Renewable and Sustainable Energy Reviews xxx (2016) xxx-xxx

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com

Integrating water and energy models for policy driven applications. A review of contemporary work and recommendations for future developments

Zarrar Khan*, Pedro Linares, Javier García-González

Instituto de Investigación Tecnológica, Universidad Pontificia Comillas, Alberto Aguilera 23, 28015 Madrid, Spain

ARTICLE INFO

Article history:
Received 24 July 2015
Received in revised form 25 May 2016
Accepted 23 August 2016
Available online xxx

Keywords:
Energy
Water
Nexus
Integrated planning

ABSTRACT

Availability of and access to water and energy are key ingredients for economic and social development. Unfortunately, more than a billion people still lack access to both safe freshwater and basic energy services. Future predictions show that the situation may become worse with about a 40% increase in energy demand and 30% increase in water demand by 2040. In addition, water and energy are highly interdependent, with water needed in all phases of the energy lifecycle and energy needed in all phases of the water lifecycle. While recent years have seen an increasing number of studies on the water-energy nexus, the research is focused on scattered individual areas of the nexus, each important in their own right. However, there is now a need to synthesize these efforts and identify the most important elements needed for a holistic water-energy nexus methodology. This paper focuses on the benefits to be gained from and the drawbacks of ignoring various water-energy interlinks for policy makers and planners in their goals to meet long term resource security. Several possible combinations of socio-economic and climate change scenarios make these goals even more challenging. The lessons learnt from reviewing different integration methodologies and studies are compiled into a list of key recommendations. It is found that current integration efforts are often biased towards the energy sector and its water requirements. There is still a need for better representations of the water infrastructure and corresponding linkages with the energy sector. There is also a need to harmonize the energy and water systems from both a technical and policy perspective. This calls for compatible disaggregation of spatial and temporal elements in both systems as well as designing model outputs to allow evaluation of the synergies and tradeoffs of multi-scale, cross-sector policies.

1. Introduction

This paper investigates water and energy resource planning models designed to aid government departments, planners and policy makers to plan, manage and provide the relevant services needed to reach a desired level of quality of life. While quality of life can be a relative term, most definitions and indicators (e.g. United Nations (UN) Human Development Index [1], UN Millennium Development Goals [2], World Bank World Development Indicators [3], UN Sustainable Development Goals [4]) include improved access to health and sanitation services, a steady reliable source of food, improved economic and industrial activity and sufficient infrastructure to facilitate implementation and operation. These goals are sought keeping in mind multiple constraints including costs, environmental impacts, international policies and other political motivations. While, there are many elements involved, water and energy are two of the key common resources shared between almost all of these activities. Up until a few decades ago, with abundant supplies relative to demands, the management and infrastructure of the two sectors evolved independently, encouraging delineated responsibility and sector-specific planning [5].

However, both systems are becoming increasingly strained as a result of rising total demand due to population growth; increased per capita consumption due to economic and lifestyle changes; and climate change impacts on demand and availability patterns [6]. At least 1.8 billion people still lack reliable access to water safe for human consumption and about 2.4 billion lack improved sanitation facilities [7]. About 1.2 billion people also still lack access to electricity and about 2.7 billion still cook using solid fuels [8] leading to nearly 2 million deaths annually [9].

The future is very uncertain with several possible socio-economic development pathways, simultaneously framing and shaped by several climate change scenarios [10]. Energy demand is expected to increase by about a third from 2014 to 2040 [8]. At the same time water demand is predicted to increase by up to 55% by 2050 [11]. This will occur as a result of the increase in global population from about 7.3 billion in 2015 to about 9.7 billion in 2050 [12] and the accompanying increases in food demand, economic growth and industrial activity. While demands are increasing, the amount of global water remains roughly constant at about 1.4 billion km^3 [13] with less than 1% being freshwater available for human uses. Accessible freshwater resources are becoming even more vulnerable due to increased pollution, uncontrolled groundwater depletion and climate change impacts on water availability patterns. According to the Intergovernmental Panel on Climate Change [14], the population at risk of increased water stress due to climate change can reach as high as 2 billion in 2040.

The problem is further complicated by the high interdependence of water and energy. Water is used in all phases of the energy cycle: in extraction and mining, directly in hydropower generation, for power plant cooling and to irrigate biofuel crops. At the same time,

* Corresponding author.
Email addresses: Zarrar.Khan@iit.comillas.edu (Z. Khan); Pedro.Linares@iit.comillas.edu (P. Linares)

http://dx.doi.org/10.1016/j.rser.2016.08.043
1364-0321/

energy is needed in all phases of the water cycle: water extraction and pumping, desalination, purification and distribution to end users. In 2010 the world energy production was responsible for 15% (583 billion cubic meters (bcm)) of total global water withdrawals, of which about 10% (66 bcm) was consumed [15]. By 2035, in the International Energy Agency (IEA) New Policies Scenario, global energy consumption rises by 35% with a corresponding increase in water withdrawals by the energy sector of 20%, while water consumption is expected to increase by 85%. The higher water consumption relative to withdrawals is predicted as a result of shifting to power plants with advanced cooling technologies which withdraw less water but consume more as well as due to the possible expansion of biofuel crops [16]. The degree of interdependence between the two systems can vary regionally based on the distribution of natural resources and existing state of infrastructure. For example, electricity consumption by the water sector varies from 5.8% in Spain (excluding end-water-use energy) [17] to about 9% in the Middle East and North African (MENA) countries [18], 12% in Ontario, Canada and 19% in California [19]. Similarly, the energy sector in the MENA regions consumes less than 0.5% of its freshwater resources, in Spain the energy sector withdraws 25% and consumes about 4%, while in the United States, water use for energy accounts for about 40% of freshwater withdrawals and 4% of consumption [20].

The problem to address then, is tackling the issue of expected energy and water scarcity in the future, by improving existing management methodologies. The overall goal is to manage the supply of water and energy to multiple sectors competing for the two resources while meeting the multiple, sometimes conflicting objectives which may include adaptation strategies, costs, emissions, efficiency, international mitigation commitments and other policies.

The escalating issues emphasize that planners no longer have the luxury to ignore the missed opportunities to be gained from integrated planning and in recent years several international organizations have identified the water-energy nexus as a key global challenge in the upcoming decades (e.g. World Bank: Thirsty energy [21], UN World Water Development Report 2014: Water and Energy [22], Asian Development Bank (ADB): Thinking about water differently [23], US Department of Energy(USDOE): The Water Energy Nexus [24], World Business Council for Sustainable Development (WBCSD): Water, food and energy nexus challenges [25], World Resources Institute (WRI): Water-energy nexus. Business risks and rewards [26], International Renewable Energy Agency (IRENA): Renewable energy in the water, energy and food nexus [27]).

Section 2 compiles a list of several key reasons to adopt integrated water and energy modeling. Section 3 then summarizes some of the barriers and issues that may be faced in achieving this integration. Integrated modeling methodologies and several existing models are reviewed in Section 4. The needs, barriers and review of existing models are then synthesized into a list of key recommendations for future developments in Section 5.

2. Need for water and energy integration

The synergetic benefits to be gained from integrated resource management will be critical in improving efficiencies, reducing trade-offs, improving governance and finding alternate solutions to future energy and water resources scarcity problems [28]. Several key issues, highlighting the advantages and need for integrated water and energy analysis over individual systems, are listed below and discussed further in this section:

1. Energy forecasting and planning with water constraints.
2. Water sustainability of decarbonization and power sector alternatives.
3. Biofuel expansion and overexploitation of water resources.
4. Water and energy decoupling issues.
5. Alternative water sources and corresponding energy demands.
6. Hydroelectric vulnerability to climate change.
7. Water temperature constraints on energy production.
8. System efficiency and cross-sector feedbacks.
9. Inter sector, regional and stakeholder conflicts

2.1. Energy forecasting and planning with water constraints

Future forecasts for increases in energy demands coupled with increases in population, water demands, industry and agriculture present a challenging picture. However, a review of most of the existing global energy scenarios (IEA, IIASA, IPCC, ETSAP TIAM, SHELL, WETO, WEC[1]) [29] show that the focus of most external drivers and policy constraints considered outside the energy sector itself are mostly limited to population, GDP growth and carbon emissions. Impacts on land and water are in almost all cases consequences of these energy policies and pathways, in contrast to taking them as input constraints.

From 2011 to 2035, the IEA forecasts energy demand to increase about 14% in the 450, 33% in the New Policies and by 45% in the Current Policies [30,31]. Electricity is one of the world's fastest growing forms of delivered energy, growing from 26% to 32% of the final energy share from 2011 to 2035 in the New Policies Scenario [30]. Across different scenarios, estimates show that at least 50% of electricity will still be generated from non-renewable sources using coal, gas, and nuclear power plants heavily dependent on water cooling [8,32,33]. Globally water withdrawals in 2000 were estimated to be about 3500 bcm with agriculture accounting for about 70% (up to 90% in developing countries), energy 15%, industry and manufacturing 5% and the residential sector about 10%. In 2050 it is estimated that total freshwater withdrawals will rise by 55% mainly due to increases in manufacturing (400%), thermal electricity generation (140%) and domestic use (130%) [7]. Recent analysis suggests the world could face a 40% shortfall between water demand and available freshwater supply by 2030. Many countries are already extracting groundwater faster than it can be replenished (Mexico by 20%, China by 25%, and India by 56%). If current trends continue, by 2030 two-thirds of the world's population may be living in areas of high water stress [34] (up from about 40% in 2010).

In the US about half of all freshwater withdrawals are used for power plant cooling. The predicted increase in energy demand by 40% using current energy systems could translate to an increase in freshwater access needs by about 165% [34]. Concerns for water constraints, has led the Electric Reliability Council of Texas (ERCOT) to verify new power plant water rights before including them in their planning models [24]. In India 79% of new energy capacity is expected to be built in areas that already face water scarcity or water stress with coal remaining a key resource (71 coal plants have been planned in the highly water stressed region of the Vidarbha). In South Africa, a new coal power station is expected to divert 2.9 million liters of water an hour from the nearby Vaal river away from current agriculture and residential use. Under the National Water Act, the

[1] International Energy Agency (IEA), International Institute for Applied Systems Analysis (IIASA), Intergovernmental Panel on Climate Change (IPCC), Energy Technology Systems Analysis Program (ETSAP) TIMES Integrated Assessment Model (TIAM), World Energy Technology Outlook (WETO), World Energy Council (WEC)

main utility, Eskom, is classified as a strategic water user and is guaranteed a supply of water despite competing users from other sectors [27]. In Spain adjusting the energy system to adapt to possible future water constraints is estimated to increase planned investment and operation costs of the energy system by upto 0.4%. However, ignoring future water scarcity is estimated to lead to increased costs of upto 8% as a result of reduced options and non-served energy in certain river basins [35].

Ignoring water constraints in energy planning can lead to several energy pathways with severe impacts on future water resources which may be diverted away from other key sectors such as the industrial, agricultural and residential sectors. Integrated planning will be critical to ensuring a more secure water and energy future.

2.2. Water sustainability of decarbonization and power sector alternatives

Climate change impacts for global temperature increases of more than 2 °C (before 2100 relative to the 1861–1900 levels) are predicted to have serious consequences including coastal city inundations, higher malnutrition rates from food production risks, exacerbated water scarcity in many regions, increased intensity of cyclones and irreversible loss of biodiversity [36–38]. The Intergovernmental Panel on Climate Change (IPCC), in its fifth assessment report (AR5), estimates that keeping global warming to less than 2 °C, will require limiting cumulative anthropogenic CO_2 emissions (since 1870) to below about 2900 $GtCO_2$. Measurements in 2011 showed that 1900 $GtCO_2$ have already been emitted [36]. UN Framework Convention on Climate Change (UNFCCC) estimates show that the implementation of the Intended Nationally Determined Contributions (INDCs) after the 2015 annual Conference of Parties (COP) will result in aggregate cumulative CO_2 emissions after 2011 of about 533 $GtCO_2$ by 2025 and 739 $GtCO_2$ by 2030 setting the world on a path to global warming of roughly between 2.7 and 3.7 °C by the end of the century [39,40].

Recognition of these risks has led to increased efforts to mitigate future warming by decreasing emissions, however, as pointed out by Circle of Blue, "unless the U.S. plans more carefully, generating energy from more sustainable alternatives is almost certain to consume much more water than the fossil fuels they are meant to replace" [34]. Carbon capture and storage (CCS) a favored tool to reduce carbon emissions can increase water consumption at coal-fired utilities from 40 up to 90%. Similar concerns are raised over the water requirements for concentrated solar thermal (CSP) plants. Thirty five CSP plants were reported to be negotiating water rights with regulators in the California/Nevada desert in 2011 with one plant requesting 4.9 billion liters or 20% of the water available in the local valley [34]. Other energy alternatives, such as shale gas expansion, are raising concerns due to the volume of water needed and the potential for water contamination during hydraulic fracking and gas production. A recent study indicates that water availability could curtail shale development in many places around the world, as nearly 38% of identified shale resources are in areas that are either arid or under high to extremely high levels of water stress (WRI, 2014) [27]. Public concern about the potential environmental impacts of unconventional gas production, in other countries such as Australia, Bulgaria, Canada and France, has prompted additional regulation and, in some jurisdictions, temporary bans on hydraulic fracturing [15]. In another example, the high water consumption of coal-to-liquid (CTL) plants led to dozens of planned CTL projects to be abandoned in China in 2008, due in part to concerns that they would place heavy burdens on scare water resources.

In our search to secure future energy resources and simultaneously limit carbon emission levels, water issues cannot be ignored. Integrated water and energy models will allow for the water needs of future energy strategies to be taken into consideration offering more holistically sustainable pathways.

2.3. Biofuel expansion and overexploitation of water resources

In contrast to several available options in power generation, the transport sector is dominated by oil. In 2010 the transport sector accounted for about 19% of global energy supplies (2200 Mtoe[2]) of which 96% came from oil, 1% from natural gas, 2% from biofuels and 1% from electricity. By 2050, total transport fuel demands are predicted to increase between30–82% with oil still supplying between 80% and 88%. Biofuels are expected to increase four fold (to about 176 Mtoe) reaching about 4.4% of total transport fuels while other alternate fuels including electricity, hydrogen, and natural gas will increase six to seven fold (to about 150 Mtoe) reaching between 3.2% and 3.5% of total shares [41].

According to some estimates, producing 5% of total transport fuels from biofuels in 2030 (about 165 Mtoe) could consume between 20% and 100% of the total global agricultural water use [34], raising concerns about the sustainability of the trade-offs in terms of both water consumption and land use, as food crop fields are converted to grow fuel. The IEA New Policies Scenario, estimates a three fold increase in biofuels from 2010 to 2035 leading to increases in biofuel water withdrawals from 25 bcm (4% of total 583 bcm in 2010) to 110 bcm (16% of total 690 bcm in 2035) and consumption from 12 bcm (18% of total 65 bcm in 2010) to 50 bcm (40% of total 120 bcm in 2035) [15]. A study from Spain [42] shows that increasing biofuels in the Spanish energy mix from 3% to 6% would lead to an increase of 25% in water consumption by the energy sector. It is important to note that the impacts of biofuels on water resources will depend heavily on the type of crop used and whether the crop is rain-fed or irrigated. For example, in Brazil, where most sugarcane is rain-fed, a liter of ethanol requires only 90 liters of irrigation water while in India a liter of ethanol can take up to 3500 liters of irrigation water [43].

While biofuels offer a low-carbon alternative to diversify the transport sector which is heavily dependent on oil, the corresponding impacts on water and land cannot be ignored. Integrating the water demands of biofuel production into energy models will allow for a better assessment of the where and to what extent such an alternative could be feasible, without putting other sectors such as agriculture to risk.

2.4. Water and energy decoupling issues

In many regions, including the United States, freshwater withdrawals are leveling off or peaking, leading to a concern for non-renewable sources like groundwater being exploited beyond sustainable limits [24,44]. With groundwater pumping costs primarily constituting energy consumption, energy subsidies and alternative energy sources like solar PV pumps, which decouple pumping from energy can have significant impacts.

In India, groundwater has been increasingly utilized since the 1970's. Lack of regulations on groundwater pumping limits has led to an accelerated decline in water tables from 18 cm a year in the 1980's to 75 cm a year in 2002–2006 [45]. Without regulation, energy costs are the predominant constraints to water pumping and thus the over-

[2] Million of tonnes of oil equivalent (Mtoe).

exploitation of non-renewable groundwater and corresponding increases in salinity and arsenic levels become directly related to over-subsidized electricity prices [46,47]. In other regions like Qatar, abundant energy resources and energy access allow almost unconstrained pumping of non-renewable groundwater, with about 250 million cubic meters (mcm) pumped in 2008 while recharge was only 50 mcm. Agriculture, accounting for the majority of groundwater use, provides 15% of the domestic food demand. Unchecked, further water table decreases and increasing salinity will increase dependency on imports and decrease the resilience of the national food supply against potential short, medium and long term supply disruptions [48]. Initiatives like the Sunflower Solar Steam and PV water pumps introduced in Kenya, while providing farmers with increased access to invaluable irrigation water by switching to automated pumps from the traditional manual, diesel or petrol pumps, can have serious long term risks associated with over-pumping if left unregulated [45].

While decoupling non-renewable groundwater pumping from energy constraints can lead to unsustainable practices, such an approach can be beneficial in other contexts such as desalination or solar based heating. Recognizing this opportunity, Saudi Arabia announced its initiative for solar water desalination in 2010, which aims to develop low cost solar-based desalination technology to address future water security. While desalination based on renewable energy may still be relatively expensive, costs of heat production based on solar water heaters are already competitive with electricity and gas-based heating in certain regions. In China, solar water heaters cost an estimated 3.5 times less than electric and 2.6 times less than gas heaters over the system lifetime. In 2012, gross energy savings from solar thermal energy amounted to 284.7 terawatt-hours (TWh) [27].

Without looking at both the water and energy systems together, new and cheaper technologies may prematurely seem to offer beneficial solutions. However, an integrated assessment may demonstrate that removing constraints as a result of improvements in one sector may exacerbate certain problems in the other.

2.5. Alternative water sources and corresponding energy demands

In the quest to secure future water resources, planners and policy makers are considering several alternative water sources to supplement traditional ground and surface water reserves, including desalination, water transfers, rainwater harvesting, improved efficiency and reuse. Each alternative has corresponding cost and energy implications which can be substantial in some cases and must be considered carefully.

Desalination and water transfers are the most energy intensive options. Desalination consumes from about 2 kwh/m^3 to about 6 kwh/m^3 [49–52] depending on the level of salinity of the water being processed. Worldwide, 52% of desalination capacity is in the Middle East followed by North America (16%), Europe (13%), Asia (12%), Africa (4%), Central America (3%) and Australia (0.3%). Across all these regions, the forecast is for widespread growth in desalination plants at between 12–20% annually with energy consumption being the main barrier [34]. Energy consumption in water transfers is heavily dependent on the pumping required to overcome net elevation along the transfer path (a rough range from recorded values is between 1 kwh/m^3 and 6 kwh/m^3) [53,54,52]. Groundwater pumping consumption will depend on the depth of the water table while surface water abstractions again depend on pumping and percentages of gravity fed flows. A study in California [55] analyzes the different options available to meet the state's future water demands. If energy intensive technologies like desalinization are used, the water sector could consume up to 52% of the state's entire energy budget in 2030 (up from 19% in 2009). The study shows that imported water would consume only 22% to meet the same demand. Another study from Southern California estimates the energy intensity of providing water ranges from around 0.5 kwh/m^3 for local sources and reclaimed wastewater to around 3.5 kwh/m^3 for desalinated seawater from reverse osmosis systems [34]. A study from Texas estimates that desalination and long-haul transfer is nine to twenty three times more energy-intensive per unit of water than conventional treatment of local surface water sources [52]. In the MENA regions, ignoring the additional feedback of electricity demand from future water system needs can lead to a 40% underestimate of electricity needs for 2050 [56].

Given the complex nature of abstracting and processing water and the large part that energy plays in dictating operating costs of several water processes it is essential to integrate and track energy consumption throughout the lifecycle of the water system.

2.6. Hydroelectric vulnerability to climate change

One of the most direct links in the water-energy nexus is seen in multi-purpose hydroelectric reservoirs. Changes in water availability translate directly into changes in potential energy availability and electricity prices. The impacts of droughts and water availability are especially significant in regions with a high share of hydropower, as witnessed in the 2007 record high electricity prices reached in Australia as a result of the drought-caused hydroelectric generation constraints [57]. The IEA reports several examples of the impacts of reduced water on the hydroelectric system and the corresponding impacts on other water and energy sources. In 2012 a delayed monsoon led to a simultaneous decrease in hydro generation and increased electricity demand for pumping irrigation groundwater, resulting in a two-day blackout and affecting over 600 million people. In 2011 in China, limited hydro generation along the Yangtze river due to droughts led to higher coal demand and prices [15]. In California, the share of hydropower in the energy mix dropped to 9% in 2013 as compared to the 30-year average of 14% as a result of prolonged drought conditions and leading to an increased use of natural gas plants [27]. Integrated water-energy models allow the impacts of reduced hydro energy and increased prices to be translated back into the water system. This is particularly relevant for energy consumptive technologies such as desalination where one study [57] finds a 12–18% increase in the operational costs of desalination as a result of a 25% increase in electricity prices.

Another important opportunity related to hydroelectricity is the increasing need for flexibility in energy systems to address higher penetrations of variable, non-dispatchable renewable energy technologies. A study from 2015 [58] reviews the important role of pumped-storage hydropower plants in addressing this issue by providing efficient storage and operating reserve opportunities as well as the corresponding economic impacts on ancillary service markets.

Integrated water and energy system models allow identifying and understanding the impacts of reservoir storage changes beyond the direct relationship with hydroelectric power potential. Changes in reservoir levels may impact several other users sharing the water resource as well as other energy producers and consumers. An integrated model will be able to track and evaluate the resulting complex feedbacks across both sectors.

2.7. Water temperature constraints on energy production

An increasing number of nuclear plant shutdowns, due to water shortages and temperature constraints, have been recorded across the globe [59–61] leading to possible increases in local electricity prices [57]. During a heat wave across Europe in 2003, France was forced to curtail a few of its nuclear reactors leading to an estimated €300 million increase in electricity imports [15]. In 2006 and 2007 as a result of high temperatures, nuclear plants in Michigan, Illinois and Pennsylvania were forced to reduce their outputs by up to 25% while in 2011, the Tennessee Valley Authority had to shut down one of its three reactors at its Browns Ferry Nuclear Plant for several days [15,34]. This has already led to proactive measures such as power plants seeking amendments to water temperature related regulations as well as increased investments in auxiliary cooling for discharges. The increase in climate driven water temperatures can have a significant impact on these plants with estimates showing possible capacity reductions of up to 19% [62] in Europe and up to 8 [63] to 16% [62] in the United States. There is thus a clear need for power providers to include climate change related impacts of water shortages and temperature changes.

Apart from the volumetric needs, integrating water quality and temperature constraints into energy models can be essential in characterizing the complete risks associated with changes in these parameters. Such integrated assessments will allow planners to prepare appropriately.

2.8. System efficiency and cross-sector feedbacks

In addition to the supply of resources, climate change will also impact consumption quantities and patterns including heating and cooling requirements, agricultural productivity and industrial processes [64]. Efficiency is the least resource intensive form of meeting future demands [19] and improved integrated monitoring, reporting and management can assist in achieving conservation of both water and energy to offset investments in new infrastructure projects [65]. These needs call for increased funding in data analysis and modeling to assist incorporation of water efficiency into energy planning and energy efficiency into water planning [66]. In Arizona, water conservation measures are estimated to have the potential to reduce state-wide electricity demand by 3% while energy-efficiency and renewable portfolios may reduce non-agricultural water demand by up to 15% [67].

While electricity prices are strongly linked to demands, water has traditionally been undervalued. With growing scarcity this can be a serious issue leading to over-use and depletion of non-renewable sources. A study from Arizona [67] shows that increasing the average price of water to \$3.20 per m^3 can incentivize residential water savings of 190 million m^3 (compared to 16 million m^3 under the current water price of \$1.20 per m^3). Spain, Italy and Greece are estimated to have water cost recovery levels of around 50% [68].

The role of promoting efficiency becomes even more important when we consider estimates showing the relative dominance of changes in water demands over changes in water supplies as the drivers of future water stress [69]. It highlights the role of efficiency policies in dramatically affecting future stress levels. The benefits in one sector can be carried through to other sectors and integrated analysis will allow the impacts of efficiency measures to be tracked and evaluated through both water and energy systems.

2.9. Inter sector, regional and stakeholder issues

Increased demands for scarce shared resources are intensifying the conflicts between different sectors, stakeholders and regions. In New South Wales, Australia lack of integrated governance led to severe impacts for downstream irrigators as a result of unchecked operations by the Snowy Hydro Power Plant (accused of conserving water until peak summer demand for higher electricity prices). The conflict led to government investigations and recommendations to increase environmental releases by 15% [70]. The challenges of prioritizing multi-sector demands and corresponding impacts on different segments of society were seen in Oregon in 2011, when the Bonneville Power administration declared a state of emergency to divert water reserved for preserving salmon populations in the Columbia river for energy production use [71]. The administration argued that it was necessary to avoid rolling blackouts in the state while downstream local tribes with treaty rights to the salmon protested the decision which led to the highest number of salmon deaths ever recorded. Policies which attempt to address emission reductions by biofuel substitutions need to carefully evaluate possible consequences such as increased food crop prices, when scarce water and land resources are diverted from other sectors such as agriculture [72]. A study in Uganda [73] discusses the tradeoffs between local energy demands met with biofuels and the impacts on deforestation. Given the scale of shared water resources these tradeoffs extend across borders as witnessed in several examples including the conflicts in Central Asia (where Southern Kazakhstan and Uzbekistan need to reserve water for summer irrigation, while northern Kyrgyzstan needs the water in the winter for electricity generation [73]), the Mekong River Commission conflicts in Southeast Asia [45,74] and the Indus-Water Treaty between Pakistan and India [75].

Integration by definition brings together two or more different components, inherently increasing the constraints and thereby offering solutions which may often be poorer for the individual components, but better for the overall system. This is frequently what is needed in many conflict resolution situations and points to the importance of integrated assessments as a formal process to guiding compromise across sectors, regions and multiple stakeholders.

3. Barriers to achieving water and energy integration

While the need for integrated water and energy methods becomes clearer, several challenges and barriers to achieving integration still remain. Some of the key issues are summarized below and then discussed afterwards.

1. Traditionally independent and isolated sector management.
2. Distinct spatial, temporal and physical characteristics.
3. Complementary data availability requirements.
4. Degree of model aggregation and generalization.
5. Complexity of multi-purpose reservoir topology and management.
6. Collaboration of expertise and effort.
7. Tracking changes in infrastructure and technological characteristics.
8. Uncertainty of energy and water futures

3.1. Traditionally independent and isolated sector management

"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" [66]. This attitude of an isolated approach to sector specific problems holds true across cultures and institutions including businesses, government departments, ministries and research groups [57,70,73]. Increased awareness has led to developments in integrated assessment models however, the challenge remains to translate these into national or state-level policy [76]. Over several decades, water and energy departments have developed specializations, regulatory instruments, and policy frameworks suited to the management of their corresponding resources characterized by different temporal and spatial scales as well as different stakeholders. As a result, there is often little or no incentive to initiate and pursue coordination or integration of policies across sectoral institutions [22]. Given that part of the industry is driven by the very concept of scarcity [77] the need for collaborative policymaking between public decision makers, private initiatives and others is stressed to counter special interest groups' influence over development projects.

3.2. Distinct spatial, temporal and physical characteristics

The integration of water and energy management systems requires the challenging task of harmonizing the spatial, temporal and physical differences between energy and water systems. Water is a unique renewable natural resource that is irreplaceable and difficult to move, while energy comes in a variety of forms, which may be easier and cheaper to distribute over long distances, e.g. electricity over transmission networks. Water systems can broadly be divided into water resources and water services. Water resources systems span over larger areas with internationally shared rivers and aquifers, while water services, comprising water treatment and delivery systems are usually limited to smaller areas such as cities and municipalities. Energy infrastructure, including pipelines and the power grid, usually span the entire nation or several nations. Regulation and governance of the two resources also vary across the lifecycles from larger scale national/federal legislation at the resource and production levels to smaller scale local governance at end-use and delivery levels [22]. Due to energy resource transmutability and the implications of climate change, energy policy offers more scope for global change adaptation than water, which remains a primarily local resource [78].

3.3. Complementary data availability requirements

Given the differences mentioned above, data collection across sectors at common temporal and spatial scales is a big challenge. Several studies point out to the need for finer site specific data as a major impediment to comprehensive analysis [79,80]. The number of studies on water consumption data in energy systems has been growing rapidly and poses another problem of uncertainty related to large ranges of parameter values. Some papers [81,82] synthesize the different studies into single documents. Other studies [83,84] also look at the energy consumption in water systems which is particularly difficult to generalize and quantify due to the differences in water sources (such as groundwater or surface freshwater), complexity of evaluating water quality (for different uses as well as salinity) and the efficiency of different water delivery systems [27]. Disaggregating the energy sector by water-shed boundaries rather than national or state level divisions is necessary to capture regional dependencies, since current and future water availability metrics are usually restricted to these boundaries [85]. A study by World Bank and IEA in 2015 [43] identified 21 different possible indicators to track energy-water nexus developments and found that data was either limited (only available in some countries, not open to the public or available mainly through self-reporting) or not available for all the indicators.

3.4. Degree of model aggregation and generalization

In addition to the need for more detailed and reliable data, another challenge is to find an appropriate level of accuracy when modeling each sector as aggregated representations. Refining simulations to finer temporal resolutions can result in significantly higher restrictions from constraints, owing to the fact that aggregated average values may neglect peaks [86]. An oversimplified modeling of the system could jeopardize the validity of the obtained results, as it may not capture some subtle cross-sector effects between the energy and water systems. For instance, the degree of aggregation used to represent the topology of hydro systems has a direct effect on the marginal water and energy values. In the case of using a composite representation of a whole river basin, it would not be possible to discriminate between the different marginal water values at each point of the hydro chain depending on its relative location with respect to upstream and downstream water sources (such as natural inflows at the reservoirs) and uses (such as water withdrawals for irrigation). Therefore, the geographic, technological and policy detail of the system representation needs to be carefully examined, weighing the required efforts to reach a very detailed representation against the corresponding benefits derived from such modeling.

3.5. Complexity of multi-purpose reservoir topology and management

Another key challenge in integrating the water and energy systems is managing multi-use reservoirs. The management of and relationship between hydroelectric power and water resources is critical for water-energy models. However, it poses several challenges, having to deal with multiple sectors, upstream and downstream cascading effects and opportunity costs of long-term multi-period water management. Depending on the watershed topology, reservoirs may be built with very large storage capacity and with only a few high-head plants in the river or alternatively, a hydro system can comprise many small dams and reservoirs needing coordination as a single system. A study from 2004 [87] presents a comprehensive review of both deterministic and stochastic models for optimizing the operation of cascaded multi-reservoir systems. In these models, apart from the operation of the reservoirs, it is crucial to model carefully the relationship between the output power, the water flow through the turbine, and the net head which may be expressed as:

$$P = \eta \rho q g h \quad (1)$$

where P represents the output power, η is the is the overall efficiency of the hydro plant (i.e. the product of the efficiencies of the turbine and the generator), ρ is the water density, q is the water flow, g is the acceleration of gravity, and h is the net head. Given the non-linear nature of Eq. (1), several approaches can be found in the literature to deal with this head dependency and is discussed further in Section 4.

Analyses can also include the topology of the reservoir system and details on the flows upstream, downstream and in between reservoirs. Alternatively, some models [88] use an aggregated representation of the reservoir system. In such cases it is important to evaluate and quantify the value of the information lost when aggregating the topology. Apart from the amount of water withdrawn and returned at different points in the watershed, the changes in the quality of the water being transferred should also be considered. Changes from period to period should also be tracked in order to reflect the possible shifts in future runoff patterns and demands as a result of demographic, economic and climate changes.

3.6. Collaboration of expertise and research groups

The same difficulty of expanding sector-specific regulatory regimes and independent governance structures to encompass multiple sectors, is also present in the research and scientific community (experts, modelers, researchers, etc.). Often, researchers from different disciplines are focused on just a single sector, and may be using different assumptions, timescales, coding languages, etc. To overcome this barrier, it is necessary to establish stronger connections among these groups, facilitating the development of more unified, inter-linked and integrated multi-sector assessments. In collaborative efforts like the CLEWS framework, cross-checking, validating and agreeing on common assumptions and frameworks can indeed be a big challenge often requiring considerable time which may not be feasible for certain policy making processes [89].

3.7. Tracking changes in infrastructure and technological characteristics

Another challenge also related to data aquisition is evaluating the sensitivity of models to different parameters and the consequences of changes and inaccuracies in characterizations. As mentioned before most data is limited and it is particularly difficult to track changes in existing technology upgrades. An example is tracking shifts of power plant cooling systems and the consequential changes in water withdrawals versus consumption, efficiency and costs. Changes from open loop cooling to closed-loop cooling decreases water withdrawals but increases water consumptions. These tradeoffs can be considerable, as shown in one study [90], with a three-fold increase in global water consumption (from 2005 to 2050) from switching to close-loop cooling systems and a fourfold increase when combined with carbon capture processes. Shifting from once-through systems to closed-loop cooling can decrease power plant efficiency by around 3%. In the case of dry-cooling, power plants can consume 90% less water compared to closed loop cooling towers but costs can increase by up to 16%. Efficiency of dry cooling systems can be around 10% less than once through cooling [43,91]. The nexus impacts of similar changes in other sectors such as traditional to drip irrigation technologies and residential sector energy efficient technology changes need to be evaluated.

3.8. Uncertainty of energy and water futures

In addition to the uncertainty, gaps and large ranges found in existing data sets, planners are faced with additional challenges of dealing with a wide spectrum of possible futures. Different socio-economic pathways characterized by: demographics; human development; economy and lifestyle; policies and institutions; technology; environment; and natural resources are closely linked with several future climate change scenarios which both influence and are influenced by each other [10]. The large number of possible scenarios requires complex decision making in order to reach balanced evaluations of preferential policies and strategies. This leads to another challenge for modelers and planners to create robust and dynamic solutions capable of addressing a range of possible scenarios [92].

4. Integrated water and energy modeling

One of the earliest studies on integrating water into energy models, from 1979 [93], lays out some key pillars which still hold today. These include regional disaggregation of the energy system to watershed boundaries; synergies of cross-sector policies; flexibility in end-user demands and technologies; water quality; and consideration of stochasticity in contrast to deterministic solutions. Today, it is accepted that a system's performance cannot be optimized by optimizing the performance of its subsystems taken in isolation from one another [94]. Integration of multiple sub-systems requires compatibility between them and it is important to identify the characteristics of each. Several different modeling approaches exist including Computable General Equilibrium (CGE) models, macro-econometric models, input-output models, agent-based models and partial equilibrium methods. The methodologies can be broadly divided into macroeconomic aggregated top-down approaches and disaggregated technology based bottom-up approaches. Key differences between the methods relate to the characterization of technologies in bottom-up models from a technical engineering viewpoint with associated performance and costs, while top-down models evaluate the suitability of technologies based on the shares of a given input in intermediary consumption, in the production function, and in labor, capital and other inputs [95]. Furthermore, energy and water models can be linked via hard or soft links. Hard-links require software and program code integration while soft-links usually entail data sharing. The links can be two-way or one-way at the cost of losing full feedback loops. Soft-linked models with two-way links can be very-resource intensive as a result of the iterations needed to pass data back and forth in order to reach convergence [96]. While soft-linked models can be highly disaggregated and detailed in their representation of the individual sectors, feedback loops are not necessarily closed and they are generally better suited for policy evaluation rather than policy optimization. Potential issues in model linking include differences in classifications (defining sectors, technologies and users), harmonizing time and spatial resolutions as well as compromising between optimization and simulation approaches.

The review of the models in this paper however, is not focused on the mathematical formulations but more so on the desired outputs, objectives and goals for which the models are being developed. Based on the needs and problems identified in the previous sections several models are discussed below in regards to the approaches they take in addressing these issues. Particular attention is given to how the models treat and capture the synergies and tradeoffs between the water and energy systems.

Several databases were used to search for different combinations of the keywords “water”, “energy”, “nexus”, “integrated” and “system”. Only studies and papers which discussed applications of integrated water and energy modeling for resource planning were considered. The results were filtered to exclude papers which addressed themes which were too specific, for example studies focusing on a individual processes [97–99] or those limited to particular technologies [100,101].

Some of the earliest examples of integrated water and energy management stem from the direct relationship of energy production and hydropower reservoir management. Multi-purpose reservoirs have always had to deal with managing water for energy production and other uses. Popular techniques for long term hydropower generation scheduling are stochastic dynamic programming (SDP) [102] and stochastic dual dynamic programming (SDDP) [103]. The use of one or another technique depends mainly on the “size” of the hydro system under study. The former is usually limited to reduced size hydro systems with one or a few reservoirs [87] while the latter has been successfully used for long-term generation scheduling of large size hydro and hydrothermal systems.

Additionally, the non-linear relationship of hydropower potential with the net head from Eq. (1) poses several challenges. Some methodologies represent the relationship by a family of curves that relate the output power with the water flow for a discrete number of possible net heads [104]. The main difficulty with this method is the need to know a priori the net-head value, which is a function of the upstream reservoir level, the tail race elevation and the losses in the penstock. This problem has been tackled by using an iterative procedure to update the “power-flow” curves at each iteration taking into account the information contained in previous executions [105]. Other approaches use mixed-integer linear programming [106,107] and non-linear programming [108] to address this issue. An alternative to using this direct relationship is to use an "energy-coefficient" representing the average ratio between the output power and the released water flow from the reservoirs in the system being considered. Historical data can be used to estimate these "energy-coefficient" values depending on the season of the year, and on the expected hydrological conditions.

One study [109], uses an optimization model developed in GAMS (General Algebraic Modeling System [110]) to manage the use of energy and water resources in the Aral Sea basin. The model considers five reservoirs, three water sources, two water users and a downstream release. More recently, another model [88] approaches the problem by using an aggregated equivalent energy reservoir in a coupled water-energy model for Spain and Portugal. The model studies the temporal and volumetric impacts of increases in temperatures and precipitation on the energy demand, irrigation water demand and hydroelectric-thermal coordination for future climate change scenarios. Both models do not account for water consumption in the energy sector nor the energy consumption in the water sector. In order to capture cross-sector impacts of climate change and offer more management capabilities the second paper [88] suggests several developments including: adding power plant water cooling needs; spatial disaggregation of energy and water needs at the watershed level; and increasing the power system time steps to hourly intervals.

As discussed in Sections 1 and 2 the various water-energy links play out at all stages of the water and energy lifecycles. To address these issues several models have been developed to include resource use parameters into individual sector models to track the usage of the corresponding resource.

The Center for Naval Analyses (CNA) published a paper [111] describing a new mixed-integer linear programming model of the power sector accounting for water used by thermal cooling. The paper discusses four case studies in which the model is applied to China, India, France and the US state of Texas. The main limitations of the model as discussed in the paper itself are its small size and water accounting methods. The small size means that the model represents a relatively small aggregated area which does not capture regional variations. The water accounting method is very simple and does not represent real water resource distribution or availability. Together these two limitations prevent the representation of water scarcity, the effects of climate change and water competition with other sectors.

Another model, TIAM-FR [90,112], was developed at MINES ParisTech by modifying the TIMES energy model. The model introduces a detailed representation of power plant cooling needs by including different water cooling systems as well as characteristics of water quality. The model also includes constraints to control the allowed water temperature increases around power plants. Water is considered an unlimited resource and the energy system is not limited by any physical water constraints. The authors have addressed these issues by including a representation of the water system to track energy consumptions in another case study in the MENA regions [56].

The National Renewable Energy Laboratory (NREL) published a paper [113] 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 Inter-Comparison Project 3 (CIMP3). As in the other models discussed, the energy model, ReEDS, is modified to include thermal power plant cooling water demands and constraints on water rights available to new generation capacity. 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 during operation. The main future development for the model mentioned in the report is including physical representations of the water resources.

A water-energy-climate model [114] was 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 impacts of water stress on energy systems in India and Thailand. This model is also biased towards an energy sector representation and ignores the water system infrastructure and the corresponding energy consumption and feedback loops.

Several other models have also been developed to track water use in the energy sector [115,85,116,117]. A few studies look at the broader links in water, energy and other economic sectors using methodologies like the open source Global Change Assessment Model (GCAM), input-output analysis and lifecycle analysis [81,118,70,119,120,6].

The SATIM (South African TIMES) model [121], was developed by the World Bank in collaboration with the Energy Research Center, at the University of Cape Town, for South Africa. Similar to the TIAM-FR model, the TIMES Energy model is modified to include water consumption parameters, however, without a representation of the physical water system or constraints. An additional economy-wide aspect is added to the model by linking it in an iterative manner with the E-SAGE general equilibrium model. The impacts of water scarcity are incorporated in the SATIM model as reduced energy demands to reflect increased energy price estimations due to water scarcity effects.

Using the same approach of integrating sub-models iteratively, the "Climate, Land, Energy and Water Strategies (CLEWS)" methodology has been developed as a collaboration of several institutions including KTH, FAO, IAEA, IIASA, SEI and UNDESA[3] [122,123]. SEI models, WEAP (Water Evaluation And Planning System) and LEAP (Long range Energy Alternatives Planning System) have been bundled together with other software packages like AEZ and OSeMOSYS (The Open Source Energy Modeling System) to provide tools like the "Climate, Land-use, Energy and Water strategies" (CLEWS) methodologies and the WEAP/LEAP/OSeMOSYS nexus packages. As stated by the developers [122], CLEWS is still not a fully integrated tool and current work is focused on improving existing approaches by including finer geographical coverage, minimizing data requirements, improving the temporal scope, representing multiple resources and their inter-linkages. A similar bundled model with several packages operating together in an iterative manner is the PRIMA (Platform for Regional Integrated Modeling and Analysis) model [124] developed at Pacific Northwest National Laboratory (PNNL).

[3] Royal Institute of Technology (KTH), Food and Agriculture Organization (FAO), International Atomic Energy Agency (IAEA), International Institute for Applied Systems Analysis (IIASA), Stockholm Environment Institute (SEI), UN Department for Economic and Social Affairs (UNDESA)

A model [67] has been developed which represents both the energy and water infrastructure and is 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 mandated renewables portfolio (15% of annual retail sales by renewables) and the energy efficiency standards (22% of expected electricity demand with increased energy efficiency from 2009). The energy system parameters for water consumption and withdrawal are modeled per plant type. 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 both the water and energy consumptions. The model needs to link the water system to physical water constraints such as stream flows, groundwater levels and water temperature. These impacts are studied by the authors in another paper [63].

The Brookhaven National Laboratory developed a model by modifying the MARKAL/TIMES energy models developed by the IEA to incorporate water consumption parameters. The model was used in an integrated management case study for New York City [125] to determine the least cost energy path based on perfect foresight and life-cycle costs of technologies. Water resources considered included surrounding rivers, freshwater, saline water, groundwater and precipitation. Energy and water systems were modeled for their whole lifecycles from primary resource extraction, conversion & treatment, distribution and finally waste management. Lifecycle accounting for both energy and water in both systems was a key development in this model. However, because of the small size of the case study the ability of the model to handle certain issues was not demonstrated. There was no competition for water resources in the system modeled since water for power plant cooling was delivered from a separate source. Furthermore, the water availability was modeled for annual time periods and thus could not capture seasonal variations.

A case study from 2016 [126] uses a fully coupled water-energy nexus model to study the impacts of groundwater constraints on low-carbon electricity supply strategies in Saudi Arabia. The model considers both energy and water supply, conversion and transmission. The model is both spatially and temporally disaggregated and considers seasonality at the monthly level. It also tracks both energy consumption in the water system as well as the water consumption in the energy system. Since the case study was based in Saudi Arabia with no hydroelectric power resources, the relationship between reservoirs storage and hydropower generation was not relevant, however pumped storage was modeled. Demand side management was limited because final energy and water technologies were not modeled and demands outside the energy and water sector were taken exogenously.

Another interesting methodology is a non-linear model [127] which shows the potential of an integrated power and water utility to optimize the simultaneous delivery of electrical power demand as well as a potable water demand. A study from 2013 [128] looks at the impacts of future carbon and water prices on long-run electricity planning and conclude that the system will be more sensitive to carbon prices than water prices. In a different approach a river basin-based model [129] using surface water rights, is used to evaluate the response of power plants to drought by simulating changes in reservoir storage. The authors also analyze the impacts of employing different power-plant cooling technologies in a different paper [130].

Another methodology is the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) approach [131] which uses several innovate concepts from Bioeconomics and Systems theory, such as the flow-fund model, multi-purpose grammars and impredicative loop analysis. The methodology can be used to track changes in flows and reserves or “funds” of resources across multiple socio-economic sectors and include technological, economic, social, demographic and ecological details. The methodology also accounts for different spatial and temporal dimensions defined as hierarchical levels. The methodology is very data intensive and has been applied in a few case studies for in Mauritius, South Africa and the Indian state of Punjab.

In a review of existing nexus tools IRENA concludes [27] that there is a need for some simpler tools with fewer data requirements suitable for rapid assessments. Some tools which offer relatively faster assessments are the simulation tools FORESEER [132] from the University of Cambridge and the WEF nexus tool from the Qatar Environment and Energy Research Institute (QEERI) [133]. These tools provide user-friendly online interfaces (for pre-prepared region specific models) that allow exploring changes in energy, water, food and emission flows, for different user input scenarios and parameters.

In addition to the modeling tools discussed above it is also pertinent to mention the development of two, more general and qualitative, nexus frameworks that address the larger context of the application of nexus methodologies in practice. The UNECE report from 2015 [134] on nexus assessments in transboundary basins stresses the importance of diverse stakeholder participation, capacity building and knowledge mobilization as key ingredients to uncovering benefits and opportunities in sensitive transboundary basins. It uses three cases studies in the Alazani/Ganykh, Sava River and Syr Darya basins to point out the need for establishing strong institutional platforms to allow open discussion of solutions which may be unpopular in some sectors. It reiterates the need for better inter-sectoral communication and the important role of developing and strengthening already existing economic and governance instruments across sectors as key enablers of nexus solutions. The second framework is the FAO methodology from 2014 [45] which recommends a two stage approach. The first step requires establishing a project specific nexus context involving qualitative and quantitative multi-stakeholder analysis to establish the baseline conditions and specific multi-sector goals against which the second stage policy or technological interventions can be measured. In the second stage an innovative visualization tool, using color scales combined with spider charts, is developed to assess the vulnerability of different nexus areas (water, energy, food, capital and labor) and the sustainability of each proposed intervention.

In summary, there have been several attempts to integrate water and energy models, however, developments are still ongoing and many challenges remain to be addressed. Among the models reviewed there is a tendency to focus more on energy models with water systems being under-represented and physical water resources often ignored. Recent developments [56,63,125,122,126] show that this trend is changing. There is also a need to further develop the synchronization of the spatial and temporal scales of water and energy systems as well as linking reservoir levels to future hydro-energy potentials. Water quality and temperature impacts on power plant cooling needs also need to be better represented.

5. Recommendations list

Guided by the motivation presented in Section 1, the needs for integrated assessments from Section 2, the barriers presented in Section

3 and the review of several contemporary models from Section 4, it is attempted here to collect the variety of important issues identified and compile them into a single list. The list is divided into two sub-categories: A. Individual sector issues to prepare models for integration and B. Integration elements to ensure relevant links are made. Each item is briefly discussed below summarizing the contents discussed previously:

5.1. Individual sector

Addressing the following issues will help prepare the individual energy and water system models for easier integration in the next phase.

1. Lifecycle: resource consumption occurs throughout the lifecycle of both the energy and water systems. It is important to track the entire flow of the resources in order to avoid ignoring important upstream or downstream details.
2. Multi Sector Demands: a particular purpose of developing integrated models is to help resolve the conflicting demands between multiple sectors for shared energy and water resources. Inclusion of multi-sector demands means allowing the models to regulate resource allocations to various sectors depending on the policy constraints and objectives of the planners.
3. Demand side management: resource management alone may not be sufficient to tackle the expected challenges. A large contribution to decreased emissions and demand will come from improving efficiency. This can be done by providing alternative technology options as well as using policies to change behavior. Future models should allow for an analysis of different resource delivery technologies options as well as policy constraints to limit inefficient behavior.
4. Nexus resource usage: in order to evaluate the impacts of changes in one sector on the demands in the other it is essential to track the use of each resource in the corresponding sector. This may be done by the addition of a usage parameter per resource unit processed.
5. Water Quality: unlike electricity, different uses of water are often constrained by particular water quality and temperature regulations. These regulations need to be modeled and tracked in order to evaluate whether water at a particular region and time is actually available for specific uses. Available water in the early stage of a lifecycle may become unsuitable at a later stage downstream after quality and temperature changes.

5.2. Integration modeling

This phase addresses the development of important links between the energy and water systems which allow planners to evaluate trade-offs and synergies, which would otherwise be missed.

6. Spatial Disaggregation and Synchronization: as mentioned before, water and energy, infrastructure; governance; availability; and use can vary considerably from small distributed village networks to large scale inter-continental links. With current infrastructure, water is relatively harder and more expensive to transport than energy. There is a need to represent the spatial disaggregation and overlapping of both administrative and physical boundaries of the energy and water systems.
7. Temporal Disaggregation and Synchronization: similar to spatial disaggregation, water and energy, resource regeneration; extraction; processing; delivery; and demands occur at a range of timescales from instant delivery to several years of recharge. Renewable energy intermittency as well as multi-year hydro resource management need to be modeled together and it is necessary to synchronize the time steps used for both sectors.
8. Multiuse Reservoir Hydropower Potential: it is important to evaluate the impacts of water allocation decisions, climate change and other policies on the reservoir levels and hydro-electric potential of a region. This relationship becomes more critical for regions with a high share of hydropower.
9. Water Constraints from Hydrological Model: in regions faced with water scarcity it will be essential to model the regional implications of water shortages. Linking the energy system to actual water constraints will allow optimal decisions in future energy technologies and siting.
10. Feedbacks: feedback responses from the inter-connected sectors need to be tracked by proper linking of the models. As seen earlier [56], feedbacks can lead to significant increases in overall demands and need to be explicitly addressed in order to avoid underestimating demands. This involves making outputs from one model into variable inputs into the corresponding model.
11. Global optimum: for models intended to seek optimal and efficient solutions reaching a global optimum in both sectors will be essential for maximizing efficiency. Weak and one-way links may lead to optimal solutions in a single sector, with negative consequences for the other.
12. Marginal Resource Values: temporal and spatial distribution of marginal values of water and energy will be essential for identifying critical areas and constraints.
13. Water Temperature Impacts on Power Plant Cooling: as discussed before [62], water temperature impacts can considerably reduce the power capacity of vulnerable power plants. These impacts need to be explicitly modeled in order to avoid overestimations of resources.
14. Multi-Objective Policy Constraints: policies in different sectors can be synergetic or result in unwanted consequences. Models should include outputs aimed to track and evaluate such policies in order to identify inter-sector synergies or oppositions.
15. Synchronized Future Scenarios: given the range of different socio-economic pathways and climate change scenarios, it is essential to harmonize the common data inputs and exogenous assumptions across both the sectors.

Several of the models reviewed were compared against the different criteria discussed above, to get a sense of which water and energy nexus areas have been addressed and which need more attention. As mentioned before, several databases were used to search for combinations of the keywords “water”, “energy”, “nexus”, “integrated” and “system”. The results were further filtered to exclude studies that were too specific or limited to particular processes or technologies. Only studies with details regarding their modeling methodologies were included in this analysis. The final selection of models analyzed in Table 1 was not intentionally biased towards any particular field or sector. The relevance of the models to the different nexus integration areas, was done using a simple three point scale which represents the subjective view point of the authors. Furthermore, the scores are given based solely on the material reviewed in the referenced papers for each model. The models may address more or less areas in other papers. The comparison is meant only as a rough indication of which areas are currently being addressed in connection with the water-energy nexus. The comparison of the models is shown in Table 1 and Fig. 1. For each criterion, each model was given a score of between 0 and 2; 0 indicating the criterion is not addressed in the cited study; 1 meaning the study alludes to the issue but may not have addressed

Table 1
Water-energy integrated modeling areas addressed in selected papers.

	Individual system									**Integrated System**								
	Energy				Water					Harmonization			Model Links		Outputs		Future impacts	
	Lifecycle	Multi-sector demands	Demand side management	Water consumption	Lifecycle	Multi-sector demands	Demand side management	Energy consumption	Water quality	Spatial disaggregation	Temporal disaggregation	Hydropower potential	Hydrological model constraints	Feedback tracking	Global optimum	Marginal resource values	Wat Temp impacts on pplants	Multi-objective constrain
Antipova 2002 [109]	0	2	0	0	0	2	1	0	0	2	2	2	1	0	1	1	0	1
Bartos 2014 [67]	2	2	2	2	1	2	2	2	0	2	1	2	0	2	2	2	0	2
Bhatt Wat-MARKAL 2008 [125]	2	2	2	2	2	2	2	2	2	1	1	0	2	2	2	2	0	2
Bhattacharya MESSAGE 2013 [114]	2	2	1	2	1	2	1	0	0	2	1	0	2	0	0	1	0	1
Buras 1979 [93]	2	2	0	2	0	2	1	0	1	2	1	0	2	0	1	1	0	2
Cameron 2014 [115]	2	2	2	2	0	0	0	0	1	0	0	0	0	0	0	1	0	1
CLEWS [122,123]	2	2	2	2	2	2	2	1	1	2	2	2	2	1	1	1	0	2
CNA 2014 [111]	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Hejazi 2014 [118]	2	2	2	2	0	2	2	0	0	0	0	0	0	0	1	2	0	1
NREL ReEDS 2014 [113]	0	1	0	2	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Parkinson 2016 [126]	2	2	0	2	2	2	0	2	2	2	2	1	2	2	2	2	0	2
Pereira-Cardenal 2014 [88]	1	0	0	0	0	1	1	0	0	1	2	2	1	0	1	2	0	1
ReEDS 2012 [85]	0	1	1	2	0	0	0	0	0	2	0	0	0	0	0	0	0	1
SATIM 2013 [121]	2	2	2	2	0	0	0	0	0	0	0	0	0	0	0	1	0	1
TIAM-FR 2012 [90,112]	2	2	2	2	0	0	0	0	2	0	0	0	0	0	0	1	2	1
TIAM-FR Wat 2013 [56]	2	2	2	2	2	2	2	2	2	0	0	0	2	2	2	1	2	2
Total	**23**	**26**	**18**	**28**	**10**	**19**	**13**	**10**	**11**	**16**	**12**	**9**	**14**	**9**	**13**	**19**	**4**	**22**

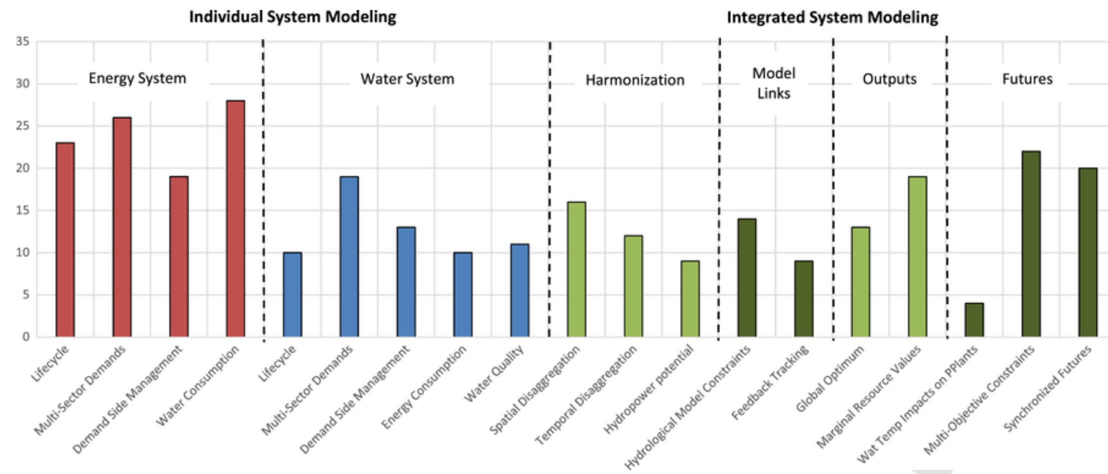

Fig. 1. Water-energy integrated modeling areas addressed in selected papers.

the issue in the particular study reviewed; and 2 indicating that the study has directly addressed the criterion.

As seen in Table 1 and Fig. 1, amongst the papers reviewed, there is a bias to focus more on the energy sector. Many models which are being developed for integrated analysis have included water consumption in their energy models and are now capable of accounting for the amount of water consumed by the energy sector. However, most models do not build further links of the energy model with temporal and spatial physical water availability. Energy models unconstrained by water limits cannot react to water shortages and may thus be inadequate for integrated analysis in critical situations.

The areas least addressed were: the representation of the full lifecycle of the water systems and processes such as water abstraction, purification and delivery; energy consumption parameters for the water system; representing the dynamic relationship of hydropower potential and other uses of water in multi-purpose reservoirs; complete feedback links between the water and energy systems; water quality; and the impacts of future water temperatures on expected power plant capacity. Another area also needing attention was representing and allowing more flexibility in water and energy end-use technologies in order to represent demand-side management, a key area to improve efficiency.

6. Limitations and further work

While it was attempted to include a range of papers from the many different areas and disciplines representing the water-energy nexus, it is acknowledged that not all the issues have been covered here. While it is clear that water and energy are highly interdependent, they also have strong dynamic links with many other sectors including but not limited to agriculture, land use, environment, climate change, industry, politics and international relations. Depending on the detail required and resources available several other issues may be added to the list presented in Section 5 as well as several other models and papers included in the comparisons made in Table 1. Further work can include identification of other secondary sectors related to the water-energy nexus and extend the methodology by creating further links between the relevant segments.

7. Conclusion

It is clear that water and energy are key interdependent resources shared across sectors and regions. The issues of water and energy shortage with increasing demands are predicted to escalate in the next few decades and to avoid serious consequences action is needed now. Traditional methods of managing water and energy systems independently can lead to management decisions which are wasteful and expensive. For optimal allocation of the resources and to maximize co-benefits it is essential to consider water and energy as one interdependent system. A popular approach to addressing the water-energy nexus has been to take an already existing energy system and modify it to account for water consumption. This has led to several energy models with water use parameters which calculate the amount of water needed by the energy system for the period analyzed. However, few models exist in which physical water availability is treated as a constraint to power production. Even fewer models include a representation of the water infrastructure system and corresponding energy use in the water abstraction, treatment and distribution phases. The addition of energy use by the water system and the physical constraints of water availability will be essential in capturing feedback implications and realistic inter-sector dependencies of water-energy nexus systems.

Given the predictions for future climate change scenarios, population increases and consumption trends there is an urgent need to develop fully integrated applicable models which consider together, both energy capacity and water resource availability constraints, as well as water and energy demands. A key recommendation based on this literature review is the need to synchronize energy and water systems to the appropriate resolutions both spatially and temporally. Given the regional constraints and characteristics of water it is particularly important to disaggregate energy to watershed boundaries. Similarly, ignoring temporal variations can lead to misestimating resource availability during certain months as a result of averaging.

Other recommendations include the need to better evaluate and track the flows of water quality, both physical and in terms of temperature. It is important to relate possible water temperature changes to future power plant capacity as the impacts can be significant. Furthermore, degraded water quality passing through a process may become unsuitable for downstream water users and this reduction needs to be accounted for. It is important to capture the feedback processes between the water and energy systems to account for important increases in cross-sectors demands from investments in technologies such as desalination or biofuels. Another key relationship to assess is the link between potential hydropower capacity and water reserved for other uses in multi-purpose reservoirs. This relationship becomes even more critical in the context of climate change and variations in expected precipitation and runoff patterns.

It is important to realize that the institutions involved in water and energy planning have developed independently over many decades with complicated and intricate sector specific methodologies, instruments and frameworks firmly in place. Given the large number of stakeholders involved at all levels of society means the transformation from isolated single sector thinking to a joint integrated structure will require much more than simply linking models. Further research and investigation will be crucial in documenting and providing the evidence needed to raise awareness of the changes required. The real challenge will lie in translating these issues into political systems, regulations and governance. The increasing number of studies, projects and events at international political forums, scientific institutions and multilateral organizations concerning sustainability, integrated systems and holistic approaches is an encouraging indicator of moving in the right direction. It is clear that integrated, holistic management approaches will be the key to sustain the kinds of lifestyle patterns and population increases that are predicted in the face of diminishing natural resources and climate change.

Acknowledgements

The study was funded by the Education, Audiovisual and Culture Executive Agency (EACEA) of the European Commission as part of the Erasmus Mundus Joint Doctorate in Sustainable Energy Technologies and Strategies (SETS). The authors would also like to acknowledge the support of the Fundación Canal, Spain as well as the support provided by the International Institute for Applied Systems Analysis (IIASA) during the Young Scientist Summer Program (YSSP). Thanks also to Simon Parkinson (IIASA) for his valuable inputs.

References

[1] Malik K, et al. Human development report 2014. Sustaining human progress: Reducing vulnerabilities and building resilience. United Nations Development Programme (UNDP), New York, NY; 2014. URL ⟨http://hdr.undp.org/sites/default/files/hdr14-report-en-1.pdf ⟩

[2] The Millennium Development Goals Report 2014, United Nations Department of Economic and Social Affairs (UNDESA), Statistics Division, New York, NY; 2014. URL ⟨http://www.un.org/millenniumgoals/2014%20MDG%20report/MDG%202014%20English%20web.pdf⟩

[3] World Development Indicators 2014, World Bank Group, Washington, DC, 2014, license: Creative Commons Attribution CC BY 3.0 IGO. http://dx.doi.org/10.1596/978-1-4648–0163-1. URL ⟨http://data.worldbank.org/sites/default/files/wdi-2014-book.pdf ⟩

[4] Ki-Moon B. The road to dignity by 2030: ending poverty, transforming all lives and protecting the planet. Synthesis report of the secretary-general on the post-2015 agenda. New York, United Nations. Accessed 24.12.14.

[5] M. Howells, H.-H. Rogner, Water-energy nexus assessing integrated systems, Nat. Clim. Change 4 (4) (2014) 246–247.

[6] W.N. Lubega, A.M. Farid, Quantitative engineering systems modeling and analysis of the energy-water nexus, Appl. Energy 135 (2014) 142–157.

[7] United Nations World Water Assessment Programme (WWAP), The United Nations World Water Development Report 2015: Water for a Sustainable World, United nations Educational, Scientific and Cultural Organization (UNESCO), Paris, France; 2016. iSBN: 978-92-3-100146-8. URL ⟨http://unesdoc.unesco.org/images/0024/002439/243938e.pdf ⟩

[8] International Energy Agency (IEA), World Energy Outlook 2015, OECD/IEA 2015; 2015.

[9] A. Jerneck, L. Olsson, A smoke-free kitchen initiating community based co-production for cleaner cooking and cuts in carbon emissions, J. Clean. Prod. 60 (2013) 208–215.

[10] O'Neill BC, Kriegler E, Ebi KL, Kemp-Benedict E, Riahi K, Rothman DS, van Ruijven BJ, van Vuuren DP, Birkmann J, Kok K, et al. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environmental Change.

[11] United Nations World Water Assessment Programme (WWAP), The United Nations World Water Development Report 2015: Water for a Sustainable World, United nations Educational, Scientific and Cultural Organization (UNESCO), Paris, France; 2015. iSBN: 978-92-3-100071-3. URL ⟨http://unesdoc.unesco.org/images/0023/002318/231823E.pdf ⟩

[12] United Nations Department of Economic and Social Affairs (UNDESA) Population Division. World population prospects. The 2015 revision, key findings and advance tables, UNDESA, eSA/P/WP.241; 2015. URL ⟨http://esa.un.org/unpd/wpp/Publications/Files/Key_Findings_WPP_2015.pdf ⟩

[13] Gleick pH, Ajami N, et al. The World's Water Volume 8: the Biennial Report on Freshwater Resources, vol. 8. Island Press; 2014.

[14] IPCC. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA; 2014. URL ⟨https://ipcc-wg2.gov/AR5/images/uploads/WGIIAR5-PartA_FINAL.pdf ⟩

[15] International Energy Agency (IEA), Chapter 17: Water for energy. Is energy becoming a thirstier resource. In: World Energy Outlook 2012, Organization for Economic Cooperation & Development (OECD); 2012. URL ⟨http://www.worldenergyoutlook.org/media/weowebsite/2012/WEO_2012_Water_Excerpt.pdf⟩

[16] International Energy Agency (IEA), World Energy Outlook 2012, OECD/IEA 2012; 2012.

[17] Hardy L, Garrido A. Challenges and opportunities related to the Spanish water energy nexus, vol. 6. Taylor & Francis Group, Londres; 2010. “Análisis y evaluación de las relaciones entre el agua y la energía en España”, Papeles de Agua Virtual, N; 2012.

[18] A. Siddiqi, L.D. Anadon, The water-energy nexus in middle East and North Africa, Energy Policy 39 (8) (2011) 4529–4540.

[19] Klein G, Krebs M, Hall V, O'Brien T, Blevins B. California's water-energy relationship. California Energy Commission.

[20] United States Department of Energy (USDOE). Energy demands on water resources: report to congress on the interdependency of energy and water, Washington DC.

[21] Rodriguez DJ, Delgado A, DeLaquil P, Sohns A. Thirsty energy. Tech rep; 2013. URL ⟨http://www.dun-eumena.com/reagri/upload/files/789230WP0Box377361B00PUBLIC0.pdf ⟩

[22] United Nations World Water Assessment Programme (WWAP), United Nations World Water Development Report 2014: Water and Energy, United Nations Educational, Scientific and Cultural Organization (UNESCO); 2014. URL ⟨http://unesdoc.unesco.org/images/0022/002257/225741e.pdf ⟩

[23] Thinking about water differently: managing the water-food-energy nexus. Asian Development Bank (ADB); 2013. URL ⟨http://adb.org/sites/default/files/pub/2013/thinking-about-water-differently.pdf ⟩

[24] US Department of Energy (USDOE). The water energy nexus: challenges and opportunities, USDOE; 2014. URL ⟨http://energy.gov/sites/prod/files/2014/07/f17/Water%20Energy%20Nexus%20Full%20Report%20July%202014.pdf⟩

[25] World Business Council for Sustainable Development (WBCSD). Water, food and energy nexus challenges. World Business Council for Sustainable Development (WBCSD); 2014. URL ⟨http://www.gwp.org/Global/ToolBox/References/Water,%20Food%20and%20Energy%20Nexus%20Challenges%20(WBCSD,%202014).pdf⟩

[26] World Resources Institute (WRI), Water-energy nexus. Business risks and rewards. WRI; 2016. URL ⟨https://www.ge.com/sites/default/files/Water-Energy_Nexus_Business_Risks_and_Rewards.pdf⟩

[27] International Renewable Energy Agency (IRENA). Renewable energy in the water, energy and food nexus. IRENA; 2015. URL ⟨http://www.irena.org/documentdownloads/publications/irena_water_energy_food_nexus_2015.pdf⟩

[28] Dodds F, Bartram J. The water, food, energy and climate nexus: challenges and an agenda for action. Routledge; 2016.

[29] Biberacher M, Gadocha S. Final report. Global energy scenarios. Analysis of thematic emphasis, main drivers and communication strategies. European Fusion Development Agreement, wP12-SER-ETM; 2015. URL ⟨https://www.euro-fusion.org/wpcms/wp-content/uploads/2015/02/ETM_WP12_GS_FINAL.pdf⟩

[30] International Energy Agency (IEA). World Energy Outlook 2013, OECD/IEA 2013; 2013.

[31] International Energy Agency (IEA), World energy model documentation 2015. IEA, accessed: 2016-04-05; 2015. URL ⟨http://www.worldenergyoutlook.org/media/weowebsite/2015/WEM_Documentation_WEO2015.pdf⟩

[32] International Energy Outlook. Report number: DOE/EIA-0484(2013). Tech rep; 2013. URL ⟨http://www.eia.gov/forecasts/archive/ieo13/electricity.cfm ⟩

[33] Delgado Martín A. Water footprint of electric power generation: modeling its use and analyzing options for a water-scarce future. Master's thesis. Massachusetts Institute of Technology; 2012.

[34] World Economic Forum (WEF) Water Initiative and others, Water security: the water-food-energy-climate nexus. Island Press; 2011.

[35] Khan Z, Linares P, García-González J. Adaptation to climate-induced regional water constraints in the Spanish energy sector: an integrated assessment. Institue for research in Technology (IIT) Universidad Pontificia Comillas de Madrid, working Paper no: IIT-16-075A; 2016.

[36] IPCC. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Geneva, Switzerland; 2014. URL ⟨http://ar5-syr.ipcc.ch/ipcc/ipcc/resources/pdf/IPCC_SynthesisReport.pdf ⟩

[37] World Bank, Turn down the heat: Why a 4 deg C warmer world must be avoided. International Bank for Reconstruction and Development. The World Bank; 2012. URL ⟨https://openknowledge.worldbank.org/handle/10986/11860 ⟩

[38] Bates B, Kundzewicz ZW, Wu S, Palutikof J. Climate change and water: Technical Paper vi. Intergovernmental Panel on Climate Change (IPCC); 2008. URL ⟨http://ipcc.ch/pdf/technical-papers/climate-change-water-en.pdf ⟩

[39] United Nations Framework Convention on Climate Change (UNFCCC). Aggregate effect of the intended nationally determined contributions: an update Synthesis report by the secretariat, UNFCCC (2016). URL ⟨http://unfccc.int/resource/docs/2016/cop22/eng/02.pdf ⟩

[40] Levin K, Fransen T. INSIDER: Why Are INDC Studies Reaching Different Temperature Estimates?, World Resource Institute (WRI), accessed: 11 May 2016 (2016). URL ⟨http://www.wri.org/blog/2015/11/insider-why-are-indc-studies-reaching-different-temperature-estimates⟩

[41] World Energy Council (WEC), Global Transport Scenarios 2050, WEC; 2011. URL ⟨https://www.worldenergy.org/wp-content/uploads/2012/09/wec_transport_scenarios_2050.pdf⟩

[42] A.M.R. Carrillo, C. Frei, Water a key resource in energy production, Energy Policy 37 (11) (2009) 4303–4312.

[43] International Bank for Reconstruction and Development (The World Bank), International Energy Agency (IEA), Progress toward sustainable energy 2015, Global tracking framework report, World Bank/IEA 2015; 2015.

[44] P.H. Gleick, M. Palaniappan, Peak water limits to freshwater withdrawal and use, Proc. Natl. Acad. Sci. 107 (25) (2010) 11155–11162. URL ⟨http://www.pnas.org/content/107/25/11155.full.pdf⟩.

[45] Flammini A, Puri M, Pluschke L, Dubois O. Walking the nexus talk: assessing the water-energy-food nexus in the context of the sustainable energy for all initiative, FAO; 2014.

[46] R. Malik, Water-energy nexus in resource-poor economies the indian experience, Int. J. Water Resour. Dev. 18 (1) (2002) 47–58.

[47] A. Mukherji, The energy-irrigation nexus and its impact on groundwater markets in eastern indo-gangetic basin evidence from West Bengal, India, Energy Policy 35 (12) (2007) 6413–6430.

[48] Linke P. On the development of strategies for water and energy management in the context of the water-energy-food nexus. In: Proceedings of the 8th international conference on foundations of computer-aided process design, vol. 34. Elsevier; 2014. p. 196.

[49] X. Bernat, O. Gibert, R. Guiu, J. Tobella, C. Campos, The economics of desalination for various uses, in: L. Martínez-Cortina, A. Garrido, E. Lopez-Gunn (Eds.), Re-thinking water and food security, CRC Press, Leiden, The Netherlands, 2010, pp. 329–346. Ch. 18.

[50] Koschikowski J. Water desalination: When and where will it make sense. Fraunhofer Institute for Solar Energy Systems ISE Freiburg; Germany.

[51] Encyclopedia of Desalination and Water Resources (DESWARE), Energy requirements of desalination processes. ⟨http://www.desware.net/desa4.aspx⟩, accessed: 2015-12-24.

[52] A.S. Stillwell, C.W. King, M.E. Webber, Desalination and long-haul water transfer as a water supply for dallas, texas a case study of the energy-water nexus in texas, Tex. Water J. 1 (1) (2010) 33–41.

[53] Ministerio de Agricultura, Alimentación y Medio Ambiente, Gobierno de España, Planes Hidrológicos Nacional; 2000. URL ⟨https://www.chsegura.es/chs/planificacionydma/planhidrologiconacional/phn/ ⟩

[54] I. Muñoz, L. Milà-i Canals, A.R. Fernández-Alba, Life cycle assessment of water supply plans in mediterranean spain, J. Ind. Ecol. 14 (6) (2010) 902–918.

[55] J.R. Stokes, A. Horvath, Energy and air emission effects of water supply, Environ. Sci. Technol. 43 (8) (2009) 2680–2687.

[56] A. Dubreuil, E. Assoumou, S. Bouckaert, S. Selosse, N. Maı, et al., Water modeling in an energy optimization framework-the water-scarce middle east context, Appl. Energy 101 (2013) 268–279.

[57] Head B, Cammerman N. The water-energy nexus: a challenge for knowledge and policy. The University of Queensland; 2010.

[58] J.I. Pérez-Díaz, M. Chazarra, J. García-González, G. Cavazzini, A. Stoppato, Trends and challenges in the operation of pumped-storage hydropower plants, Renew. Sustain. Energy Rev. 44 (2015) 767–784.

[59] Water shortages slow energy production worldwide. Renewable Energy Magazine; 2014. URL ⟨http://www.renewableenergymagazine.com/article/water-shortages-slow-energy-production-worldwide-20140120⟩

[60] 4 Ways Water is Connected to India's Blackouts. World Resources Institute Blogs: Robert Kimball; 2014. URL ⟨http://www.wri.org/blog/4-ways-water-connected-indias-blackouts ⟩

[61] Water scarcity forces shutdown of 4 RTPS units, Deccan Herald; 2014. URL ⟨http://www.deccanherald.com/content/244325/water-scarcity-forces-shutdown-4.html⟩

[62] M.T. van Vliet, J.R. Yearsley, F. Ludwig, S. Vögele, D.P. Lettenmaier, P. Kabat, Vulnerability of US and European electricity supply to climate change, Nat. Clim. Change 2 (9) (2012) 676–681.

[63] Bartos MD, Chester MV. Impacts of climate change on electric power supply in the western united states. Nature Climate Change.

[64] Wilbanks T, Bhatt V, Bilello D, Bull S, Ekmann J, Horak W, Huang Y, Levine M, Sale M, Schmalzer D, et al. Effects of climate change on energy production and use in the United States, synthesis and assessment product 4.5 br; 2008.

[65] Maas C. Ontario's water-energy nexus: will we find ourselves in hot water–or tap into opportunity?, POLIS Project on Ecological Governance; 2010.

[66] The water energy nexus in Utah: Meeting the water and energy challenges. Tech rep; 2012. URL ⟨http://www.water.utah.gov/OtherReports/Water%20Energy%20Nexus%20in%20Utah.pdf⟩

[67] M.D. Bartos, M.V. Chester, The conservation nexus: valuing interdependent water and energy savings in arizona, Environ. Sci. Technol. 48 (4) (2014) 2139–2149.

[68] European Environment Agency (EEA), Assessment of cost recovery through water pricing, EEA, iSSN 1725–2237, Technical report No. 16/2013; 2013. Accessed: 18.03.16. URL ⟨http://www.eea.europa.eu/publications/assessment-of-full-cost-recovery ⟩

[69] Luck M, Landis M, Gassert F. Aqueduct water stress projections: decadal projections of water supply and demand using CMIP5 GCMs. World Resources Institute (WRI); 2015. URL ⟨http://www.wri.org/sites/default/files/aqueduct-water-stress-projections-technical-note.pdf⟩

[70] Marsh DM. The water-energy nexus: a comprehensive analysis in the context of new south wales. pH.D. thesis, University of Technology, Sydney; 2008.

[71] D. Lofman, M. Petersen, A. Bower, Water, energy and environment nexus: the California experience, Int. J. Water Resour. Dev. 18 (1) (2002) 73–85.

[72] Pate R, Hightower M, Cameron C, Einfeld W. Overview of energy-water interdependencies and the emerging energy demands on water resources. Tech rep. Report: SAND 2007-1349C; 2007. URL ⟨http://www.circleofblue.org/waternews/wp-content/uploads/2010/09/SANDIA-research-needs2007-1349C_revised.pdf⟩

[73] M. Bazilian, H. Rogner, M. Howells, S. Hermann, D. Arent, D. Gielen, P. Steduto, A. Mueller, P. Komor, R.S. Tol, et al., Considering the energy, water and food nexus towards an integrated modelling approach, Energy Policy 39 (12) (2011) 7896–7906.

[74] T.V.H. Le, H.N. Nguyen, E. Wolanski, T.C. Tran, S. Haruyama, The combined impact on the flooding in vietnam's mekong river delta of local man-made structures, sea level rise, and dams upstream in the river catchment, Estuar. Coast. Shelf Sci. 71 (1) (2007) 110–116.

[75] Mehta JS. The indus water treaty: a case study in the resolution of an international river basin conflict. In: Natural resources forum, vol. 12. Wiley Online Library; 1988. p. 69–77.

[76] M. Howells, H.-H. Rogner, Water-energy nexus assessing integrated systems, Nat. Clim. Change 4 (4) (2014) 246–247.

[77] C.A. Scott, M.J. Pasqualetti, Energy and water resources scarcity critical infrastructure for growth and economic development in arizona and sonora, Nat. Resour. J. 50 (2010) 645.

[78] C.A. Scott, S.A. Pierce, M.J. Pasqualetti, A.L. Jones, B.E. Montz, J.H. Hoover, Policy and institutional dimensions of the water–energy nexus, Energy Policy 39 (10) (2011) 6622–6630.

[79] K. Hussey, J. Pittock, et al., The energy–water nexus managing the links between energy and water for a sustainable future, Ecol. Soc. 17 (1) (2012) 31. URL ⟨http://www.ecologyandsociety.org/vol17/iss1/art31/⟩.

[80] Stillwell AS, King CW, Webber ME, Duncan IJ, Hardberger A. The energy-water nexus in texas.

[81] E.G. Davies, P. Kyle, J.A. Edmonds, An integrated assessment of global and regional water demands for electricity generation to 2095, Adv. Water Resour. 52 (2013) 296–313.

[82] J. Meldrum, S. Nettles-Anderson, G. Heath, J. Macknick, Life cycle water use for electricity generation a review and harmonization of literature estimates, Environ. Res. Lett. 8 (1) (2013) 015031.

[83] Thirlwell GM, Madramootoo CA, Heathcote IW. Energy-water nexus: energy use in the municipal, industrial, and agricultural water sectors. In Canada-US Water Conf; 2007.

[84] A. Plappally, et al., Energy requirements for water production, treatment, end use, reclamation, and disposal, Renew. Sustain. Energy Rev. 16 (7) (2012) 4818–4848.

[85] J. Macknick, S. Sattler, K. Averyt, S. Clemmer, J. Rogers, The water implications of generating electricity water use across the united states based on different electricity pathways through 2050, Environ. Res. Lett. 7 (4) (2012) 045803.
[86] H. Koch, S. Vögele, Hydro-climatic conditions and thermoelectric electricity generation–part I development of models, Energy 63 (2013) 42–51.
[87] J.W. Labadie, Optimal operation of multireservoir systems state-of-the-art review, J. Water Resour. Plan. Manag. 130 (2) (2004) 93–111.
[88] S.J. Pereira-Cardenal, H. Madsen, K. Arnbjerg-Nielsen, N. Riegels, R. Jensen, B. Mo, I. Wangensteen, P. Bauer-Gottwein, Assessing climate change impacts on the Iberian power system using a coupled water-power model, Clim. Change 126 (3–4) (2014) 351–364.
[89] Welsch M. Enhancing the treatment of systems integration in long-term energy models. KTH Royal Institute of Technology, doctoral Thesis; 2013.
[90] S. Bouckaert, E. Assoumou, S. Selosse, N. Maïzi, A prospective analysis of waste heat management at power plants and water conservation issues using a global times model, Energy 68 (2014) 80–91.
[91] Littleton D, McGurl G, Feeley T, Shelton W, Parsons E, Smith D, Gross R, Veil J. Energy penalty analysis of possible cooling water intake structure requirements on existing coal-fired power plants. NETL,DOE/OFE and Argonne National Laboratory Report; 2002. URL ⟨http://www.veilenvironmental.com/publications/pp/ANL-EnergyPenaltyReport.pdf ⟩
[92] S.C. Parkinson, N. Djilali, Robust response to hydro-climatic change in electricity generation planning, Clim. Change 130 (4) (2015) 475–489.
[93] Buras N. Determining the feasibility of incorporating water resource constraints into energy models. Final report, Tech rep, Stanford Univ., CA (USA). Dept. of Operations Research; 1979.
[94] B. Newell, D.M. Marsh, D. Sharma, Enhancing the resilience of the australian national electricity market taking a systems approach in policy development, Ecol. Soc. 16 (2) (2011) 15.
[95] IPCC. Climate change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA; 2014. URL ⟨http://www.ipcc.ch/report/ar5/wg3/⟩
[96] Pollitt H, Barker A, Barton J, Pirgmaier E, Polzin C, Lutter S, Hinterberger F, Stocker A. A scoping study on the macroeconomic view of sustainability. Final report for the European Commission, DG Environment. Tech rep; 2010. URL ⟨http://ec.europa.eu/environment/enveco/studies_modelling/pdf/sustainability_macroeconomic.pdf⟩
[97] Murphy CF, Allen DT. Energy-water nexus for mass cultivation of algae, environmental science and technology; 2011, 45(13): p. 5861–8.
[98] Ormsbee LE, Lansey KE. Optimal control of water supply pumping systems. Journal of Water Resources Planning and Management.
[99] T.M. Jackson, S. Khan, M. Hafeez, A comparative analysis of water application and energy consumption at the irrigated field level, Agric. Water Manag. 97 (10) (2010) 1477–1485.
[100] X. Li, K. Feng, Y.L. Siu, K. Hubacek, Energy-water nexus of wind power in China the balancing act between CO_2 emissions and water consumption, Energy Policy 45 (2012) 440–448.
[101] J. Gao, F. You, Optimal design and operations of supply chain networks for water management in shale gas production Milfp model and algorithms for the water-energy nexus, AIChE J. 61 (4) (2015) 1184–1208.
[102] J.R. Stedinger, B.F. Sule, D.P. Loucks, Stochastic dynamic programming models for reservoir operation optimization, Water Resour. Res. 20 (11) (1984) 1499–1505.
[103] M. Pereira, L. Pinto, Stochastic optimization of a multireservoir hydroelectric system: a decomposition approach, Water Resour. Res. 21 (6) (1985) 779–792.
[104] Wood AJ, Wollenberg B. Power generation operation and control, 2nd edition. In: Fuel and energy abstracts, vol. 3; 1996. p. 195.
[105] J. García-González, E. Parrilla, A. Mateo, Risk-averse profit-based optimal scheduling of a hydro-chain in the day-ahead electricity market, Eur. J. Oper. Res. 181 (3) (2007) 1354–1369.
[106] A.J. Conejo, J.M. Arroyo, J. Contreras, F.A. Villamor, Self-scheduling of a hydro producer in a pool-based electricity market, Power Syst. IEEE Trans. 17 (4) (2002) 1265–1272.
[107] A. Borghetti, C. D'Ambrosio, A. Lodi, S. Martello, An milp approach for short-term hydro scheduling and unit commitment with head-dependent reservoir, Power Syst., IEEE Trans. 23 (3) (2008) 1115–1124.
[108] J. Catalao, S. Mariano, V. Mendes, L. Ferreira, Scheduling of head-sensitive cascaded hydro systems a nonlinear approach, Power Syst., IEEE Trans. 24 (1) (2009) 337–346.
[109] E. Antipova, A. Zyryanov, D. McKinney, A. Savitsky, Optimization of syr darya water and energy uses, Water Int. 27 (4) (2002) 504–516.
[110] Brooke A, Kendrick D, Meeraus A, Raman R. The general algebraic modeling system; GAMS Development Corporation.
[111] Faeth P, Sovacool BK, Thorkildsen Z, Rao A, Purcell D, Eidness J, Johnson K, Thompson B, Imperiale S, Gilbert A. A clash of competing necessities: water adequacy and electric reliability in China, India, France, and Texas, CNA Research Memorandum.
[112] S. Bouckaert, S. Selosse, E. Assoumou, A. Dubreuil, N. Maïzi, Analyzing water supply in future energy systems using the times integrating assessment model (tiam-fr), J. Syst. Cybern. Inform. 10 (1) (2012) 89–94.
[113] Cohen SM, Macknick J, Averyt K, Meldrum J. Modeling climate-water impacts on electricity sector capacity expansion. In: ASME 2014 Power Conference, American Society of Mechanical Engineers; 2014. pp. V002T10A007-V002T10A007.
[114] Bhattacharya A, Mitra BK. Water availability for sustainable energy policy: assessing cases in South and South East Asia. IGES Research Report 2013-01. Tech rep; 2013. URL ⟨http://pub.iges.or.jp/modules/envirolib/upload/4836/attach/IGES_Research__Report_2013-01_Water_energy_nexus.pdf ⟩
[115] C. Cameron, W. Yelverton, R. Dodder, J.J. West, Strategic responses to CO_2 emission reduction targets drive shift in us electric sector water use, Energy Strategy Rev. 4 (2014) 16–27.
[116] A.T. Dale, M.M. Bilec, The Regional Energy and Water Supply Scenarios (REWSS) model, Part I Framework, procedure, and validation, Sustain. Energy Technol. Assess. 7 (2014) 227–236.
[117] Y. Qin, E. Curmi, G.M. Kopec, J.M. Allwood, K.S. Richards, China's energy-water nexus–assessment of the energy sector's compliance with the “3 red lines” industrial water policy, Energy Policy 82 (2015) 131–143.
[118] M. Hejazi, J. Edmonds, L. Clarke, P. Kyle, E. Davies, V. Chaturvedi, M. Wise, P. Patel, J. Eom, K. Calvin, et al., Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework, Technol. Forecast. Soc. Change 81 (2014) 205–226.
[119] Marsh D, Sharma D. A framework for assessing integrated water and energy management scenarios; 2007.
[120] D. Perrone, J. Murphy, G.M. Hornberger, Gaining perspective on the water-energy nexus at the community scale, Environ. Sci. Technol. 45 (10) (2011) 4228–4234.
[121] Rodriguez DJ. Quantifying the tradeoffs of the water energy nexus. World Bank, World Water Week 2013, Stockholm; 2013. URL ⟨http://www.wsp.org/sites/wsp.org/files/publications/Water-and-Energy-World-Bank-SIWI2013.pdf⟩
[122] M. Welsch, S. Hermann, M. Howells, H.H. Rogner, C. Young, I. Ramma, M. Bazilian, G. Fischer, T. Alfstad, D. Gielen, et al., Adding value with clews–modelling the energy system and its interdependencies for Mauritius, Appl. Energy 113 (2014) 1434–1445.
[123] M. Howells, S. Hermann, M. Welsch, M. Bazilian, R. Segerström, T. Alfstad, D. Gielen, H. Rogner, G. Fischer, H. van Velthuizen, et al., Integrated analysis of climate change, land-use, energy and water strategies, Nat. Clim. Change 3 (7) (2013) 621–626.
[124] I. Kraucunas, L. Clarke, J. Dirks, J. Hathaway, M. Hejazi, K. Hibbard, M. Huang, C. Jin, M. Kintner-Meyer, K.K. van Dam, et al., Investigating the nexus of climate, energy, water, and land at decision-relevant scales the platform for regional integrated modeling and analysis (prima), Clim. Change 129 (3–4) (2014) 573–588.
[125] Bhatt V, Crosson KM, Horak W, Reisman A. New York city energy water integrated planning: a pilot study (BNL-81906-2008). Tech rep, Brookhaven National Laboratory (BNL); 2008.
[126] S.C. Parkinson, N. Djilali, V. Krey, O. Fricko, N. Johnson, Z. Khan, K. Sedraoui, A.H. Almasoud, Impacts of groundwater constraints on Saudi Arabia's low-carbon electricity supply strategy, Environ. Sci. Technol. 50 (4) (2016) 1653–1662.
[127] A. Santhosh, A.M. Farid, K. Youcef-Toumi, Real-time economic dispatch for the supply side of the energy-water nexus, Appl. Energy 122 (2014) 42–52.
[128] F. Ackerman, J. Fisher, Is there a water–energy nexus in electricity generation? long-term scenarios for the Western United States, Energy Policy 59 (2013) 235–241.
[129] A.S. Stillwell, M.E. Webber, Evaluation of power generation operations in response to changes in surface water reservoir storage, Environ. Res. Lett. 8 (2) (2013) 025014.
[130] A.S. Stillwell, M.E. Clayton, M.E. Webber, Technical analysis of a river basin-based model of advanced power plant cooling technologies for mitigating water management challenges, Environ. Res. Lett. 6 (3) (2011) 034015.
[131] Giampietro M, Aspinall RJ, Bukkens SGF, Benalcazar JC, Diaz-Maurin F, Falmmini A, Gomiero T, Kovacic Z, Madrid C, Ramos-Martin J, Serrano-Tovar T. An innovative accounting framework for the food-energy-water nexus. Application of the MuSIASEM approach to three case studies, Food and Agriculture Organization (FAO), LIPHE4; 2013. URL ⟨http://www.nexus-assessment.info/⟩
[132] University of Cambridge, foreseer, University of Cambridge, accessed: 2016-04-05; 2016. URL ⟨https://www.foreseer.group.cam.ac.uk/⟩
[133] Daher BT, Mohtar RH. WEF Nexus Tool. The resource management strategy guiding tool. Qatar Environment and Energy Research Institute (QEERI), accessed: 2016-04-05; 2013. URL ⟨http://www.wefnexustool.com/login.php⟩

[134] United Nations Economic Commission for Europe (UNECE), Reconciling resource uses in transboundary basins: assessment of the water-food-energy-ecosystem nexus, UNECE; 2015. URL ⟨https://www.unece.org/fileadmin/DAM/env/water/publications/WAT_Nexus/ece_mp.wat_46_eng.pdf⟩