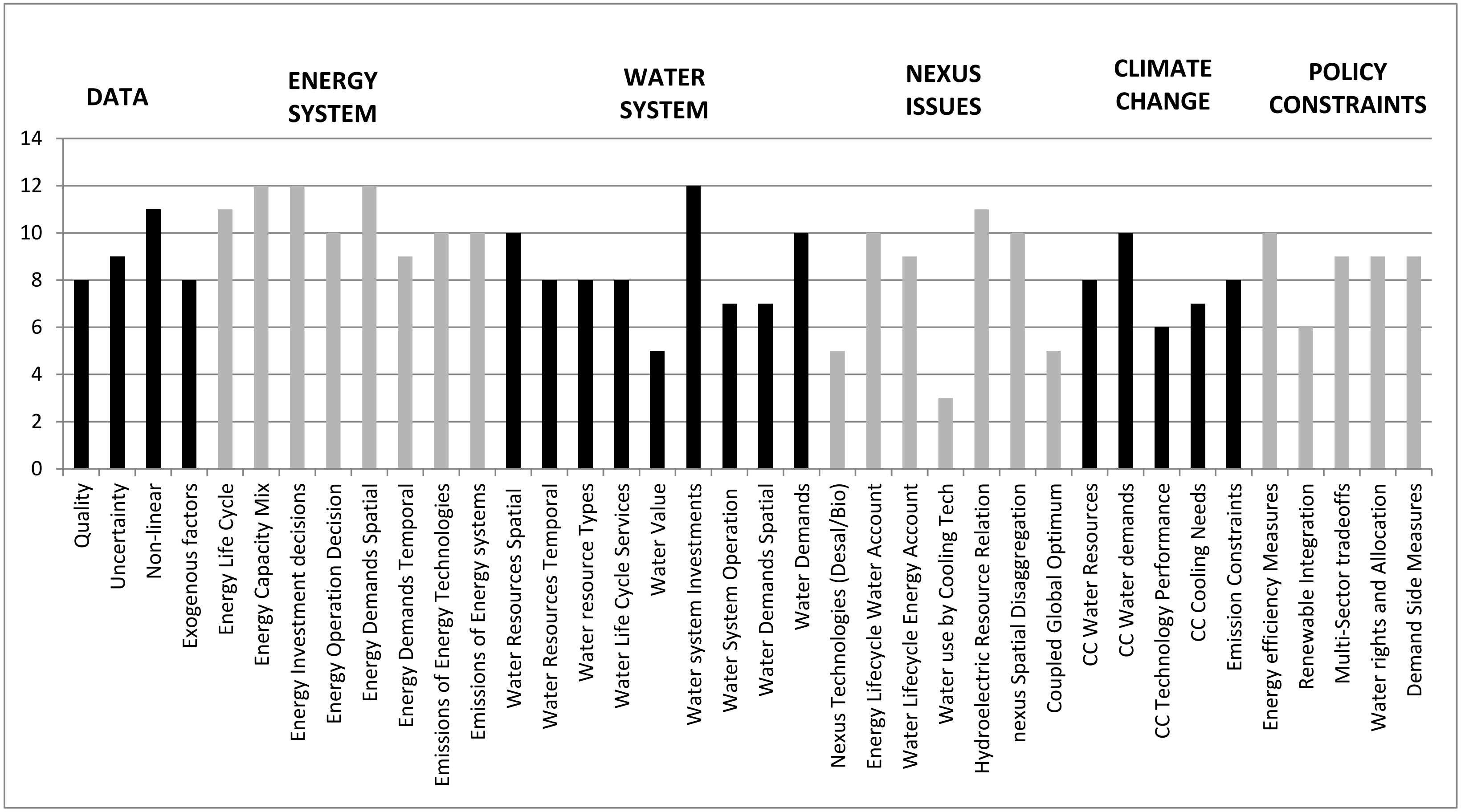
TABLE XX COMPARISON OF MODELS (CURRENTLY RANDOM VALUES NEED TO UPDATE)

0 – Not included in model
1 – Included to some extent
2 – Well represented in model

Can see which models cover what areas as well as how existing models in general cover the important themes

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	TOTAL
DATA											
Quality	1	1	0	1	2	0	0	2	1	0	8
Uncertainty	0	0	1	0	2	1	2	1	2	0	9
Non-linear	1	1	1	0	2	1	1	1	2	1	11
Exogenous factors	0	0	0	0	2	2	2	0	2	0	8
ENERGY SYSTEM											
Energy Life Cycle	0	2	2	0	1	1	2	0	1	2	11
Energy Capacity Mix	1	2	0	1	2	1	2	1	1	1	12
Energy Investment decisions	0	1	0	1	2	2	2	1	2	1	12
Energy Operation Decision	2	2	2	0	1	1	0	1	0	1	10
Energy Demands Spatial	2	1	0	1	1	2	1	2	1	1	12
Energy Demands Temporal	2	1	0	1	2	1	0	0	1	1	9
Emissions of Energy Technologies	0	0	0	2	1	0	2	2	2	1	10
Emissions of Energy systems	0	1	0	0	0	2	2	2	2	1	10
WATER SYSTEM											
Water Resources Spatial	1	1	1	0	2	2	2	0	0	1	10
Water Resources Temporal	1	0	2	0	0	0	1	0	2	2	8
Water resource Types	0	0	1	1	0	0	2	1	2	1	8
Water Life Cycle Services	0	0	0	0	1	0	2	2	2	1	8
Water Value	0	1	0	0	0	0	0	2	1	1	5
Water system Investments	0	0	2	2	1	0	2	2	1	2	12
Water System Operation	0	1	2	1	0	1	0	1	0	1	7
Water Demands Spatial	1	1	0	0	0	1	0	2	2	0	7
Water Demands	1	0	2	2	2	1	1	0	1	0	10
NEXUS ISSUES											
Nexus Technologies (Desal/Bio)	0	1	0	0	0	2	0	2	0	0	5
Energy Lifecycle Water Account	0	1	2	2	0	2	1	2	0	0	10
Water Lifecycle Energy Account	0	1	2	2	0	1	0	1	0	2	9
Water use by Cooling Tech	0	0	0	0	1	0	0	1	1	0	3
Hydroelectric Resource Relation	2	1	0	2	2	1	0	2	1	0	11
nexus Spatial Disaggregation	0	2	0	2	1	2	1	0	1	1	10
Coupled Global Optimum	1	1	0	0	0	0	1	1	0	1	5
CLIMATE CHANGE											
CC Water Resources	0	1	1	0	2	0	0	2	0	2	8
CC Water demands	0	2	0	2	2	0	1	1	0	2	10
CC Technology Performance	0	0	1	1	0	0	0	2	2	0	6
CC Cooling Needs	0	0	0	1	0	2	1	1	1	1	7
POLICY CONSTRAINTS											
Emission Constraints	0	0	0	2	1	1	0	2	1	1	8
Energy efficiency Measures	0	0	0	2	2	2	2	1	1	0	10
Renewable Integration	0	1	0	0	1	1	0	0	1	2	6
Multi-Sector tradeoffs	1	1	1	1	2	0	1	0	0	2	9
Water rights and Allocation	2	0	1	0	1	1	0	2	1	1	9
Demand Side Measures	0	1	2	2	0	1	2	1	0	0	9
Energy Export Caps	2	0	2	0	2	1	2	1	0	1	11
TOTALS (Max 117)	21	29	28	32	41	36	38	45	38	35	

FIGURE XX (NEEDS TO BE UPDATED AND WILL THEN REFLECT WHERE CURRENT MODELS ARE WEAKEST IN)



5. Conclusions & Recommendations

Summary of everything

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