ECN

Understanding the Energy-Water Nexus

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Overview

Energy, water and food resource systems are fundamentally interrelated. We need energy to produce food and to treat and move water; we need water to cultivate food crops and to generate essentially any form of energy; and we need food to support the world's growing population that both generates and relies on energy and water services. Land availability also constitutes an important element in each of these three resources, for example for crop production for either food or energy purposes. This mutual relationship is defined as the "Energy-Water-Food Nexus".

To date, the three individual resource systems of energy, water, and food have mostly been organised and studied independently. In a rapidly developing world with ever more pressing environmental challenges, however, choices and actions in each of these three domains can significantly affect the others, positively or negatively. Therefore it is important to take a "nexus approach" to analysing these three resource systems. Conventional policy- and decision-making with regards to each of these domains in isolation is not necessarily anymore the most effective or optimal course of planning or action. A "nexus approach", which in our context refers to a multidisciplinary type of analysis of the relationship between energy, water and food, can help to reduce trade-offs and to build synergies across these different sectors. In an increasingly complex and interrelated world this approach can lead to better and more efficient resource use as well as cross-sectoral policy coherence.

This report begins by reviewing the current thinking reported in the existing literature on the "Energy-Water-Food Nexus" (hereafter, for reasons of brevity, simply referred to as the nexus). Given that the nexus constitutes a broad, recently emerging, and still largely undefined and poorly understood concept and associated field of research, we narrow down our focus to predominantly inspect the interrelationship between energy and water in the remainder of our report. We leave a more elaborate study of the connection of energy and water to the dimension of food for follow-up work. This report aims to inform local and regional decision-makers responsible for development and implementation of policies related to energy and water resource systems.

1

Introduction

Water scarcity already affects every continent. Around 1.2 billion people, almost one-fifth of the world's population, live in areas of scarcity. Another 1.6 billion people, almost one quarter of the global population, face economic water shortage (meaning that countries lack the necessary infrastructure to take water from rivers and aquifers). It is estimated that by 2030 almost 50% of people on the planet will be living in areas of high water stress with a likely impact on energy and food security (UN, 2012). Even though water is a renewable resource, and there is sufficient water globally to satisfy an expanding and wealthier population, demand for water exceeds supply in many regions of the world. This supply-demand imbalance is most commonly seen in India, China, and the Middle East and North Africa (MENA) region (SEI, 2011).

Before pursuing any analysis involving water-related issues, one needs to distinguish between three different types of water use: water withdrawal, water consumption, and water discharge. Water withdrawal is the total amount of water taken from a source (groundwater or surface water). Water consumption is the proportion of water that is not returned to its source after it has been withdrawn. Water that is consumed is no longer available because it has evaporated, been transpired by plants, incorporated into products or crops, consumed by people or livestock, or otherwise been permanently removed from its source. Water discharge is the difference between water withdrawal and consumption, it is water that is not consumed and is returned to a body of water.

Energy and water are inextricably linked. Non-renewable energy sources currently dominate the global energy generation landscape. These thermal sources of energy generation mostly derived from fossil fuels are at present particularly water-intensive, mainly due to the cooling systems they use that require large amounts of water. A push towards a less carbon-intensive energy sector with a larger share of renewables, stimulated by efforts to mitigate global climate change, requires careful consideration of the potential impacts of such energy transition on the other nexus sectors. For example, biofuels and hydropower are also very water-intensive, sometimes as much as fossil fuels in terms of water use per unit of energy generated. Even energy use itself for biomass production may in some cases outweigh the energy it produces (SEI, 2011).

Energy and water are also interconnected to food and agriculture. Agriculture is the largest user of fresh water (water can be either fresh or saline) globally, accounting for approximately 70% of fresh water withdrawals from rivers, lakes, and aquifers. This ratio can rise to up to 90% in some developing countries. An increasing population and shifting dietary trends mean demand for food and feed crop cultivation is rising (UNESCO, 2008). Food production and its associated supply chain account for approximately one-third of the world's total energy consumption (UN, 2014). Rising food production has led not only to agricultural land expansion, largely at the expense of forests, but also in many regions an intensification of agricultural processes on existing land. This expansion and intensification places more stress on agricultural input resources, such as water and energy.

A paper by Bruinsma (2011) investigates the implications on natural resources of the 2006 Food and Agriculture Organisation's (FAO) baseline food and agriculture projections up to 2050. Even though the growth rate in agricultural production continues to slowdown - as a result of a declining population growth rate and a higher percentage of the world's population reaching medium to high levels of food consumption - agricultural production will still need to rise by approximately 70% by 2050 to serve a 40% increase in population and rising average food consumption levels. 90% of the growth in crop production would be a result of higher yields and increased agricultural intensity, with the remainder being provided via land expansion. Mainly due to gradual improvements in water use efficiency, water withdrawals for irrigation would grow more slowly but still increase by almost 11% by 2050. In terms of the availability of both land and water, both of these resources are more than sufficient globally, but are unevenly distributed throughout the world with certain regions and countries facing scarcity of either land or water for crop production (Bruinsma, 2011). Scarcity of these resources could restrict the potential for both the expansion of agriculture and intensification of agricultural processes (IEA; OECD, 2013).

While we recognise that the food and agriculture sectors are an important part of the nexus, we will not be focusing on these areas in this report. The main aim of this study is to develop an understanding of how different conventional and innovative energy technologies can be distinguished in relation to their water needs. We will investigate several future energy scenarios and the water needs relating to these scenarios, including some in which climate policy is adopted. We will begin to develop a tool to analyse future short-, medium- and long-term impacts of energy on water, and the implications of energy and climate policy on these two resources. Much of what happens in the field of energy is determined by global climate change; therefore we will inspect low-carbon technologies in particular. The other core aim of the report is to present an extensive literature review of the energy-water-food nexus in order to provide an understanding of the current state of affairs with regards to research in this area.

Following this brief introduction, section 2 examines the existing literature, models and frameworks that have been developed on the subject of the nexus. The section provides a general overview of many issues relating to the nexus that we have encountered during our research on the subject. This includes examining the full energy-water-food nexus, and further extending the analysis by investigating briefly the role that climate change might also play in the nexus. There are a broad range of issues and perspectives on what the nexus is and how it should be analysed, each of which are important to consider when addressing a topic of such complex nature. However, it is important to emphasise that the scope of our work will be confined to focusing on the energy-water part of the nexus, and more specifically on the water requirements of energy technologies. While we understand the importance of the energy requirements of water technologies, defining a narrower scope will enable us to conduct a more thorough investigation of the water requirements of energy.

In section 3 we will investigate the water requirements of different (conventional and innovative) electricity generation technologies and provide an overview of water consumption and withdrawal factors for these various technologies. We will also introduce the main cooling systems used in thermal electricity generation, and examine the impacts of these systems on water withdrawal and consumption levels for the different energy technologies. Next, in section 4 we investigate regional water availabilities and possible shortages across the world, and identify which regions could be most susceptible to water stress in the future. We also inspect more closely the issues surrounding water use faced by Jordan, our representative case study for the Middle East region.

In section 5 we perform an initial scenario analysis, in which we preliminarily inspect what the water withdrawal and consumption implications could be of different scenarios for future energy needs and the technologies employed to satisfy this demand. We do this for the Middle East as a case study, which we have identified as a region in which water stress could become particularly important. Matching scenarios for water requirements and availabilities with scenarios for energy needs and the water intensities of different energy technologies, allows us to analyse which of the electricity generation options could potentially be most suitable for this particular region. This may assist an institution like the Energy Research Centre of The Netherlands (ECN) in formulating its R&D agenda. We finish, in section 6, with a few main conclusions and recommendations on how we think one could pursue this research field in the future.

2

Nexus overview

A recent initiative led by the World Bank entitled *'Thirsty Energy'* aims to support its client countries in addressing issues surrounding the energy-water part of the nexus. The publication provides a general overview of the global challenges and trade-offs involved in the energy-water nexus. It investigates the water requirements of different power generation options, but does not provide much in the way of technical data on these water requirements of different energy technologies. However, the report does provide a clear, basic description of the various types of cooling systems used in power plants. It highlights potential technical and institutional solutions for improving management of the nexus, including a summary of alternative power plant cooling systems to reduce water use, alternative water sources to fresh water and integrated water and energy planning. The report concludes that "integrated energy-water modelling allows resource planners to consider whether water supply today and in the future will be sufficient to meet the cooling requirements of different power plants" (World Bank, 2013).

The United Nations (UN) 'World Water Development Report (WWDR) 2014' was launched recently which includes a publication on the energy-water nexus. This report provides probably the most extensive analysis of the nexus within the literature to date, drawing upon information, data and analyses from a broad range of literature on the subject. The report investigates water demands, energy requirements for water provision, water availability, and the demand for water from power generation. It also expands the nexus to include issues related to food and agriculture, broadening the scope of the nexus. Furthermore, the WWDR examines regional aspects relating to the water-energy nexus. It suggests that the public policy response to the interconnectedness of energy and water, and related domains, requires a hierarchy of actions aimed at creating an enabling environment to allow the changes necessary for the development of water and energy resource systems to be implemented. These actions include: coherent policy development; legal and institutional frameworks to promote coherence; ensuring reliable data and statistics to make and monitor decisions; encouraging awareness; supporting innovation and research into technological development; making sure finance is available; and allowing markets and businesses to develop (UN, 2014). The report also concludes that there is a marked difference between the speed of change within the two domains of water and energy.

The energy sector is driven by evolving markets and technological development, and energy issues are high on the political agenda. The report suggests that actors in the water sector need to increase their governance reform efforts, otherwise the sector will suffer as a result of direct pressures from the energy sector. These failures in the water sector could then perversely lead directly to failures in energy and other related sectors.

The International Energy Agency (IEA) *'World Energy Outlook 2012'* report dedicates a chapter to the energy-water part of the nexus. Chapter 17 of the report investigates issues such as global water requirements for energy production and the availability of water in different geographical regions of the world, under the different future IEA energy scenarios, indicating 'regional stress points' for water. The Chapter also provides a clear summary of the different cooling techniques used in thermal power generation, and how the differences between these techniques impact water withdrawal and consumption factors. It gives a visual overview of the water use of different primary energy production sources and electricity generating technologies (in turn split by the cooling system used). It shows some useful examples of the water impacts of power production in different regions of the world, which emphasises the current and growing importance of the nexus especially in those regions. The report suggests that a more water-constrained future due to population growth, global economic growth, and climate change, will impact reliability and costs in the energy sector. It suggests that the water requirements of fossil fuel-based and nuclear power plants can be reduced substantially with the adoption of advanced cooling systems, but this will be at the expense of increased capital costs and lower plant efficiency. Furthermore, it concludes that energy efficiency, wind and solar PV can contribute to a low-carbon future without significantly putting further pressure on water resources. Moreover, regional availability and access to water may become a more serious issue for unconventional gas and power development in China and the United States, fossil fuel-based power plants in India, production in the Canadian oil sands, and maintaining reservoir pressures supporting oil output in Iraq. The report states that these kinds of issues are manageable, but will require improved technologies and a better integration of water and energy policies.

The Stockholm Environment Institute (SEI) report '*The Water, Energy and Food Security Nexus: Solutions for the Green Economy*', gives a broad understanding of how the nexus approach "...can enhance water, energy and food security by increasing efficiency, reducing trade-offs, building synergies and improving governance across sectors" (SEI, 2011). The paper is an attempt to fill some of the knowledge gaps surrounding the nexus, and presents an array of opportunities available for improving energy, water and food security by using a nexus approach.

The World Energy Council report in 2010, entitled *'Water for Energy',* inspects the energy-water part of the nexus assessing the scale of the challenge and the steps that need to be taken to ensure that water is available for energy demands. It includes data on the water requirements of energy technologies and regional water needs. The report concludes that we can probably meet the future water demands of energy production, but we need water issues to be integrated into policy-makers decisions, and a new paradigm of international cooperation between governments, between businesses, and between governments and businesses.

The ‘Water Security: The Water-Food-Energy-Climate Nexus’ book, launched in 2011 by the World Economic Forum (WEF) draws upon a range of viewpoints (from Non-Governmental Organisation’s (NGOs), academics, entrepreneurs, etc.) to identify the challenges we face in managing the world’s future water needs, and the implications of these challenges to our social, political, and economic well-being if we fail to take action. It seeks to deepen the understanding and raise awareness of the nexus, and examines solutions to the global water scarcity issue.

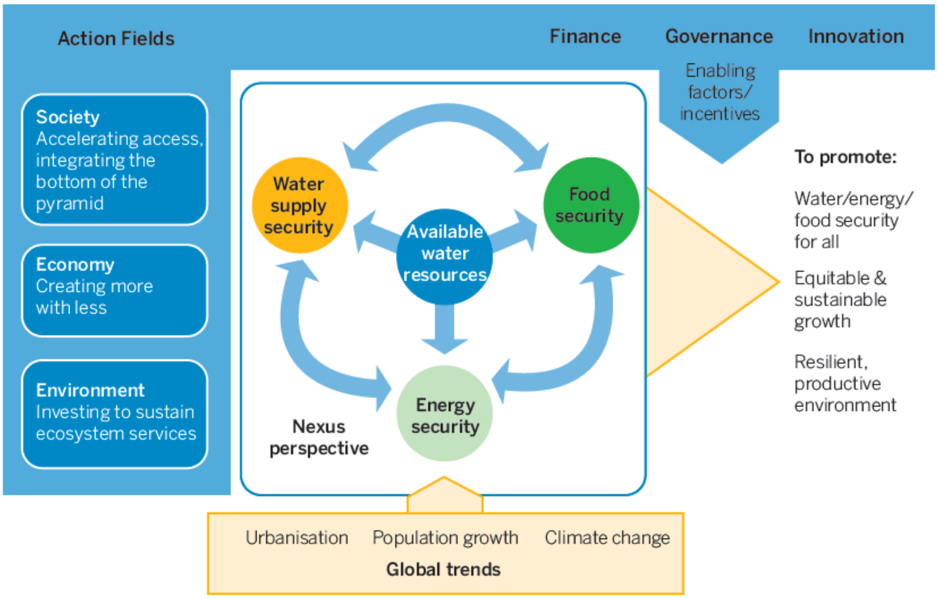
A 2012 Chatham House report entitled ‘Resources Futures’ offers a general perspective on the global linkages between resource systems emphasising that the world is experiencing intensified resource stress. The report highlights the attention given to the nexus of energy, water, and food, and how integrated resource management and governance is advocated across sectors and regionally. While the report doesn’t give any new insights into the nexus itself, it does confirm that natural resource systems are under increasing pressure from global, structural forces such as the interconnectedness of the resource systems themselves, and the distribution of power and income across the world.

The GRACE Communications Foundation report, released in 2013, ‘Food, Water and Energy: Know the Nexus’ incorporates the food dimension into the nexus and focuses upon how research on the subject is being addressed in the United States. It provides a broad overview of the three elements of the nexus, but does not provide much in the way of data or analysis.

The Intergovernmental Panel on Climate Change (IPCC) Working Group III (W III) Mitigation of Climate Change report (WGIII contribution to the IPCC’s 5th Assessment Report) touches upon the water scarcity issue in Chapter 6, section 6.6.2.6. It comments that during the last decades the world’s fresh water resources have come under increasing pressure. Water withdrawals for energy, and industrial processes and municipal applications, are projected to grow considerably over the next decades, jointly surpassing irrigation as the primary water user by 2050 (Alcamo and Henrichs, 2002; Shiklomanov and Rodda, 2003; Molden, 2007; Fischer et al., 2007; Shen et al., 2008; Bruinsma, 2011).

The interdependence between energy, water and food is considered to be of increasing importance within the literature, even though research in the area is still limited. Figure 1 below provides a visual representation of the nexus framework and how water availability is crucial in determining energy and food security.

Figure 1: The Nexus Framework



Source: SEI, 2011.

Much of the current literature highlights world population and economic growth projections, as well as changing lifestyles and consumption patterns, as the crucial factors leading to an increase in demand for energy, water and food resources in the future (SEI, 2011; IEA, 2012). There is also a rapidly growing global middle-class, particularly in emerging economies. In Asia alone, this sector of society tripled in size between 1990 and 2005 to 1.5 billion people (The Economist, 2011). The consumption patterns of this growing middle-class are in particular putting increased pressure on the world's resources, including energy, water and food.

Developing country economic growth is expected to be the main global driver of resource demand, averaging 6% compared to 2.7% in developed countries (World Bank, 2013). The Food and Agriculture Organisation (FAO) has estimated that feeding a population in excess of 9 billion by 2050 will require a 60% rise in agricultural production and 15% increase in water withdrawal (FAO, 2011). Total global water withdrawal is expected to increase by around 55% by 2050, placing more pressure on fresh water availability and leading to projections of more than 40% of the population living in areas of water stress by 2050 (UN, 2014). The UN WWDR (2014) report also states that there is clear evidence of groundwater supplies diminishing, with estimations of 20% of the world's aquifers currently being over-exploited.

2.1 Energy and water

1.3 billion people in the world still do not have access to electricity (IEA, 2012). Worldwide energy consumption is projected to increase by almost 50% by 2035, and electricity demand is expected to grow by approximately 70% by 2035 (UN, 2014). Most of this increase will be in non-OECD countries (IEA, 2012).

According to the IEA ‘reference scenario’, which projects current energy trends into the future; China, India and the Middle East would double their primary energy demand by 2035, while demand in Africa and Latin America would increase by around 40%. It should be noted, however, that there are other scenario projections in the literature that suggest a significant reduction in energy demand growth rates due to intensive demand management measures being adopted (WWF, 2011).

The declining availability of fresh water will have an increasing impact on the energy sector. According to the OECD, the energy sector required 15% of global fresh water withdrawal in 2010 (OECD, 2014). By 2030, global demand for water, including from energy, is predicted to outstrip supply by approximately 40% (World Bank, 2010). More recent estimates by the World Energy Council (WEC) have indicated that emerging economies such as China, India and Brazil will double their energy consumption within the next 40 years. The amount of electricity generated in Latin America is expected to increase fivefold over the next 40 years, tripling the amount of water required (WEC, 2010). The water footprint of different energy sources can therefore be expected to become an increasingly competitive issue especially in regions where water stress is more pronounced. For example, a recent study by the World Resources Institute (WRI) suggested that more than one-third of commercially viable shale gas deposits worldwide are in areas that are either dry or have water supply constraints. Out of 20 countries in the WRI study, 8 have deposits of shale gas in areas that face either ‘high’ or ‘extremely high’ water stress.

The projected increase in the demand for energy will inevitably place increasing pressure on water withdrawal and consumption, predominantly via cooling systems in thermal power generation, but also via non-conventional power sources, in particular hydropower and biofuels. A large increase in the contribution of biofuels to total energy supply would place high demands on land and water resources.

2.1.1 Bioenergy and water

Bioenergy is generated from biomass e.g. agricultural crops, forestry products, agricultural and forestry wastes and by-products, manure, microbial matter, and waste from industry or households. Bioenergy includes different forms of energy including heat and electricity from burning biomass, and biofuels. First generation biofuels are produced using the starch, sugar, or oil from a crop. Second generation biofuels are generated from feedstock such as crop wastes or forestry residues. Third generation biofuel is the production of biodiesel from algae (IEA, OECD, 2013).

The IEA and OECD Joint Research Centre (JRC) report ‘Bioenergy and Water’ highlights that sustainable water management is essential in the development of bioenergy, while taking into consideration a global increase in food production over the coming decades, and other uses of water resources. The IEA Technology Roadmaps of ‘Bioenergy for Heat and Power’ and ‘Biofuels for Transport’ suggest that primary bioenergy supply could increase from 50 Exa Joules (EJ) today to some 160 EJ by 2050. By 2050 bioenergy could provide around 7.5% of global electricity generation; heat from bioenergy could provide 15% of final energy consumption in industry and 20% in the building sector; and biofuels could provide 27% of world transport fuels (IEA, OECD 2013). The Technology Roadmaps indicate that energy from biomass has the potential to contribute heavily to greenhouse gas (GHG) reductions leading up to 2050 and beyond (as much as 3.6 Gt CO_2e per year in 2050 compared to a business-as-usual scenario (IEA, OECD 2013)). This will be dependent upon the type of feedstock used, and how efficiently and sustainably it is produced.

Demand for bioenergy adds to the pressure on water resources particularly in important agricultural areas of the world where water scarcity is a concern, for example in India and China. Water scarcity could be a major barrier to bioenergy expansion (Berndes, 2002; Gerbens-Leenes et al., 2008). However, there are also opportunities for producing bioenergy in areas where water scarcity is more pronounced, which may open up new opportunities to improve the productivity of water use (Berndes, 2008).

The impact of bioenergy development on water will depend heavily upon the types of bioenergy system that are adopted. Using residues and by-products from agriculture and forestry, and organic consumer waste for bioenergy has clear efficiency advantages because the same water is being used to produce the waste, residues, and by-products as is used to produce the bioenergy. Currently, these resources constitute a large proportion of available biomass for energy, but they are unlikely to meet biomass demand in the future. IPCC energy scenarios suggest bioenergy deployment levels in 2050 of between 80 to 150 EJ per year for a 440-600 parts per million (ppm) CO_2e atmospheric target to be met, and 118 to 190 EJ for a less than 440 ppm CO_2e target. The energy content in the global harvest of major crops (cereals, oil, sugar, roots, tubers, and pulses) is only approximately 60 EJ per year. This suggests that there is a significant gap, which indicates that a major part of the supply of bioenergy feedstock would have to be produced specifically for bioenergy needs. This has implications in terms of additional water requirements in order to grow the feedstock.

Technological advancements in water management and agricultural productivity offer potential ways to improve water conservation, and bioenergy may offer opportunities in terms of new types of crop production that use water more efficiently. Water use efficiency varies depending on the crop type due to varying climatic conditions, growing periods and agronomic practices (IEA, OECD 2013). The demand for bioenergy can be met while improving water availability and use. For example, where water scarcity prevents the growth of sufficient conventional food and feed crops, plants that are tolerant to such arid conditions can be cultivated instead; and plants that can grow in conditions of high salinity are also being investigated as bioenergy crops. There is considerable scope globally for bioenergy development to improve the productivity of water, and policy should be developed to promote optimal use of land, water and biomass to meet the combined demands of food, materials and energy demands (IEA, OECD, 2013).

A particularly policy relevant question highlighted in the JRC paper is whether, and to what extent, water should be used for food, fibers or fuel (IEA, OECD, 2013). In areas where population is rising rapidly, such as China and India, this question is even more relevant due to the increasing demand for food. Bioenergy production requires large amounts of water which makes that water unavailable for food production; therefore there is an important trade-off to consider for policy-makers in these sectors.

Alternative renewable energy sources have lower water footprints; the water footprint of bioenergy is much larger than for fossil, nuclear, wind and thermal solar energy (IEA, OECD, 2013), but if bioenergy development is the chosen pathway then feedstock should be produced in a way that limits its water footprint. More efficient irrigation, less water-intensive crops, and increasing land productivity are all potential ways of doing this.

Another report entitled ‘The Bioenergy and Water Nexus’ (UNEP, Oeko-Institut and IEA Bioenergy Task 43, 2011) investigates how the production and use of bioenergy products is likely to influence water resources in the future, and how society can mitigate the impacts by sustainably developing the use of these resources. The report examines the impact that bioenergy feedstock production and conversion may have on water resources. It makes several recommendations of how to manage water resources going forward, including taking a holistic approach and long-term perspective; designing and implementing effective water-related policy instruments; basing decisions on impact-assessments to ensure sustainable water management; and promoting technological development to help mitigate pressure on water resources. The report highlights that further research is needed on the subject including filling gaps in data especially in developing countries.

2.1.2 Water withdrawal and consumption factors

There are several papers that investigate water withdrawal and consumption factors of different energy technologies. Data collected by Macknick et al. (2012) provides an analysis of these factors from the existing literature. The National Renewable Energy Laboratory (NREL) uses the data from this report in their 2011 review of operational water usage by electricity generating technologies in the United States, in which Macknick was the lead author. The report suggests that the data could be utilised in energy planning models to better understand the regional and national impacts on water resources for various electricity future scenarios, and can inform policy makers. It highlights that improved power plant data and further studies into the water requirements of existing and emerging technologies (such as carbon capture technologies) are necessary to better assess the water impacts of a developing, decarbonising economy.

Meldrum et al. (2013) present an overview of estimates for withdrawal and consumption for the full life cycle (component manufacturing, fuel acquisition, processing, transport, and power plant operation and decommissioning) of different electricity generation technologies. The article uses a broad variety of publicly available resources and from our initial research appears to provide the most comprehensive consolidation of life cycle water use of electricity generating technologies.

The European Photovoltaic Industry Association (EPIA) has produced a fact sheet on the Water Footprint of Photovoltaic systems, which provides a succinct overview of water withdrawal and consumption ranges for various electricity generation technologies, but does not add any further details than Macknick et al. (2012) or Meldrum et al. (2013).

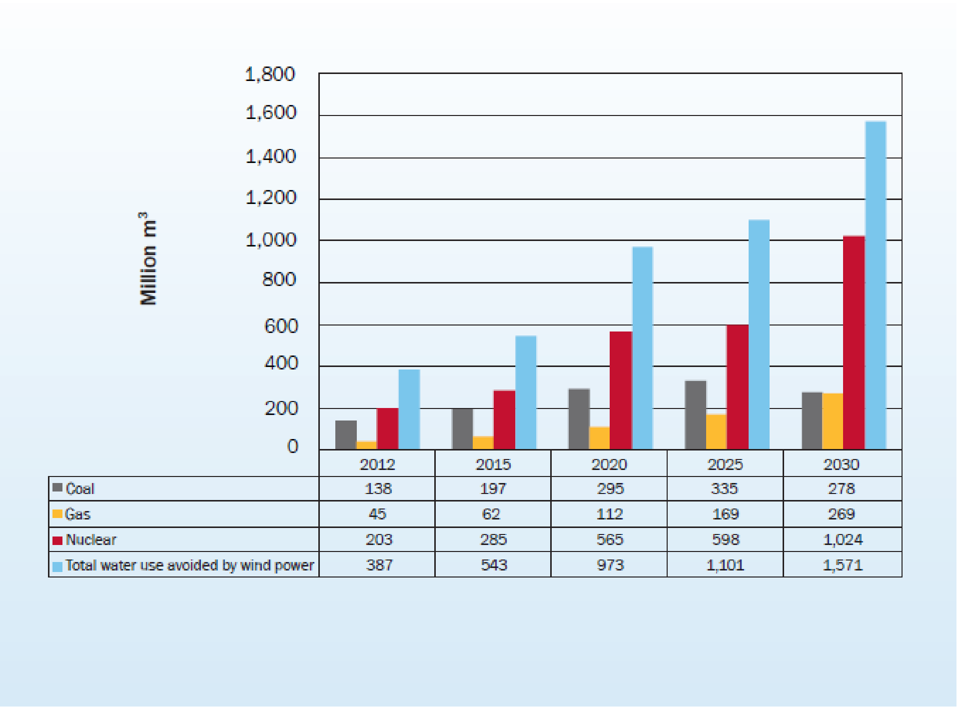
2.1.3 Wind energy and water

The link between energy and water could be viewed by analysts in several different ways. For example, to some it may mean that wind turbines can be built on dikes or dams. However, here we focus on the water use of wind energy, a technology which uses virtually no water. In fact replacing thermal and nuclear power stations with wind energy could be one potential method of conserving water. Wind energy avoided 387 million m^3, avoiding costs of up to EUR 734 million, in Europe in 2012 alone. According to the European Commission's (EC) 2050 Energy Roadmap projections, in 2030 wind energy will avoid between 1.22 and 1.57 billion m^3 of water, and avoid costs of water use of between EUR 3.34 and 4.4 billion (European Wind Energy Association (EWEA), 2014).

Non-thermal technologies, such as wind, have the lowest operational and lifecycle water consumption per unit of electricity generated. Wind turbines usually only require small amounts of water for cooling purposes (generator, transformer, inverter) and blade washing (DOE, 2006), and even then the blades can be washed by the rain (EWEA, 2014).

Figure 2 shows the potential water use that can be avoided by deploying wind at a rate that is aligned with converting to renewables on a scale projected by the EC's Roadmap for 2050.

Figure 2: Avoided water use by deployment of wind energy up to 2030



	2012	2015	2020	2025	2030
Coal	138	197	295	335	278
Gas	45	62	112	169	269
Nuclear	203	285	565	598	1,024
Total water use avoided by wind power	387	543	973	1,101	1,571

Source: EWEA, 2014.

Due to the fact that, especially in some regions, water-scarcity is of growing concern intensified by population expansion and climate change, the water savings that wind energy can provide offers opportunities for using wind as an alternative energy source in areas where conditions for wind energy generation are favorable.

2.1.4 Desalination and water production

The link between energy and water can also be explored in reverse, meaning the energy requirements of water. Energy is required for the transportation, distribution and treatment of water. Clean water from non-conventional sources such as wastewater and seawater, is often very energy intensive. The energy intensity per m^3 of clean water is about 0.37 kWh from locally produced surface water, 0.66-0.87 kWh from wastewater, and 2.6-4.36 kWh from desalinated seawater (Webber, 2008). Groundwater is also generally about 40% more energy intensive than surface water due to the additional energy that is required for pumping (WEF, 2011).

Desalination is the process of removing dissolved slats from seawater or brackish water in order to produce fresh water. Seawater desalination, as with any other treatment or separation process, requires energy to produce fresh water, but it requires more energy than most other water treatment methods. Desalination is a crucial part of the solution to global water issues, and is a growth industry characterised by new advancements in technology directed towards addressing environmental issues and reducing costs (Henthorne et al., 2009). The growing importance and use of desalination is evidenced, for example, by the International Desalination Association (IDA) who report that in 2007 total global contracted desalination capacity increased by 43% compared to 2006. This growth is due to several factors including higher costs and lower availability of groundwater supply, population and economic growth in regions that rely heavily on desalinated water, climate change and drought impacts, coastal migration, and the reduced costs of desalination. There are currently in excess of 14,000 desalination plants worldwide in over 150 countries (Henthorne et al., 2009).

Although we acknowledge that desalination is a pertinent issue in the energy-water nexus; it is not a focus of this report and is beyond the scope of our analysis at this stage. Specific, in depth research is required to investigate the various desalination technologies available, factors such as the costs of these technologies and their energy requirements, and how desalination can impact the energy-water nexus.

Aside from desalination there are several other processes that produce water as a by-product. An example is the use of the Fischer-Tropsch process which is a set of chemical reactions that convert a mix of carbon monoxide and hydrogen into liquid hydrocarbons. The process is typically used to produce synthetic fuel from coal, natural gas, or biomass. A further example of water production is the Methanation reaction which is used in the purification of synthesis gas, and to manufacture methane. This reaction is also a net producer of water. These methods are important aspects of the energy-water nexus, but are again not the focus of our report. Further research on the nexus could incorporate such water production options and the impact that these technologies can have on the global water-scarcity issue.

2.2 Food, agriculture and water

Food production and its associated supply chain account for approximately one-third of the world’s total energy consumption (UN, 2014). Although water productivity varies widely among different crops, as a rule of thumb to produce 1 calorie of food energy takes on average approximately 1 liter of water (FAO, 2009). Water consumption via agricultural processes is projected to increase by approximately 20% by 2050 (UN, 2014), which will inevitably further increase the stress on available water resources. Furthermore, modernisation and developments in the agricultural industry have served to intensify agricultural processes, which have in turn increased the energy-intensity of the sector. In its *‘Understanding the Nexus’* report, SEI explains the strong correlation between crop and oil prices, which reflects the energy dependency of agriculture (SEI, 2011).

Agriculture and food are closely linked to bioenergy and future planning for each of these sectors has implications for the others. The water demands of bioenergy are heavily dependent on the growing and processing of feedstocks such as crops, which in turn has implications for agriculture, land use and food. Growth of feedstocks for bioenergy is in direct competition with food production, and the intensity of this competition will increase as demand for food increases along with a growing world population. However, there are also synergies between bioenergy and food production systems that can bring about win wins for both the energy and food sectors (UNEP, Oeko-Institut and IEA Bioenergy Task 43, 2011).

2.3 Climate change, energy and water

Climate change is a global problem, and one of the main challenges facing mankind this century. Climate change is driven mainly by energy use and land use changes, but at the same time climate change mitigation and adaptation measures place increased pressure on water and land resources. The use of conventional energy technologies contributes negatively to climate change, and some technologies require large amounts of water. However, water and land are often crucial resource inputs for implementing climate mitigation and adaptation measures. For example, Concentrated Solar Power (CSP) plants can require large amounts of water for cooling purposes, and energy from biomass requires land for biomass cultivation which competes with other land uses. Climate policies can therefore impact energy, water and food security, and if mitigation and adaptation policies are not aligned well in a nexus approach then they can have a detrimental impact on the sectors in the nexus rather than a positive one.

Already approximately 2.8 billion people live in areas of water stress and by 2030 this is projected to be almost 50% of the world’s population (UN, 2014). According to the OECD, if the world follows a baseline pathway to 2050 (i.e. no new policies are implemented), more than 40% of the world’s populations will be living in areas experiencing severe water stress. A global water scarcity assessment was conducted by Hanasaki et al. (2013) which suggested that by the period 2071-2100 the population living under severely water-stressed conditions will reach between 39% and 55% of the total world population; the exact percentage depending upon different future water use and climate scenarios. Even in the scenario with the least change in water use and climate, global water scarcity increases substantially mainly as a result of a growing population and economic activity in developing countries, and in part due to hydrological changes brought about by global warming (Hanasaki et al., 2013). There are few studies investigating the impact of climate change policy on global water scarcity. However, a study by Gosling, S.N. and Arnell, N.W. (2013) uses the Water Crowding Index (WCI) and Water Stress Index (WSI) to calculate global exposure to increases and decreases in global water scarcity due to climate change. They find that 1.6 (WCI) and 2.4 (WSI) billion people are estimated to be currently living within watersheds exposed to water scarcity. Using the WCI, by 2050, 0.5 to 3.1 billion people will be exposed to an increase in water scarcity due to climate change (across 21 Global Climate Models).

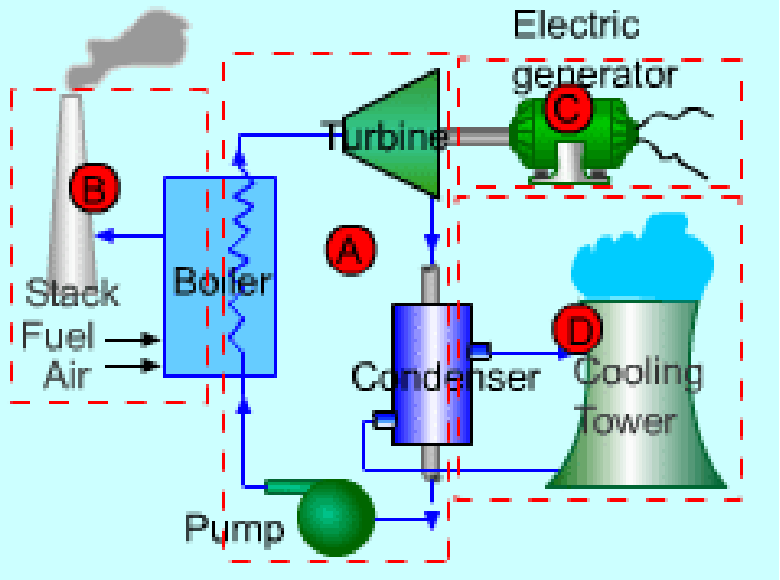
The ‘Climate change, water and agriculture: towards resilient agriculture and water systems’ report by the OECD, 2014, highlights that interactions between climate change, water and agriculture are complex and region-specific. The report does not delve into the energy-water nexus itself therefore it is not that useful for our analysis, but it does highlight the added impact of climate change, and climate change mitigation and adaptation activities, can have on agriculture and water.

3

Water requirements of energy technologies

This section focuses on the water requirements of different electricity generating technologies. It is important here to introduce the Rankine cycle which closely describes the process by which steam- operated heat engines, commonly found in thermal power generation plants, generate power. Often referred to as 'vapour' power plants, these plants generate electrical power by using fossil fuels like coal, oil or natural gas. Fuel is burned in a boiler and then heats water to generate steam. This steam is then used to run the turbine which powers the generator. Electrical energy is generated when the generator windings rotate in a strong magnetic field. After the steam leaves the turbine, it is cooled to its liquid state in the condenser by transferring heat to the cooling water system. The liquid is pressurized by the pump prior to going back to the boiler. Figure 3 below provides a visual overview of this process.

Figure 3: Thermal power plant electricity generation: The Rankine cycle



Source: www.ecourses.ou.edu (http://www.ecourses.ou.edu/cgi-bin/ebook.cgi?topic=th&chap_sec=10.1&page=theory)

The Rankine cycle, in the form of steam engines, generates about 90% of all electric power used throughout the world, including virtually all biomass, coal, solar thermal and nuclear power plants. While many substances could be used as the working fluid in the Rankine cycle, water is usually the fluid of choice due to its favorable properties, such as its non-toxic and unreactive chemistry, abundance, and low cost, as well as its thermodynamic properties.

Thermal power plants are responsible for generating approximately 80% of global electricity, and as a sector they use a large amount of water. Approximately 90% of global power generation is water-intensive (UN, 2014). For example, in a coal-fired power plant with cooling towers, it's estimated that 90% of the water used in the plant is for cooling purposes, and only 10% for other processes (US Department of Energy (DOE), 2006). Some innovative and/or renewable energy options may also need large amounts of water, depending on the type of technology and cooling system chosen. It is estimated that power plant cooling is responsible for around 43% of total fresh water withdrawals in Europe, almost 50% in the United States, and greater than 10% of in China (UN, 2014). We therefore restrict our analysis in section 3 to predominantly focus upon electricity generation by thermal power plants.

3.1 Cooling systems

There are several types of cooling system that can be used in thermal power plants, all of which have varying levels of water requirements. Table 1 below summarises the four main systems that are used.

Table 1: Four different water cooling systems for power plants.

Cooling system	Description
Once-through	The simplest cooling method. It withdraws large quantities of water, but almost all of this is returned to water bodies once passed through the heat exchanger. Only a small amount of water is lost via evapouration. The warm water returned to water bodies can cause damage to ecosystems.
Recirculating	This includes both cooling towers and ponds, although towers are most common. The process cools the water by exchanging heat from water to the air. Some water is lost through evapouration and the rest of the water is reused in the steam condenser of the power plant. These systems withdraw much less water than once-through systems, but approximately 85% of the water is consumed (World Bank, 2013).

Cooling system	Description
Dry Cooling	Uses air instead of water to cool the steam in the power plant. Using dry cooling can reduce water consumption by up to 90%. It has much less environmental impact, but because air is not as efficient as water at cooling, it requires more surface area to release waste heat to the environment. Therefore, it is between two to four times more expensive than wet cooling (World Bank, 2013). Also, plant efficiency is diminished with dry cooling; therefore the system is generally used in areas where water scarcity is an issue.
Hybrid	This is a combination of dry and wet cooling systems.

The relative water requirements and trade-offs of using these different systems are summarised in Table 2 below. The choice of which cooling system to use is largely determined by the prevailing conditions in the region (IEA, 2012).

Table 2: Cooling systems and their trade-offs (Adapted from the IEA World Energy Outlook, 2012.

Cooling system	Advantages	Disadvantages
Once-through	- Low water consumption - Mature technology - Lower capital cost	- Higher water withdrawals - Negative impact on ecosystems - Exposure to thermal discharge systems
Recirculating	- Much lower water withdrawal than once-through cooling - Mature technology	- Higher water consumption than once-through - Lower plant efficiency - Higher capital cost than once-through
Dry Cooling	- Minimal or no water withdrawal or consumption	- Higher capital cost than once-through and recirculating - Lower plant efficiency - Large land area requirements
Hybrid	- Lower capital cost than dry cooling - Less water consumption compared to recirculating - No efficiency penalty on hot days - Flexible operation	- Less technology experience

Source: Mielke et al., 2010.

3.2 Water withdrawal and consumption factors

Figures 4 and 5 provide a visual representation of the ranges of water withdrawal and consumption for different energy technologies based on our review of the relevant literature. A table detailing the data displayed in these figures and the sources of this data can be found in Appendix A.

Figure 4: Water withdrawal factors for electricity generating technologies.

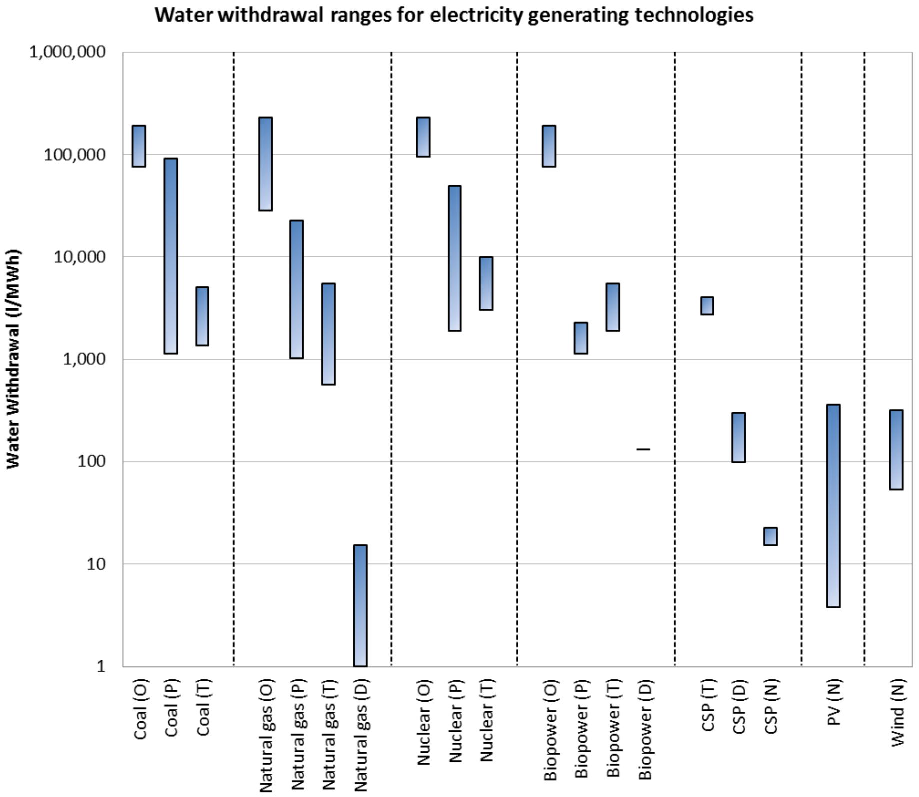
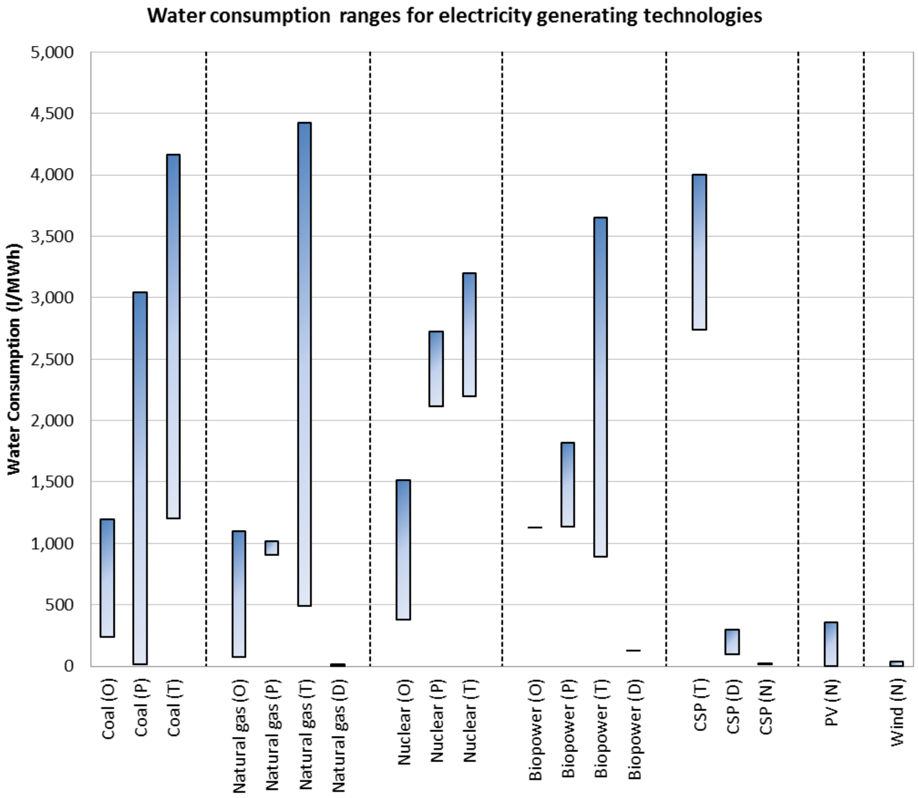


Figure 5: Water consumption factors for electricity generating technologies.



Notes:

The different types of cooling system are given in brackets following the energy technology (O=once-through; P=Pond; T=Tower (both Pond and Tower are recirculating systems); D=Dry; N=No cooling).

The withdrawal and consumption factors for both PV and wind are life cycle estimates which include water withdrawal for power plant procurement and building; and fuel extraction, transportation and recycling. Life cycle data is taken from Meldrum et al. (2013).

The data for PV does not include water use of concentrated PV. Withdrawal factors can be approximately 16 times higher for concentrated PV technology. The higher water use of concentrated PV is likely to be because of certain shared operational characteristics with CSP, such as a need for mirror washing (Meldrum et al. 2013).

We do not include geothermal and hydropower generation sources due to the diversity of technologies used within these two categories that all involve widely diverging water usage factors –deviating from each other sometimes by several orders of magnitude. Technologies within these two categories are also inherently complex, and it is difficult to assess their water withdrawal and consumption factors with a credible degree of accuracy, unless entire studies are dedicated to each of them. We also avoid tidal energy because of similar reasons. Furthermore, the impact of electricity generation from tidal power on water resources may be considered minimal as it could be argued that there is no withdrawal or consumption of water during the operational phase. However, we would recommend future studies on the water withdrawal and consumption factors of these technologies, and this is one such area ECN could focus upon.

Our analysis broadly agrees with the previous literature studies of Macknick et al. (2012) and Meldrum et al. (2013) showing that large differences in both water withdrawal and consumption levels exist between not only different types of electricity generating technologies, but especially between cooling systems used. The results show that the cooling system that is adopted often impacts water usage more than the actual electricity generating technology being used. As an example, once-through cooling systems can withdraw between 10 to 100 times more water per unit of electricity generation than cooling tower technologies, but cooling towers can consume typically twice the amount of water of once-through systems (Macknick et al., 2012).

Once-through cooling systems withdraw the highest amount of water per MWh of electricity produced within each of the applicable generation sources (coal, natural gas, nuclear, or biopower). Generally, closed-loop pond cooling systems are the next biggest withdrawers of water, followed by towers, and finally dry cooling which uses minimal water for cooling purposes. This general declining trend of water withdrawal from once-through to dry cooling systems for each of the energy generation technologies can be seen in Figure 4.

With respect to the water consumption of different technologies, the trend that is seen in water withdrawal is somewhat reversed. Once-through cooling systems return almost all of the water withdrawn back to a water body (only a small amount of water is lost via evapouration), hence water consumption factors are relatively low compared to water withdrawal for each of the generation technologies. Recirculating cooling systems (ponds and towers) retain water that is withdrawn from water bodies for reuse therefore the water consumption of these systems is higher than for once-through systems. This increasing trend for each technology is shown in Figure 5.

Although the water footprints of fossil-fuel based generation technologies such as coal and natural gas are high, our analysis shows that the withdrawal and consumption factors for both bioenergy and CSP are also large. The water use of these renewable technologies may influence policy-making as countries move towards low-carbon development and begin to deploy renewables on a mass scale, especially in regions of the world where water-scarcity is an important factor. Large scale deployment of renewable energy technologies will be reliant upon, yet at the same time have serious consequences for, water availability.

The data in the two figures above relate predominantly to water withdrawal and consumption during the operational phase of electricity generation. However, from our research we have identified that the water footprints of both PV and wind in other life-cycle phases are relatively significant compared to their footprints during the operational phase. Therefore we have used water withdrawal and consumption factors for PV and wind that include water usage during the stages of power plant procurement and building; and fuel extraction, transportation and recycling. This is the case in both Figures 4 and 5. The water footprints of the remaining technologies, during these other life-cycle phases, are not included as part of this analysis as they have minimal impact on the data. It can be seen that even when taking the full life-cycle into consideration for PV and wind technologies, they remain the least water-intensive electricity generation options. This conclusion is supported by previous work by Meldrum et al. (2013), which incorporates a life cycle analysis of water consumption and withdrawal of different electricity generating technologies. It is important to emphasise here though that despite renewable energy sources generally using less water than fossil fuels, if a full life-cycle analysis is performed for bioenergy then this technology would become by far the most water-intensive option (Shell, 2014).

Fresh water usage can be reduced by using dry cooling; however this may lead to increased costs and decreased plant efficiency. CSP using dry cooling might lead to an annual reduction in electricity output of 2%-5%, and an increase in levelised cost of electricity of 3%-8% compared to wet cooling systems (Turchi et al. 2010). In the US the annual performance loss of switching to dry cooling from wet cooling systems is 6.8% for nuclear facilities, 1.7% for combined cycle plants, and 6.9% for other fossil fuel based generation plants (EPA, 2011).

The cooling system chosen is likely to play an important role in our future electricity generation mix. Given future uncertainties surrounding water availabilities and the consequences for power plants, particularly in regions of water scarcity, the use of alternative cooling techniques, such as dry cooling, may be necessary. Utilising dry cooling or non-fresh water resources avoids some of the risks associated with drought and climate change. By 2035 water withdrawals could potentially increase by 20% and water consumption by 85% if we shift towards higher efficiency power plants with more advanced cooling systems which reduce water withdrawal levels, but increase water consumption (UN, 2014).

We observe that general conclusions can be made from existing data, but further work is required to develop more accurate and comprehensive water withdrawal and consumption estimates across the various energy technologies. Improved data on water availability and regional water use factors is also required in the future to better understand how cooling system and electricity generation technology decisions will be made. Macknick et al. (2012) seem to agree with this statement remarking that more accurate estimations of water usage in power plants, and the regional effects of this water use, will only be possible if more studies are conducted that investigate the various impacts on water of different technologies and their water cooling systems.

Some of the alternative cooling systems to more conventional power plant cooling approaches offer potential water savings. However, this usually comes at a price because of factors such as high costs of the cooling system equipment, more power requirements, lower plant efficiency, and limited plant capacity. There are several trade-offs to consider (as previously outlined in Table 2, Section 3.1) when choosing which cooling system to use. For example, deciding to use a larger, higher capacity system will increase capital costs, yet at the same time provide more plant output and operational efficiency over the plant’s lifetime. The cost of water is another important consideration if choosing between wet and dry cooling systems, while it is not important in choosing between wet systems themselves, as water consumption factors between these systems are very similar. Even between dry cooling systems, capital and operating costs can vary substantially therefore it is important to make cost comparisons before deciding on which system to use. The use of either dry or hybrid cooling systems can result in large reductions in the amount of water used by the power plant, but they require larger capital investments and lead to lower plant performance resulting in further economic losses relative to wet cooling systems.

We recommend further work to be done on assessing the impact that the various costs involved in using the different power plant cooling systems may have on the choice of which system to adopt. In our view a co-optimisation analysis, in terms of both the water use of the power plant and the cooling system costs, would be a neat way to help determine which cooling system should be used in different regions of the world, but this requires more in depth research that is beyond the scope of this report.

While not investigated in this report, it is important to note that energy storage and the flexibility to respond to fluctuating demand for energy are likely to become increasingly important issues in the world’s future energy system. Many energy storage systems, such as pumped hydropower systems and Aquifer Thermal Energy Storage (ATES) – an advanced geothermal technology, withdraw significant water volumes. Hence, we would recommend further work to explore the water requirements of such energy storage systems.

It is worth mentioning here that energy production for transport is also an important area of research to consider. It is not region-bound and bioenergy in particular can play a critical role as it can be produced in areas where water stress has yet to become a dominant issue. This is in contrast to infrastructure development for electricity generation, which is region-bound and relies heavily upon the availability of water resources. An analysis of energy production for transport falls outside the scope of this report due to its complexity and scale. However, we recommend future research into the topic.

4

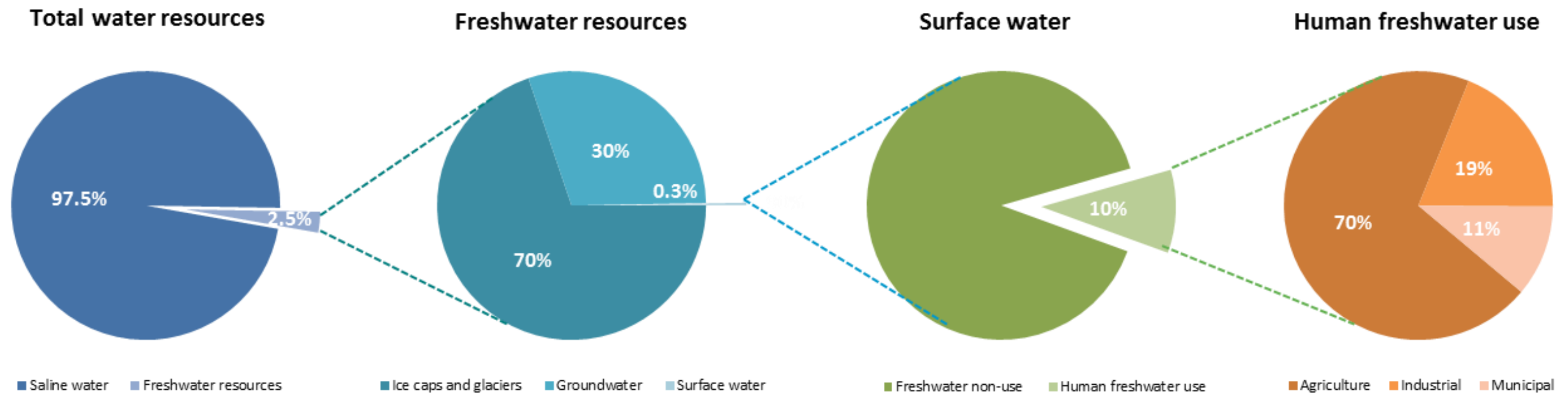
Regional water availability

While water is a renewable resource, demand continuously exceeds availability in many regions of the world, notably China, India and the MENA region (SEI, 2011). Water is of growing concern in assessing the physical, economic and environmental viability of energy projects throughout the world. Water availability could become a serious issue for unconventional gas development in regions of China and the US, in India's water-dependent power plants, in Canadian oil sand production and in sustaining reservoir pressures supporting oil production in the Middle East (OECD; IEA, 2012). These are just a few examples from the literature of where water stress in specific regions has the potential to destabilise energy production.

Water is an abundant resource, but it is not always available for human use in the quantities, quality, time and place it is needed. As shown in the left hand pie chart in Figure 6, only approximately 2.5% of the world's water is fresh water and, as is observed in the second pie chart from the left, less than 1% is available via surface sources and aquifers. The remainder is inaccessible, stored in glaciers and ice caps, or deep underground (IEA, 2012). Furthermore, approximately 87% of surface fresh water is concentrated in lakes, and many of these are located in inhospitable areas that are difficult to access. A few large lakes contain most of the Earth's surface fresh water, for example Lake Baikal in Siberia, Russia alone holds roughly 20% of the world's total, and the Great Lakes of North America account for another 21%. This further emphasizes the regional disparity in global fresh water resource availability.

The third chart from the left in Figure 6 shows that less than 10% of globally available fresh water is withdrawn for human use. About 19% of this water is withdrawn for use in the industrial sector, as is displayed in the pie chart furthest to the right. Moreover, roughly 5% of total global water withdrawal is attributed to energy generation in our current fossil-based system (Shell, 2014). An interesting observation can be made here: total water resources (fresh and saline) on Earth are around 10,000 times all directly usable fresh water, which is roughly comparable to the fact that solar energy irradiated on Earth is about 10,000 times what we consume globally.

Figure 6: Total water resources and human fresh water use, ECN 2014

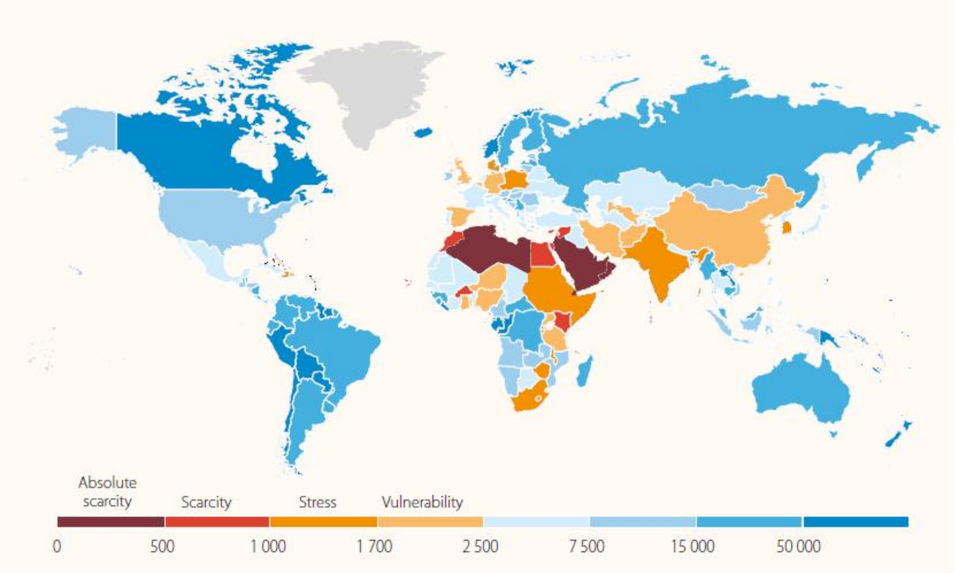


Sources: Shiklomanov, 1993; UN FAO Aquastat Database; Graedel et al., 2014.

Although precipitation data is available for most regions, river runoff and groundwater levels are more difficult to measure, therefore trends in the availability of fresh water supply in most areas of the world are hard to determine (UN, 2014). However, there is clear evidence of diminishing groundwater supplies, with over 20% of the world's aquifers being over-exploited (Gleeson et al., 2012). The rate of global groundwater use is also increasing by between 1% and 2% per year (UN, 2012).

It is evident that regional variations in water availability are large across the world. For example in Brazil, where there is high rainfall, water resources are abundant. In contrast, areas such as the MENA region face water scarcity and have to rely on using or transforming other sources of water. Examples are the use of saline water for cooling in industry and power production, avoiding water use through dry cooling techniques in power plants, or extracting water from non-renewable aquifers. The IEA WEO report uses renewable water resources per capita to present water scarcity, where population is a proxy for demand. Figure 7 below is taken from this report and shows that all continents face some degree of water scarcity, although in certain regions, MENA in particular, the issue of scarcity is more pronounced. Below Figure 7, Box 1 presents a case study investigating some of the water issues faced by Jordan, in many respects representative of the Middle-East which is the regional focus of our research in section 5 of this report.

Figure 7: Renewable water resources per capita in 2010



Source: UN WWDR 2014, UN FAO Aquastat database.

Box 1: Casy study, Jordan

Jordan is among the most water scarce countries in the world with only 145 m3 per capita per year in 2007 (Ministry of Water and Irrigation (MWI), 2009) available to meet domestic, industrial, agricultural, and environmental demand. This compares to 1,123 m3 and 461 m3 per capita per year in Egypt and Israel respectively (Shannag and Al-Adwan, 2000), and is approximately the same as the average of 175 m3 for Saudi Arabia, Kuwait, Oman and the United Arab Emirates (UAE) (Seckler et al., 1998). Estimates of the total fresh water potential in Jordan vary, but the MWI has reported that the figure in 2007 was approximately 867 million cubic metres (MCM) per year (MWI, 2009). The source of this fresh water is concentrated mainly in the Jordan river basin.

The total demand for water still exceeds the renewable supply. Water demand outstripped supply by over 20% in 1997 (MWI, 1997). The deficit between supply and demand was estimated at 565 MCM in 2007 (MWI, 2009). This has led to depletion of the Jordan river basin and consequently contributed to significant declines in levels of the Dead Sea.

The majority of Jordan's fresh water demand is from agriculture, which is estimated to use approximately 71% of total fresh water supply (MWI, 2009). However, urban and industrial demand for water is placing increased pressure on already strained water resources.

With respect to energy, Jordan relies heavily on imports to support its economy. The financial and economic costs of energy are particularly high in Jordan and water supply is estimated to account for about 25% of electricity demand. This is mainly because the country relies heavily on pumping surface and groundwater to higher elevations, sometimes over 1000 metres, where the demand for water exists, and this process is very energy-intensive (MWI, 2009). This makes the co-management of energy and water even more important for Jordan, which has been emphasised by the MWI.

Table 3 provides a breakdown of water withdrawal by regions of the world. In columns 2 and 3 of the table we can see that the quantity of total fresh water withdrawal is very similar to total water withdrawal, indicating that fresh water is by far the predominant source of water that is withdrawn for use in the world.

The table also shows that the lion's share of the world's total water withdrawal is concentrated in Asia (2,508 km^3), which accounts for approximately 64% of the global total per year. This is unsurprising given the high water requirements for agricultural purposes in the region.

Table 3: Total regional water withdrawal

Region	Total fresh water withdrawal (km^3)	Total water withdrawal (fresh and saline) (km^3)	Industrial water withdrawal per year (km^3)	% of total water withdrawal by industry (km^3)
World Total	**3752**	**3,902**	**731**	**19**
Africa Total	**202**	**214**	**11**	**5**
Northern Africa	82	94	6	6
Sub-Saharan Africa	120	120	6	5
Americas Total	**827**	**829**	**285**	**34**

Region	Total fresh water withdrawal (km^3)	Total water withdrawal (fresh and saline) (km^3)	Industrial water withdrawal per year (km^3)	% of total water withdrawal by industry (km^3)
North America	602	604	260	43
Central America and the Caribbean	31	31	4	12
South America	194	194	22	11
Asia Total	**2373**	**2,508**	**244**	**10**
Middle East	267	276	20	7
Central Asia	136	145	10	7
South & East Asia	1970	2,086	214	10
Europe Total	**332**	**333**	**188**	**57**
West & Central Europe	238	239	128	54
Eastern Europe	95	95	60	64
Oceania Total	**18**	**18**	**3**	**15**

Source: Aquastat database, 2006.

Table 4 provides an overview of potential fresh water resources by world region. This further demonstrates the regional disparity between water availabilities, showing that over 45% of the world's total fresh water resources are concentrated in the Americas, and a further 26.3% in South and East Asia (in the year 2011). The lowest water availability per capita is recorded in Northern Africa (279 m^3) and the Middle East (1,559 m^3), in which only 0.1% and 1.1% of the planets total fresh water resources are located respectively.

Table 4: Regional fresh water availability

Region	Volume per year (km^3)	Volume per capita (m^3)	% of world fresh water resources
World Total	**42,370**	**6,079**	**100.0**
Africa Total	**3,931**	**3,764**	**9.3**
Northern Africa	47	279	0.1
Sub-Saharan Africa	3,884	4,431	9.2
Americas Total	**19,104**	**20,272**	**45.1**
North America	6,077	13,147	14.3
Central America and the Caribbean	781	9,328	1.8
South America	12,246	30,890	28.9
Asia Total	**11,865**	**2,816**	**28.0**
Middle East	484	1,559	1.1
Central Asia	242	2,576	0.6
South & East Asia	11,139	2,924	26.3
Europe Total	**6,578**	**8,884**	**15.5**
West & Central Europe	2,128	3,998	5.0
Eastern Europe	4,449	21,389	10.5
Oceania Total	**892**	**30,447**	**2.1**

Source: Aquastat database, 2011.

Table 5 below shows a breakdown of water availability per capita by region, and trends projected up to 2050. The table is adapted from the UN WWDR 2014, which sources data from FAO AQUASTAT database (accessed Dec 2013).

Table 5: Projections of total world renewable water resources up to 2050 (m^3 per capita per year)

Region	2000	2010	2020	2050
World Total	**6,936**	**6,148**	**5,095**	**4,556**
Africa Total	**4,854**	**3,851**	**2,520**	**1,796**
Northern Africa	331	284	226	204
Sub-Saharan Africa	5,812	4,541	2,872	1,983
Americas Total	**22,930**	**20,480**	**17,347**	**15,976**
North America	14,710	13,274	11,318	10,288
Central America and the Caribbean	10,736	9,446	7,566	6,645
South America	35,264	31,214	26,556	25,117
Asia Total	**3,186**	**2,845**	**2,433**	**2,302**
Middle East	1,946	1,588	1,200	1,010
Central Asia	3,089	2,623	1,897	1,529
South & East Asia	3,280	2,952	2,563	2,466
Europe Total	**9,175**	**8,898**	**8,859**	**9,128**
West & Central Europe	4,258	4,010	3,891	3,929
Eastern Europe	20,497	21,341	22,769	24,874
Oceania Total	**35,681**	**30,885**	**24,873**	**21,998**

Source: adapted from the UN WWDR (2014).

It should be noted here that the projections above are based on underlying assumptions about the world's population growth up to 2050. The estimates are therefore quite sensitive to changes in these population growth expectations, and the primary determinant of future water availability is population levels. Despite this it is not surprising to see that as the global population expands, water needs will increase placing further strain on water resources to meet rising energy demand and a requirement for increased food production. Hence, the projections indicate a substantial decline in water availability worldwide up to 2050, with regions such as Africa (particularly Sub-Saharan Africa), for example, experiencing relatively higher per capita declines in percentage terms than other regions (63% decline in the whole of Africa between 2000 and 2050). Low to middle income countries, for example in the Middle East region, are already struggling to meet growing demands for water and energy (UN, 2014), and these projected reductions in water availability reflect a likely exacerbation of the problem in these countries. Data from the World Resources Institute (WRI) suggest that water availability in many areas of the Middle East in particular is at 'extremely high' or 'high' risk of threatening the social, economic, and political stability of the region (WRI, 2014). We will thus investigate in the next section the water usage of the power sector particularly for this region.

The issue of climate change, combined with economic growth and population expansion, threatens to generate additional pressure on water availability in many regions. More frequent and severe climate conditions including droughts, heat waves and floods; falling average surface water flows; and sea level rise are some of the expected impacts of rising temperatures (IPCC, 2013), which will increase water stress in affected regions.

5

Energy-Water Nexus Scenarios

In this section we inspect what the water withdrawal and consumption implications might be of two main types of scenarios for future energy needs and the technologies employed to meet this energy demand: a baseline and a stringent climate policy scenario. We do this for the Middle East as a case study since it is one of the regions in the world where water stresses are becoming most apparent (as shown in Figure 6, section 4). Having inspected in the previous two sections both water requirements and availabilities, and in particular the water intensities of different energy technologies, we here investigate scenarios that enable us to analyse which of the electricity generation options could potentially be most suitable for this particular region from a water use perspective. Knowledge of water usage levels of the power sector in the Middle East allows for matching them with data for water availability in this region.

In essence our baseline scenario does not include existing and planned climate policies, which means that it does not include GHG emission reduction targets stated by countries in their Copenhagen and Cancun pledges. However, the scenario does include policy measures on renewable energy which were in place before 2010, and which are assumed to remain in effect in the foreseeable future. In the 2C climate policy scenario we assume that all low-cost options to reduce GHG emissions are deployed to reach the global 2°C target, regardless in which world region or sector the emission reductions take place. This corresponds to a globally harmonized action to mitigate climate change, such as a global carbon certificate market which would mean GHG emission reduction obligations are allocated based purely on cost-efficiency criteria. This also corresponds to the ‘450 scenario’ developed by Kriegler et al., 2013.

The left-hand plot of Figure 8 shows a possible baseline scenario for electricity generation in the Middle East (which is here defined as the countries of the Levant and the Arabian Peninsula, Iran, Iraq and Turkey). It represents of course just one of the many ways business-as-usual power production could expand over the next several decades, but it constitutes in our view a realistic one, due to the abundant role it gives to the use of natural gas in the power sector given the local availability of this resource in the region. This baseline scenario has been developed with the bottom-up energy systems model TIAM-ECN, which is one of ECN's tools to make internally consistent long-term energy supply and demand scenarios (for more details and examples of how this model can be used for energy and climate policy analysis, see for example van der Zwaan *et al*., 2013a; van der Zwaan *et al*., 2013b; Kober *et al*., 2014; Rösler *et al*., 2014). As one can see, relatively modest roles are also reserved for coal and oil in power production in this scenario, but by the middle of the century natural gas remains practically the only fossil fuel left for the electricity sector. Hydropower plays a non-negligible role throughout the forthcoming decades, given the potential of this option in countries such as Iran and Turkey.

The right-hand plot of Figure 8 shows how power supply may significantly alter over the next decades if one assumes that in the Middle East, just as elsewhere in the world, stringent climate policy is introduced (capable of reaching the global 2°C target), which we determine by applying a constraint on emissions of CO_2 in the TIAM-ECN model. TIAM-ECN calculates that the cost-optimal transition path involves not only a drastic reduction in the role of the single most important fossil fuel, natural gas (part of whose use will be subjected to CCS implementation), but also a massive introduction and diffusion of solar energy (in particular CSP, according to our model). The latter makes sense in view of the large solar irradiation resources the Middle East possesses. In addition to CSP and some PV, relatively small but non-negligible roles are reserved for power production options such as biomass, wind and hydropower. It also proves cost-effective to introduce a certain level of energy savings in this climate policy scenario, as evidenced by its lower level of power production in 2050 in comparison to that in the baseline. Otherwise, as could be expected, the climate change control stringency necessitates a massive introduction of low-carbon renewables.

Figure 8: Baseline and stringent climate policy scenario for power production in the Middle East.

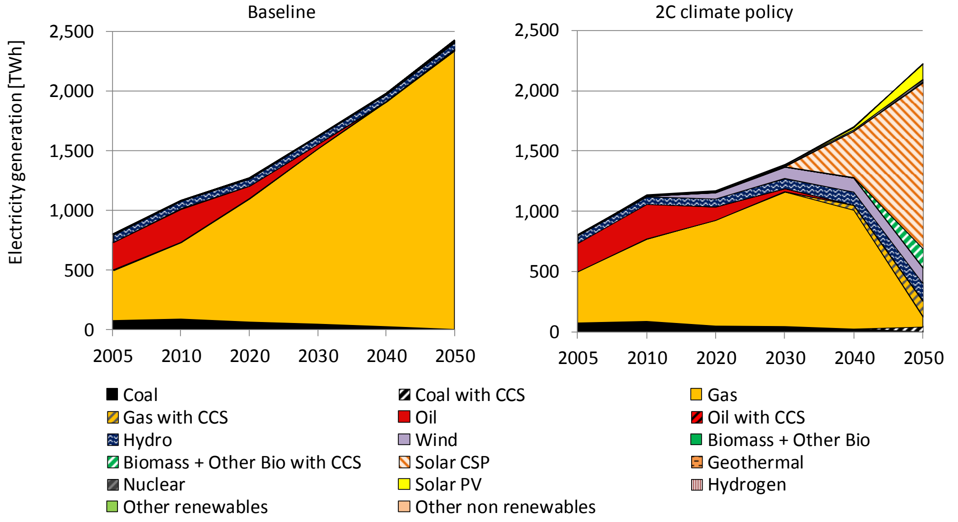
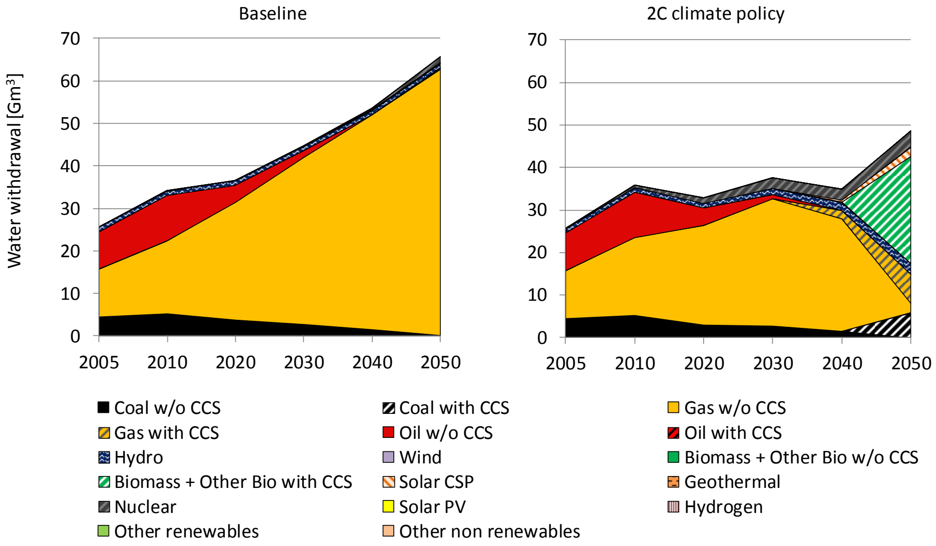


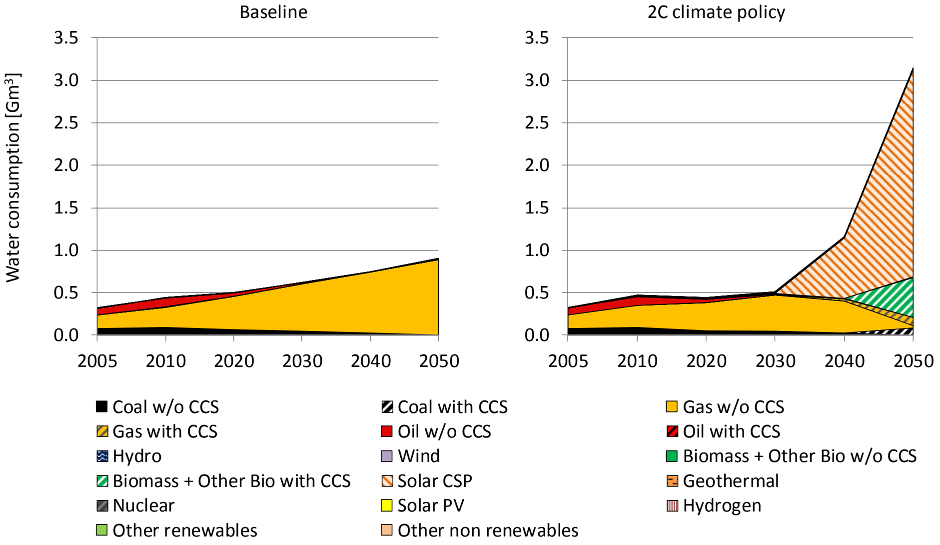
Figure 9 depicts what the water withdrawal levels would be, if we superimpose the water intensity factors as reported in section 4 onto the power production patterns of Figure 8. The color shading of the left plot of Figure 9 (for the baseline) looks very similar to that of the left plot of Figure 8, except for the fact that the oil and coal shares are slightly fatter in the former. This is an expression of the fact that the water withdrawal intensity of natural gas based electricity generation is somewhat smaller than that of its fossil fuel counterparts. The color composition of the right plot of Figure 9, on the other hand, looks very different from that of the right plot of Figure 8. The reason is, first of all, that CCS (deployed in consequence of the stringent climate policy) is a very water-intensive technology, as demonstrated by the large water withdrawal shares in Figure 9 (right plot).This is especially apparent for the use of biomass in combination with CCS, as non-CCS biomass use for power production is also a water-intensive option. In terms of water withdrawal, CSP has a much smaller water footprint, as evidenced by the relatively small contribution of CSP to the right-hand-side graph of Figure 9. Hydropower withdraws, naturally, substantial amounts of water. Nuclear power, finally, while hardly discernible in the right-hand-side graph of Figure 8, occupies a disproportionally large share in the right-hand-side graph of Figure 9, the explanation for which is the water-intensive nature of nuclear power.

Figure 9: Baseline and stringent climate policy scenario for water withdrawal in the Middle East.



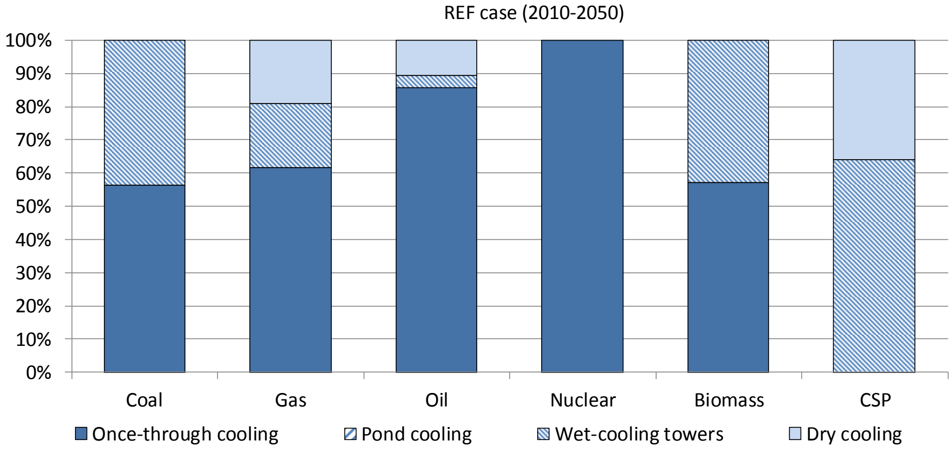
Over the course of the coming few decades it can be expected that at least four countries in the region (Iran, Saudi Arabia, United Arab Emirates and Turkey) consume domestically produced nuclear-based electricity. The right plot of Figure 10 shows that in terms of water consumption, the stringent climate policy scenario looks quite different from that in terms of water withdrawal. In the former case, CSP is by far the dominant force, since it is substantially more water-consuming than even biomass power production complemented with CCS technology.

Figure 10: Baseline and stringent climate policy scenario for water consumption in the Middle East.



Underlying the results depicted in Figures 9 and 10 are the cooling techniques associated with the respective individual electricity generation options, since these cooling technologies are responsible for the vast majority of the indicated water withdrawal and consumption levels. Figure 11 shows what the breakdown is today of different types of cooling techniques in the Middle East for each of the main current and future power generation alternatives. For calculating the water usage profiles shown in Figures 9 and 10, we have assumed that this breakdown continues to hold until 2050, which we refer to as the reference (REF) case. In other words, for coal usage, for example, we assume that until the middle of the century about 55% of all power plants remain equipped with once-through cooling technology (using either fresh or, especially, saline water in this region), while 45% of the coal-based power plants use recirculating methods to cool (either cooling tower or pond-based techniques). Likewise, approximately 60% of natural gas based power plants remain equipped with once-through cooling, while 20% of these plants use recirculating methods and another 20% dry cooling techniques. For CSP plants we suppose that the current breakdown of some 65% of recirculating and 35% of dry cooling techniques continues to hold for the forthcoming decades.

Figure 11: Current and future shares of cooling techniques for the main power production options in the Middle East in the REF case.



NB: shares refer to technology with the Rankine cycle.

Due to serious water constraints, especially in the Middle East, which may intensify over the years to come, it is likely that efforts will be made to reduce the water usage of power plants in the region. This can be achieved by replacing once-through cooling by recirculating cooling, and/or substituting the latter with hybrid or dry cooling options. Such replacement will be a gradual process, given the capital intensity of both power plants and cooling technologies, and since water constraints will probably gradually emerge in various locations rather than abruptly come to the fore in the region at large. A possible scenario for this process is depicted in Figure 12, in which for all major electricity generation options (based on, respectively, coal, natural gas / oil, nuclear, biomass and CSP) a pattern is supposed for the gradual phase-in of water-saving technologies. This scenario is referred to as the SAVE case. Of course, this scenario engenders certain additional costs, the overall magnitude of which was briefly investigated in the previous section. This cooling options scenario, however, was not developed or calculated on the basis of a combined cost-minimization procedure for energy and water technologies simultaneously (but on the basis of that for energy technologies only). In practice, a SAVE scenario may thus materialize differently, that is, with other energy and water technologies.

Figure 12: Current and future shares of cooling techniques for the main power production options in the Middle East in the SAVE case.

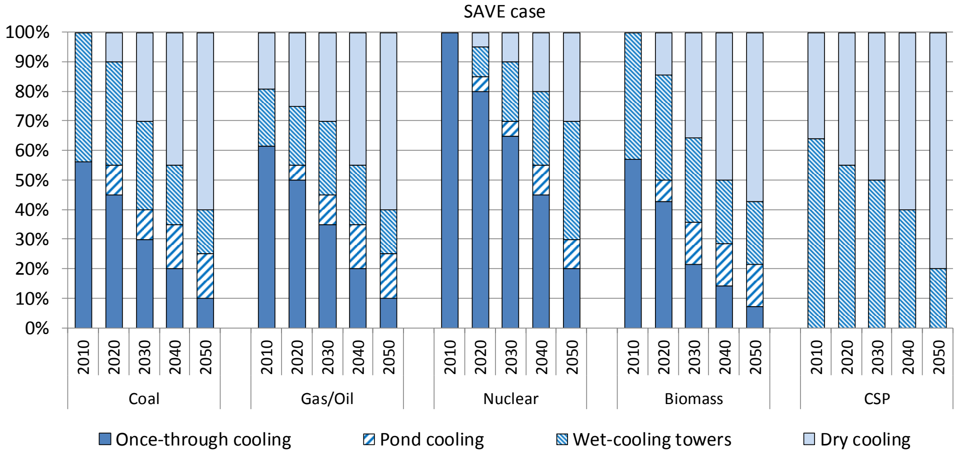
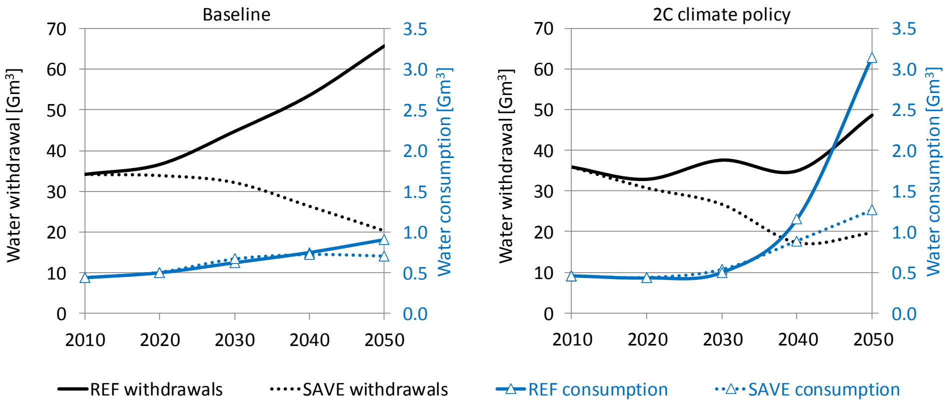


Figure 13 shows how our water withdrawal and consumption projections modify, both in the baseline and stringent climate policy scenario, if one switches from REF-case cooling techniques to those we assume in the SAVE-case. The large reduction in water withdrawal in the baseline scenario when switching from the REF to the SAVE case is obvious, which is mostly the result of the gradual phasing out of once-through cooling and the introduction of recirculating, hybrid and dry cooling systems instead for natural gas based power production (see the left-hand plot of Figure 13). The same plot in Figure 13 points out that this switch has little effect on water consumption levels during the first couple of decades, which can be explained by the fact that recirculating types of cooling actually possess higher water consumption levels than once-through systems. In the period 2040-2050 though, a reduction in water consumption materializes of about 30%, thanks to the savings introduced as a result of in particular dry cooling systems (which do not use any water). For the stringent climate policy scenario (see the right-hand plot of Figure 13) we see a few notable differences. First of all, in terms of water withdrawal the savings are substantially lower than in the baseline scenario, the explanation for which is the large role played in the climate control scenario by CCS and biomass based power production technologies. For water consumption the difference between the REF and SAVE cases is small initially, like in the baseline scenario, but from about 2030 the discrepancy between these two cases becomes very large. The reason is that particularly CSP, and to a lesser extent biomass, are assumed to rely largely on dry cooling systems by the middle of the century in the SAVE case.

Figure 13: Water withdrawal and consumption for two electricity sector scenarios under REF and SAVE cases in the Middle East.



A recent study by Bouckaert *et al*. (2014) also involved a scenario type of investigation of energy-water interdependencies. They added water footprints related to the power system (including cooling systems, gasification and flue gas desulfurization processes), to their global TIAM-FR energy system model. With their modification, the TIAM-FR model can be used to ascertain whether future energy mixes might be plausible in terms of water availability. The authors evaluated diverse policies concerning water and carbon emissions, and suggested that the choice of the cooling system and the use of CCS when applying climate policies to the energy system may significantly increase overall fresh water consumption. In our study we confirm this finding, as can be seen from Figure 13: if climate policy is implemented and no dedicated water consumption savings strategy is adopted, water consumption may exponentially increase, even in comparison to the baseline scenario.

In regions such as the Middle East where water is already scarce or is likely to become so, an increase in fresh water consumption levels or withdrawals may not be sustainable for the energy system. Hence we suggest that in the future we adapt TIAM-ECN so as to incorporate water use factors, which would allow us to consider water as a constraint and evaluate the impact of water scarcity on electricity production in a region such as the Middle East. Even better, subsequently, we could improve our model so as to introduce the costs of cooling systems as well as the costs of water employed therein (as water often does not receive a proper cost price, contrary to energy for example, therefore is not always visible), which would allow us to perform a combined cost minimization analysis of energy and water systems simultaneously. It could well prove that the resulting optimal regional energy systems look different from the ones that we obtain with the current format of our model, which is based on cost minimization of the energy system only. Given that the subjects of energy and water are becoming increasingly intertwined in a future climate-constrained world, this joint analysis would not only be an exciting type of new research, but may also constitute an essential requirement for any study that attempts to determine the desirable energy system of the future.

6

Conclusions and Recommendations

This report has shown that both the energy and water sectors face key challenges over the coming decades. We have demonstrated that in many respects these challenges are interrelated and thus need to be simultaneously addressed. The joint challenges associated with the energy-water nexus, however, are clearly different from those for climate change. The former may pose substantial problems at the local or regional level, but that are often addressable, one way or the other. They may in some cases last only relatively short periods of time, although potential solutions may sometimes come at a high cost. The latter is a truly global *problematique* with challenges that are not easily solvable and are long-lived, that is, span centuries. The costs required to mitigate climate change, although quite uncertain, may amount to an order of magnitude of a percent of global world product. In this report we direct our attention primarily to the energy-water nexus, rather than the energy-climate nexus, while addressing – from a scenario analysis perspective – the possible effect of climate change on the former.

The first main conclusion that we draw from our work is that the type of cooling system used for electricity generation is at least as influential for the water needs of power production as the type of energy technology used. This is certainly the case for conventional thermal power generation technologies, such as based on coal, natural gas, oil and nuclear energy, but possibly also for other more modern techniques, including for example a renewable technology such as CSP. This does not apply, however, to renewable technologies such as PV and wind, which do not require water for cooling purposes.

Second, we conclude that even when taking the full life-cycle into consideration, PV and wind technologies remain the least water-intensive electricity generation options relative to other energy technologies considered in this report. This is true even when we only take into account the operational phase for the other energy technologies (thereby making in some sense an unfair comparison), and irrespective of the fact that the water footprint of PV and wind electricity options in the stages of manufacturing and production is often relatively high in comparison to other energy technologies.

Indeed, the very high water use of technologies such as based on coal, natural gas and oil, or nuclear energy and CSP, takes place predominantly in the operational phase of electricity generation. Overall, technologies like PV and wind thus appear to be clear winners in terms of water-saving potential.

Third, it has been suggested in the literature - and we support this claim - that in certain world regions water availability is becoming as important as security of energy supply. In view of the linkages between water and energy supply, integrated optimization analyses and policies regarding energy and water resource systems are necessary. Rather than first finding least-cost energy systems and subsequently finding the least-cost water supply that these systems require, instead one should attempt to minimize the costs of energy-water systems jointly.

Fourth, due to water constraints it is likely that further efforts will need to be made to reduce the water usage of power plants in regions such as the Middle East. To achieve these reductions, once-through cooling may need to be replaced by recirculating cooling, which in turn can be substituted by hybrid or dry cooling options. The gradual increase of regional water constraints may make these replacements necessary, but the capital intensity of both power plants and cooling technologies will mean that such replacements will take place over years or decades.

Fifth, in a future that involves more stringent climate policy a large role may be reserved for CCS and biomass based power production. These two technologies withdraw large quantities of water. The water withdrawal savings that otherwise would perhaps be achieved in a business-as-usual scenario, would perhaps be over-shadowed by the sizeable water usage of these low-carbon technologies. This is an example of the kind of trade-offs that policy makers need to consider when designing and implementing policies related to the energy-water nexus sectors, as well as climate policies.

Sixth, we conclude that while regions already exist where there is substantial water-stress, the problems in principle, from at least a technical perspective, can often be overcome, albeit sometimes at a high cost. In the long run both water withdrawal and consumption can be reduced significantly if decisions are made, particularly (but not only) in the field of energy production and consumption, that take water issues into account. We thus find that water-stress issues, also in those regions where at present they are not yet apparent but may emerge in the farther future, can often be addressed either by using different (energy and water) technologies or by moving certain (e.g. industrial) activities to different regions. The real question though is at what cost.

This report has detailed some insights into the energy-water nexus, in particular highlighting the analysis gaps that still remain in our understanding of various important issues related to the nexus. This has led us to make some key recommendations.

Our first main recommendation is that for water-stressed regions the scaling-up of PV and wind technologies for electricity generation is compatible both with transitioning toward low-carbon development and dealing with water-scarcity issues. This is important information for policy-makers who may face the simultaneous responsibilities of considering both climate targets and water resource constraints when confronted with making choices or trade-offs in the energy and water sectors. ECN is a leading research institution in both solar and wind technology. This report highlights that opportunities exist for ECN to further direct and exploit the expertise it possesses of these technologies. Future efforts of ECN could increasingly be targeted toward developing water-efficient solutions for generating electricity in water-stressed regions of the world, and advising policy-makers on their best course of action in relation to energy and water resource systems.

Second, more research is needed to determine the water intensity of a large variety of energy production options. As we have seen in this report, large gaps in our knowledge exist with regards to accurate estimates of water withdrawal and consumption factors for different electricity generating technologies. In particular, although some work has been carried out in this field, there are large gaps in the available data for full lifecycle water withdrawal and consumption factors. We recommend future work to be carried out in this area, which could become a research focus of ECN. It would in any case be beneficial for both the research and policy making communities to attempt to fill these gaps and enhance our understanding of the energy-water nexus in this respect.

Third, this report predominantly focused on the water requirements of energy production, and electricity generation in particular. Conversely, much more needs to be understood and improved about the energy consumption of fresh water production, which we recommend as another potential subject for more elaborate analysis. This could particularly benefit countries with already apparent water scarcities, such as in the Middle East and North Africa, or in other regions in Africa and Asia.

Fourth, the costs of different cooling system technologies should be further investigated. The divergent costs between various distinct systems can have far-reaching implications in terms of the water saving potential of power plants in all regions of the world, as well as in terms of the opportunities that may exist for less water-intensive cooling technologies deployable in water-stressed regions.

Fifth, further research should be undertaken to understand the energy requirements and costs of desalination technologies. This is an area of growing importance and will become particularly relevant in the future for regions that have good accessibility to seawater, yet at the same time suffer from fresh water scarcity. Our region of focus in this report, the Middle East, is a good example that deserves further study. There are also opportunities to produce or save fresh water through other methods, such as via combustion processes , and further studies are required to examine these options in detail.

Sixth, the complex interrelationship between energy and water production and consumption is another domain that requires further in-depth analysis from an energy-systems perspective. Such analysis can, for example, be performed with integrated assessment models (IAMs), in particular those of a so-called bottom-up nature. These models could be rendered capable of performing joint optimisation of energy and water production, whereas they have so far traditionally only been used to focus on energy production and use only. IAMs may be useful, as they allow for analyzing trade-offs between costs, efficiencies and emissions of energy, and perhaps in the future also and simultaneously availability and costs of water. This could be a strategic field of work for

ECN, in which it has already built a good level of understanding given its broad energy sector expertise.

Seventh, we recommend further assessments like the ones presented in this report in order to develop country-specific and region-specific scenarios. This would provide decision-makers at the country or regional level with a more realistic set of scenarios which can guide them in developing plans and policies related to energy and water resource systems.

Eighth, we recommend more work on the water implications of energy production and use in the transport sector. This sector is less region-bound and bioenergy could play a critical role because it can be produced in areas where water stress issues are less stringent. This is a broad and complex area of study that fell outside the scope of this report. We do recognize the importance of it, however, which we thus leave for subsequent research.

Ninth, energy storage and the flexibility to respond to fluctuating demand for energy are likely to become increasingly important issues in the world’s future energy systems. Several energy storage systems, such as pumped hydropower and Aquifer Thermal Energy Storage (ATES), or advanced geothermal technology, withdraw significant water volumes. We recommend further studies to explore the water requirements of such energy storage systems.

Finally, the main focus of this study has been the energy-water interrelationship and our corresponding interpretation of the nexus including the linkages between energy, water and climate change. In follow-up work we may extend this to more explicitly include the dimension of food production and consumption. Essential for such subsequent work will be to connect to a research institution with dedicated expertise in the field of food, agriculture and land use.

Research on the energy-water nexus is still in its infancy. There are substantial gaps in the data that have so far been collected or calculated, particularly in terms of water availability, and withdrawal and consumption factors of energy technologies, but also in terms of the depth of analysis on the subject. There is much still to explore regarding the interdependencies between each part of the nexus, and how humans can better balance the trade-offs that exist between the different elements, both spatially and temporally. Different regions of the world face different stresses and subsequently they have different priorities. For example, water stress is more pronounced in the MENA region, which inevitably means that the choice of energy technology deployed, and the technology types used within each generation category, will be more heavily dependent on their respective water withdrawal and consumption factors.

Regional cooperation could become pivotal in order to successfully balance the trade-offs within the nexus, for example between water-rich and water-stressed countries. Over time, due to factors such as rising population levels, changing consumption patterns, and more extreme climatic conditions, water stress is likely to increase even in regions which currently have sufficient supply. These pressures will affect both the supply of, and demand for, water resources in the longer-term. It is therefore necessary to assess the trade-off between the cost of investing in water technologies now, and the potential benefits these investments may bring in the future. Our nexus approach is a dynamic, integrated way of tackling the complex issues involved in energy and water, and soon hopefully food, globally.

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Appendix A.

Table 6 provides an overview of the water withdrawal and water consumption ranges for different electricity generating technologies used in our analysis. Figures 4 and 5 in section 3 are based on the data contained in this table.

Table 6: Water consumption and withdrawal factors of different electricity generating technologies.

Technology	Cooling system	Water consumption range (l/MWh)		Water withdrawal range (l/MWh)		Data source
		Min	Max	Min	Max	
Coal	Once-through	242	1,200	75,708	189,270	EPRI (2002); Dziegielewski and Bik (2006); NETl (2009); Macknick et al. (2012)
	Pond	15	3,043	1,135	90,850	EPRI (2002); Dziegielewski and Bik (2006); NETl (2009)
	Tower	1,204	4,164	1,355	5,031	EPRI (2002); NETL (2009, 2010); Macknick et al. (2012)
Natural gas	Dry	1	15	1	15	EPRI (2002); NETL (2009); Macknick et al. (2012)
	Once-through	76	1,102	28,391	227,124	EPRI (2002); NETL (2009)
	Pond	908	1,022	1.022	22,712	NETL (2009)
	Tower	492	4,429	568	5,527	Gleick (1993); EPRI (2002); Leitner (2002); NETL (2009, 2010); Macknick et al. (2012)
Nuclear	Once-through	379	1,514	94,635	227,124	EPRI (2002); Dziegielewski and Bik (2006); NETL (2009)
	Pond	2,120	2,725	1,893	49,210	EPRI (2002); Dziegielewski and Bik (2006)
	Tower	2,199	3,199	3,028	9,842	Gleick (1993); EPRI (2002); Dziegielewski and Bik (2006); NETL (2009); Macknick et al. (2012)
Biopower	Dry	132	132	132	132	EPRI, DOE (1997)
	Once-through	1,136	1,136	75,708	189,270	EPRI (2002)
	Pond	1,136	1,817	1,136	2,271	EPRI (2002)

Technology	Cooling system	Water consumption range (l/MWh)		Water withdrawal range (l/MWh)		Data source
		Min	Max	Min	Max	
	Tower	890	3,653	1,893	5,527	EPRI, DOE(1997); EPRI (2002); Mann and Spath (1997); Macknick et al. (2012)
CSP	None	15	23	15	23	Leitner (2002); Macknick (2012)
	Dry	98	299	98	299	Burkhardt et al. (2011); Macknick et al. (2012)
	Tower	2,744	4,001	2,744	4,001	Gleick (1993); Cohen et al. (1999); Leitner (2002); Stoddard et al. (2006); Viebahn et al. (2008); Burkhardt et al. (2011); DOE (2009); Macknick et al. (2012)
PV	None	4	356	4	356	DOE (2012); Hsu et al. (2012); Kim et al. (2012)
Wind	None	1	42	53	318	DOE (2006); Inhaber (2004); Doland and Heath (2012)

Many of the data underlying the ones listed in Table 6 above can be found in Macknick et al. (2012) and Meldrum et al. (2013), but our data are all presented in litres per MWh (rather than gallons per MWh). There are also some other notable exceptions. For example, we have updated the data in a couple of instances, and filled in some of the earlier gaps. Also, while we follow these earlier works in the sense that we in principle present data only for water withdrawal and consumption estimates at the operational level for all technologies, we make an exception for PV and wind. The estimates for these two technologies include the full life-cycle of water usage. Even with purposefully introducing this bias, PV and wind prove to be technologies that possess low water intensities in comparison to other power production technologies.

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